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Oak decline risk rating for the southeastern United States

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Summary — Oak decline risk rating models were developed for upland hardwood forests in the southeastern United States using data gathered during regional oak decline surveys. Stepwise discriminant analyses were used to relate 12 stand and site variables with major oak decline incidence for each of three subregions plus one incorporating all subregions. The best model for the northern Appalachian subregion included soil depth class, oak basal area, site index, and stand age (R^2 = 0.65). In the southern Appalachian subregion, significant variables included slope gradient, soil depth class, oak basal area, and clay content (R^2 = 0.30). The Ozark model included clay content, slope gradient, and oak basal area (R^2 = 0.32). The composite model included site index/age, clay content, slope gradient, soil depth class, and oak basal area (R^2 = 0.22). The relatively low R^2 values and variation in the relationships for some attributes suggest that major oak decline events may be influenced by additional factors.

oak decline / risk rating / predictive model

Résumé — Évaluation du risque de dépérissement des chênes pour le sud-est des États-Unis. *Des modèles d'évaluation du risque de dépérissement de chênes ont été établis pour des forêts feuillues d'altitude du sud-est des États-Unis en utilisant des données recueillies au cours des enquêtes régionales sur le dépérissement des chênes. Au total, 15 variables relatives au site et aux placettes ont été corrélées à l'intensité du dépérissement en utilisant des analyses discriminantes par étapes. Des modèles prédictifs ont été développés pour chacune des trois sous-régions, ainsi que pour une zone plus vaste comprenant les trois sous-régions. Le meilleur modèle pour la sous-région «Nord-Appalache» comportait les facteurs suivants : profondeur (par classe) du sol, surface basale, index de site et âge du placeau* (R^2 = *0,65). Dans la sous-région «Sud-Appalache», les variables les plus significatives étaient la pente, la profondeur du sol, la surface basale, et la quantité d'argile* (R^2 = *0.30). Le modèle «Ozark» comprenait les variables : quantité d'argile, pente, et surface basale* (R^2 = *0.32). Le modèle global comprenait les facteurs : index du site/âge du placeau, quantité d'argile, pente, profondeur du sol et surface basale* (R^2 = *0.22). Les valeurs* R^2 *relativement faibles et la variation des relations entre ces paramètres suggèrent la possibilité que les incidents majeurs de dépérissement de chênes soit fortement influencés par des facteurs additionnels.*

dépérissement de chênes / évaluation de risque / modèles prédictifs

INTRODUCTION

Oak decline in the southeastern United States is a widespread disease complex with a long history. Reported occurrences date to the mid-1850s (Hopkins, 1902) and the early part of this century (Beal, 1926; Balch, 1927). A perceived increase in visible damage during the early 1980s stimulated efforts to determine whether these increases were in fact occurring. Periodic multi-resource inventories based on a network of permanent plots covering the region already existed and have confirmed these perceptions. Large increases in hardwood mortality (Bechtold et al, 1987; Brown, 1993) were detected. Oak decline symptoms occurred on approximately 1.6 million ha in 12 states (Starkey et al, in preparation). This area represented nearly 10% of the host type.

Other work was initiated to determine stand and site attributes of affected and healthy areas. Surveys were concentrated in, but not limited to, national forests in the Appalachian and Ozark Mountains in the southeastern United States. These combinations of landforms and ownership class are dominated by mixed hardwood forests with a large oak component and were perceived to have the highest incidence of decline in the region. Surveys included an evaluation of 38 severely affected areas in ten states (*Survey 1*; Starkey et al, 1989); an aerial photo-ground survey of three widely dispersed national forest districts (*Survey 2;* Oak et al, 1990); and a detailed analysis of the multi-resource inventory of western Virginia (*Survey 3;* Oak et al, 1991), the state with the highest incidence and largest affected area in the region (Starkey et al, in preparation). Consistent associations between certain stand-site factors and oak decline and mortality were detected in the different surveys. Relatively high incidence of oak mortality and advanced decline symptoms (ie, progressive crown dieback of dominant and codominant oaks) was associated with stands composed of a high proportion of oak in the overstory, especially red oaks (*Erythrobalanus* spp); average or lower site quality (site index < 21 m); older age classes (> 70 years); relative physiologic maturity as defined by the ratio site index/stand age (SI/age < 0.40); and relatively xeric site conditions (ie, shallow or excessively drained soils). Variation in the strength of these relationships was also detected among geographic subregions. These findings led to an hypothesis that oak decline risk rating systems could be developed from standard forest inventory data for predicting the relative probability of future decline events in individual forest stands, and for evaluating conditions on large landscapes. Such systems would be useful to resource managers in prioritizing areas where mitigating actions would be most effectively employed. This paper reports the results of analyses of these associations and the development of practical applied models to predict the probability of major incidence of oak decline in the future.

METHODS

Data collected in *Surveys 1* and *2* were used in these analyses. *Survey 3* could not be used due to fundamental differences in survey objectives, design, and sampling methods.

Plots were segregated into three geographic subregions (fig 1) based on differences in local physiography, climate, latitude, and tree species composition that had proved important in earlier analyses (Starkey et al, 1989). These subregions were northern Appalachian (NAPP), southern Appalachian (SAPP), and Ozark (OZ). Plots from seven stands were not included in our work because they fell within the boundaries of other subregions and did not contain sufficient observations for a separate model.

Twelve stand-site variables were used in our analyses (table I). Plot values for each variable represented the mean of four *(Survey 1)* or five *(Survey 2)* basal area factor 2.296 subplots. Incidence of oak decline (INCIDNCE; table I) was the percentage of dominant and codominant oaks

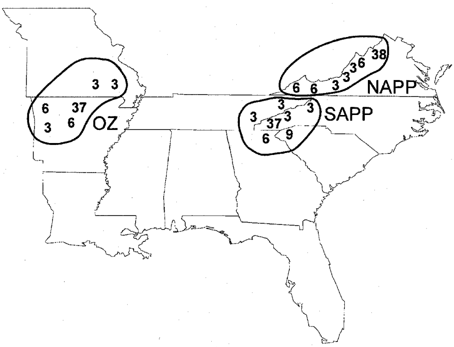

Fig 1. Location and number of plots evaluated for oak decline in geographic subregions in the southeastern United States (NAPP = northern Appalachian; SAPP = southern Appalachian; OZ = Ozark).

with decline symptoms encompassing at least 34% of the crown volume and including recently dead standing trees with evidence of prior dieback (moderately fine crown structure remaining). Plots within subregions individually and combined were classified as major or minor damage cases using a 20% INCIDNCE threshold. To the forest manager, decline symptoms of the severity described occurring in one in five overstory oaks would likely prompt some type of ameliorative action. Therefore, a stand with less than 20% INCIDNCE was classified as a minor case, while one with 20% or more was classified as major. The means for each variable in major and minor damage groups were then subjected to *t*-tests to identify variables (table I) with significant statistical differences with respect to major and minor damage to guide further analyses. Different threshold INCIDNCE levels were also tested to determine if better statistical separation of major and minor damage cases could be obtained. The optimal INCIDNCE threshold was determined to be the value where significant statistical differences were detected for the most variables while also maintaining the criterion of a meaningful management threshold.

Subsequent statistical procedures were selected that would yield practical applied models whereby the probability of major INCIDNCE could be related to stand-site variables. Stepwise discriminant analyses (SAS Institute, 1990a) were run in an effort to select variables that, in interaction with each other, were useful in separating the plots into major and minor damage groups. Logistic regression procedures (SAS Institute, 1990b) were then used to develop probability functions and tables for application by resource managers in forest health assessments.

RESULTS

Geographic subregions varied with respect to most variables. The predominant landforms in NAPP are series of narrow valleys and high ridges oriented in a northeast–southwest direction. Plots were predominantly on side slopes and ridges, as the valleys are mainly in agriculture. NAPP sites were characterized by shallow soils with relatively low clay content (low values for DEPCLS and CLAY, respectively; table I). Slope gradient (SLOPE) and site quality (oak site index base age 50; SI) were intermediate. Sampled stands had large oak components both in terms of the percentage of all stems 12.7 cm and larger that were oak species (OAKPCT) and basal area of oak stems 12.7 cm and larger (BAOAK); relatively low ratios of site index to stand age (SI/AGE); and the highest mean stand age (STANDAGE; 84.9 years). Mean INCIDNCE was 27.83%.

By contrast, SAPP plots were characterized by deep soils with intermediate clay content, high elevation (ELEV) with steep slopes, and the highest site productivity. Better site quality was reflected in a more diverse species composition, as OAKPCT and BAOAK were lowest of all subregions. STANDAGE and SI/AGE were intermediate but INCIDNCE was highest of the subregions (31.44%). Topography in this subregion is more variable and deeply dissected and rainfall is more abundant than in NAPP.

The Ozark Mountains are the predominant topographic features of the OZ subregion. The mountains are low, with a mean ELEV of 500 m. Broad ridges predominate in these eroded highlands of the Ozark Plateau that border grasslands to the west. OZ soils

Table I. Site and stand variables from oak decline surveys used to develop models with means for geographic areas.

Variable	*Explanation*	*Units*	*Geographic area* [a]			
			M_{NAPP}	M_{SAPP}	M_{OZ}	M_{REGION}
Site						
CLAY	Clay content of soil	%	16.00	19.70	21.90	19.10
DEPCLS	Depth of soil to impermeable layer	15 cm classes to > 105 cm	2.57	4.79	2.45	3.24
SLOPE	Slope gradient	%	25.11	34.32	18.60	26.46
SI	Site index (height of red oak at 50 year)	m	20.17	21.84	19.95	20.60
ELEV	Height above sea level	m	686	978	497	726
AZMTH	Direction of slope gradient	degrees	181.45	160.53	194.31	111.15
Stand						
OAKPCT	(Oak stems/all stems) x 100 for all stems > 12.7 cm dbh	%	86.59	67.80	88.30	81.06
BAOAK	Oak basal area for all stems > 12.7 cm dbh	m^2/ha	18.64	13.80	15.29	16.03
STNDAGE	Prevailing age of dominant and codominant oaks	years at dbh	84.90	77.80	60.90	74.50
SI/AGE	SI/STNDAGE		0.267	0.318	0.350	0.311
BATOT	Total basal area for all stems > 12.7 dbh	m^2	21.53	20.35	17.32	19.96
INCIDNCE	(declined + dead oaks/all oaks) x 100 for dominant and codominant oaks	%	27.83	31.44	15.97	25.36

[a] M_{NAPP} = mean for northern Appalachian subregion; M_{SAPP} = mean for southern Appalachian subregion; M_{OZ} = mean for Ozark subregion; M_{REGION} = mean for all subregions combined.

were the most shallow and had the highest clay content of all subregions. Slope gradient, site productivity, age, elevation, and INCIDNCE were also lowest among the subregions while oak density as measured by OAKPCT was highest.

The threshold INCIDNCE used to classify plots as having major oak decline damage for further analysis was confirmed at 20%. INCIDNCE exceeding this level provided adequate statistical separations with respect to most attributes and represents a meaningful and practical management threshold.

The variables most consistently showing significant statistical differences ($P < 0.05$) among geographic areas for major and minor damage groups in *t*-tests were CLAY, DEPCLS, SLOPE, OAKPCT, and BAOAK (table II). Means for major and minor damage groups were significantly different for these variables in at least two geographic areas. Deep soils with high clay content, low slope gradients, and high oak densities were associated with major damage cases.

Of the remaining variables, SI, SI/AGE, and ELEV were most promising. SI means were significantly higher for major damage cases only in NAPP. SI/AGE and ELEV means differed in two geographic areas, but the relationships were contradictory. Major damage cases had a higher SI/AGE mean in NAPP but the reverse was true for OZ. High ELEV was associated with major damage in NAPP but in SAPP, the ELEV mean was lower for major damage cases. Due to the confounding influence of differing latitude among subregions, ELEV was not included in further analyses.

These results guided stepwise discriminant analyses for the subregions and region. Eight different variables were found to have significant interactions in at least one area (table III). OAKPCT, DEPCLS, SLOPE, and CLAY each had a significant interaction in three of four geographic areas. In the NAPP subregion, OAKPCT, DEPCLS, SI, and STNDAGE were significantly related to major INCIDNCE ($R^2 = 0.67$). Four variables in the SAPP subregion were significant including OAKPCT, CLAY, DEPCLS, and SLOPE ($R^2 = 0.34$), while in the OZ subregion only OAKPCT, CLAY, and SLOPE were significant ($R^2 = 0.38$). The composite model (REGION) included SI/AGE, CLAY, SLOPE, DEPCLS, and BAOAK ($R^2 = 0.22$).

Closer examination of these results showed that BAOAK was only slightly less significant than OAKPCT for the three subregions. We substituted BAOAK for OAKPCT in subsequent analyses because it is closely related to OAKPCT and provides a more reliable measure of the predominance of the oak component for the mostly mature stands in our sample populations (table II). It is also an easily and quickly measured attribute for resource managers, who are the end users of the models. R^2 values were depressed only slightly by the substitution (R^2(NAPP) = 0.65; R^2(SAPP) = 0.30; R^2(OZ) = 0.32). Logistic regression procedures demonstrated that major and minor decline cases were correctly predicted for 87.9% of the cases in NAPP, 67.2% in SAPP, 81.0% in OZ, and 70.3% for REGION overall. Logistic regression equations are displayed in table IV. From these equations, probability of decline tables can be developed for use by forest managers. An example of a probability table is presented in table V.

DISCUSSION

Drought stress is an important predisposing and inciting factor in oak decline etiology (Manion, 1991). Some of the same stands that provided data for this work were sampled by Tainter et al (1990) for comparing radial growth increments of healthy and decline-killed oaks. They concluded that a severe and prolonged drought in the

Table II. The *t*-test significance probabilities and means for major and minor oak decline cases for selected variables by geographic area.

Variable	*Units*	*NAAP*			*SAPP*			*OZ*			*REGION*		
		Prob	M_{maj}^{a}	M_{min}^{b}	*Prob*	M_{maj}^{a}	M_{min}^{b}	*Prob*	M_{maj}^{a}	M_{min}^{b}	*Prob*	M_{maj}^{a}	M_{min}^{b}
Site													
CLAY	%	0.0088	18.55	13.38	0.0477	22.24	16.87	0.0093	27.18	19.78	0.0013	21.78	16.93
DEPCLS	class [c]	0.0001	3.42	1.66	0.0910	4.36	4.97	0.0240	2.82	2.29	0.0005	3.67	2.89
SLOPE	%	0.0088	20.39	29.97	0.0070	29.78	40.77	0.0001	9.03	22.54	0.0006	21.81	30.20
SI	m	0.0001	21.98	18.18	0.5902	21.53	22.18	0.2085	18.38	20.04	0.0868	21.19	20.11
ELEV	m	0.0018	773	598	0.0270	898	1 064	0.2410	458	513	0.2060	758	700
Stand													
OAKPCT	%	0.9250	86.73	86.45	0.0100	74.39	59.40	0.0005	95.49	86.06	0.0770	83.62	78.99
BAOAK	m^2/ha	0.346	19.09	18.13	0.0470	15.17	12.26	0.1130	16.56	14.74	0.0130	17.02	15.14
STNDAGE	years	0.4749	80.13	86.50	0.5024	75.33	80.55	0.3608	65.53	59.49	0.9028	74.76	74.23
SI/AGE	–	0.0097	0.29	0.23	0.5320	0.30	0.33	0.0270	0.29	0.36	0.5570	0.30	0.31

[a] M_{maj} = mean for major decline cases (> 20 percent INCIDNCE); [b] M_{min} = mean for minor decline cases (≤ 20 percent INCIDNCE) ; [c] 15 cm classes to > 105 cm.

Table III. Significant[a] variables in stepwise discriminant analysis for predicting major and minor oak decline cases by geographic area.

Variables	*NAPP*	*SAPP*	*OZ*	*REGION*
Site				
		CLAY	CLAY	CLAY
	DEPCLS	DEPLCS		DEPCLS
		SLOPE	SLOPE	SLOPE
	SI			
Stand				
	OAKPCT	OAKPCT	OAKPCT	
				BAOAK
	STNDAGE			
				SI-AGE

[a] $P < 0.15$

Table IV. Logistic regression equations for determining the probability of oak decline events with > 20% incidence from stand site factors in the southeastern United States, by subregion.

Area	*Model*
NAPP	Logit (p) = –27.4483 + 0.2557 (BAOAK) + 0.3186 (SI) + 4.9504 (DEPCLS) + 0.0553 (STNDAGE) $R^2 = 0.65$
SAPP	Logit (p) = 0.9990 + 0.1507 (BAOAK) – 0.4526 (DEPCLS) – 0.0542 (SLOPE) + 0.0506 (CLAY) $R^2 = 0.30$
OZ	Logit (p) = –1.8117 – 0.1866 (SLOPE) + 0.0708 (CLAY) + 0.1224 (BAOAK) $R^2 = 0.32$
REGION	Logit (p) = –2.7956 – 1.2513 (SI/AGE) + 0.0446 (CLAY) – 0.0397 (SLOPE) + 0.4566 (DEPCLS) + 0.1002 (BAOAK) $R^2 = 0.22$

mid-1950s acted to predispose a population of physiologically mature oaks to decline when subsequently stressed by a series of short-term but acute droughts in the mid-1980s.

The importance of moisture relations in decline etiology was implicitly demonstrated by the site variables that emerged from stepwise discriminant analyses for most of the models, namely SLOPE, CLAY, and DEPCLS (table III). We would expect a higher probability of major oak decline damage where xeric site conditions exist, ie, shallow and/or rapidly drained soils. Low slope gradients were associated with major oak decline damage in three of four models. In mountainous areas like those surveyed, these landforms are typically xeric ridge

Table V. Probability of a site in the SAPP subregion with soils 47 cm deep and 30% clay being affected by an oak decline event of > 20% incidence for the ranges of slope gradients and oak basal areas.

Slope (%)	*Oak basal area (m²/ha)*										
	2.29	*4.59*	*6.88*	*9.17*	*11.46*	*13.76*	*16.05*	*18.34*	*20.63*	*22.93*	*25.22*
10	0.553	0.636	0.712	0.778	0.832	0.875	0.908	0.933	0.952	0.965	0.975
20	0.419	0.504	0.590	0.670	0.742	0.802	0.852	0.890	0.920	0.942	0.958
30	0.295	0.372	0.456	0.542	0.626	0.703	0.770	0.825	0.870	0.904	0.930
40	0.196	0.256	0.327	0.408	0.493	0.579	0.660	0.733	0.795	0.846	0.886
50	0.124	0.167	0.221	0.286	0.361	0.444	0.530	0.615	0.693	0.761	0.818
60	0.076	0.104	0.141	0.189	0.247	0.317	0.396	0.481	0.568	0.650	0.724
70	0.046	0.063	0.087	0.119	0.161	0.213	0.276	0.351	0.433	0.519	0.604
80	0.027	0.038	0.053	0.073	0.100	0.136	0.182	0.239	0.307	0.385	0.470
90	0.016	0.022	0.031	0.044	0.061	0.084	0.114	0.154	0.205	0.267	0.340
100	0.009	0.013	0.018	0.026	0.036	0.050	0.070	0.096	0.131	0.175	0.231

Logit(p)=0.9990 + 0.1507(BAOAK) – 0.4526(DEPCLS) – 0.0542(SLOPE) + 0.0506(CLAY).

topographic positions, confirming our expectations.

The interactions among soil texture and depth were more complex and differed among regions. In SAPP, shallow soils with higher clay content were associated with a higher probability of decline. Decline sites represent the xeric end of the scale in this subregion where deep, well-drained soils predominate, averaging about 35 cm deeper than elsewhere (table I). By contrast, soils in NAPP have the lowest values of CLAY of all subregions and are quite shallow overall. Deeper soils had a higher decline probability in this subregion. Shallow, clay soils are common in OZ, where high clay content was associated with high decline probability and depth was not a significant factor. Edaphic conditions in the subregions, while very different, could present similar drought stress to oaks under highly variable moisture conditions. Soils with higher clay content would be capable of holding more water and would drain more slowly, but would yield proportionately less water to plants during extended drought. Shallow, sandy soils would have the lowest storage capacity and would be quickest to present critical moisture deficits to plants. These dynamics would also have a large effect on species composition and, hence, the probability of major oak decline damage. For example, shallow sandy soils in NAPP, though more droughty, may have supported stands with a small oak component and had a nonsignificant decline interaction.

Overall, stand attributes were less consistently associated with major oak decline damage than site attributes. High oak density (OAKPCT or BAOAK) was the only attribute associated with major damage for all models. Age, site productivity, and physiologic maturity were each significant in only one model. This may be due to local differences in land use (disturbance) history; cause, duration, and severity of predisposing stress; variability in abundance and/or species of root pathogens; or other factors not accounted for in these data.

The relationship of oak decline probability with SI and SI/AGE did not always conform to results from earlier work. Starkey et al (1989) and Oak et al (1991) showed that severe oak decline cases in the southeastern United States were associated with low SI and low SI/AGE but these variables emerged in the models for NAPP and REGION only. In NAPP, higher SI and SI/AGE values were associated with higher oak decline probability. Closer examination suggests that means may be biologically similar, despite being statistically different (table II). SI and SI/AGE for major decline cases were 21.9 m and 0.29, respectively. Both of these are higher than means for minor damage cases but nevertheless fall in the range of values associated with severe decline cases cited by Starkey et al (1989) and Oak et al (1991) (< 21.3 m and < 0.30–0.40, respectively). Alternatively, oak stands growing on productive sites in NAPP might be more prone to severe decline damage when stressed, compared with stands that are exposed to chronic stress while growing on more harsh sites. This view is supported by observations of Oak et al (1991), who reported high mortality losses when decline occurred on productive sites in western Virginia, despite a low frequency of occurrence.

Relatively low R^2 values are not unexpected when considered in light of decline etiology concepts of predisposing, inciting, and contributing factors (Manion, 1991). The attributes used in these analyses are found exclusively among predisposing factors. Important inciting and contributing factors for oak decline in the southeastern United States include short-term acute drought, spring defoliation, especially by gypsy moth caterpillars, and *Armillaria* root disease. None of these were included among the variables in our analyses. Significant research advances are needed in measuring local and regional drought and the identity and roles of *Armillaria* spp. We are presently incorporating gypsy moth defoliation occurrence and periodicity into the NAPP model to account for this important inciting factor.

Air pollution is often mentioned as both a predisposing and inciting factor (Manion, 1991). However, little support exists for including it as a major factor in oak decline etiology in the southeastern United States. Of known regional air pollutants, only O_3 causes visible plant injuries on a wide scale in the southeastern United States. Anderson et al (1988) reported regional gradients of O_3 damage in *Pinus strobus* L but these gradients bear little resemblance to known concentrations of oak decline (Oak et al, 1991; Starkey et al, in preparation). Nevertheless, emissions may be important on a local level, near point sources (Puckett, 1982; McClenahan and Dochinger, 1985).

One advantage of our approach is the ability to generate tables displaying the probability of major oak decline now or in the future, given a set of stand and site conditions (table V). Resource managers can vary the threshold probability for mitigating actions according to management objectives (eg, high timber value, public safety, protection of aesthetic values, watersheds, or unique biological resources). Mitigating actions could include accelerating or deferring harvest schedules, selection of cutting methods to minimize the imposition of additional stress on residual trees, prioritizing stands for protection against stress-inducing spring defoliators, and evaluating sustainable species composition and structures for future stands. Until further research illuminates the interactions of other inciting and contributing factors, the models presented here are useful tools for analyzing the forest health status of landscapes and for guiding management actions to mitigate oak decline effects.

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