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Predicting stump sprouting and competitive success of five oak species in southern Indiana

Dale R. Weigel and Chao-Ying Joanne Peng

Abstract: We measured 2188 oak trees (*Quercus* spp.) on the Hoosier National Forest in southern Indiana before and 1, 5, and 10 years after clear-cutting to determine the influence of parent tree age, diameter breast height, and site index on the probability that there was one or more living sprouts per stump: (*i*) 1 year after clear-cutting (sprouting probability) or (*ii*) that were competitively successful 5 or 10 years after clear-cutting (competitive success probability). We used logistic regression to develop predictive models for five species in each of the three measurement years. Two species were in the white oak group: white oak (*Quercus alba* L.) and chestnut oak (*Qurcus prinus* L.). Three species were in the red oak group: black oak (*Quercus velutina* Lam.), scarlet oak (*Quercus coccinea* Muenchh.), and northern red oak (*Quercus rubra* L.). Black oak site index ranged from 15 to 25 m at an index age of 50 years on the study sites. Parent tree age and diameter at breast height were significant predictors in all models. Sprouting and competitive success probabilities decreased with increasing parent tree age and diameter at breast height. Increasing site index was a significant contributor of increasing sprouting probabilities for year 1 and competitive success probabilities for year 5. By year 10, site index was negatively related to competitive success for the white oaks but was not a significant predictor for the red oaks. The models have practical value for predicting the stump sprouting potential of oak stands in southern Indiana and possibly in ecologically similar regions.

Résumé : Nous avons mesuré 2188 chênes (*Quercus* spp.) dans la forêt nationale de Hoosier située dans le sud de l'Indiana avant et 1, 5 et 10 ans après une coupe à blanc pour déterminer l'influence de l'âge de l'arbre parent, de son diamètre à hauteur de poitrine et de l'indice de station sur la probabilité qu'il y ait plus d'un rejet vivant par souche : (*i*) 1 an après la coupe à blanc (probabilité qu'il y ait production de rejets) ou (*ii*) qui ont réussi à vaincre la compétition 5 ou 10 ans après la coupe à blanc (probabilité de réussir à vaincre la compétition). Nous avons utilisé la régression logistique pour développer des modèles de prédiction pour cinq espèces pendant chacune des trois années de prise de données. Deux espèces appartenaient au groupe des chênes blancs : le chêne blanc (*Quercus alba* L.) et le chêne des montagnes (*Quercus prinus* L.). Trois espèces appartenaient au groupe des chênes rouges : le chêne des teinturiers (*Quercus velutina* Lam.), le chêne écarlate (*Quercus coccinea* Muenchh.) et le chêne rouge (*Quercus rubra* L.). L'indice de station du chêne des teinturiers variait de 15 à 25 m à 50 ans sur les stations à l'étude. L'âge de l'arbre parent et son diamètre à hauteur de poitrine étaient des prédicteurs significatifs dans tous les modèles. Les probabilités qu'il y ait production de rejets et de réussir à vaincre la compétition diminuent avec l'augmentation de l'âge de l'arbre parent et de son diamètre à hauteur de poitrine. L'augmentation de l'indice de station contribue de façon significative à l'augmentation de la probabilité qu'il y ait production de rejets à l'an 1 et de la probabilité de réussir à vaincre la compétition à l'an 5. À l'an 10, l'indice de station était négativement relié à la capacité de vaincre la compétition pour le groupe des chênes blancs mais n'était pas un prédicteur significatif pour le groupe des chênes rouges. Les modèles ont un intérêt pratique pour prédire la production potentielle de rejets de souche dans les peuplements de chênes du sud de l'Indiana et possiblement dans des régions écologiques semblables.

[Traduit par la Rédaction]

Introduction

Oaks (*Quercus* spp.) are a major component of the upland forests throughout the Central Hardwood Region, and maintaining them in the regional landscape is important for wildlife, timber, and biodiversity. Regenerating oaks has been and continues to be a problem in many regions including southern Indiana (Fischer et al. 1987; Lorimer 1989, 1993). Various silvicultural methods to regenerate oaks have been suggested (Hannah 1987) including the shelterwood method (Johnson 1993), prescribed burning (Barnes and Van Lear 1998; Brose and Van Lear 1998), and enrichment planting (Weigel and Johnson 1998*a*, 1998*b*, 2000).

The presence of adequate oak reproduction in advance of the final harvest of even-aged stands is generally considered the key to ensuring the presence of oak in future stands (Dey et al. 1996; Sander et al. 1984). However, stump sprouts originating from harvested trees are another potential source of oak reproduction. The importance of and the role stump sprouts play was recognized as early as 1936 (McIntyre 1936). Because these sprouts are often the fastest growing sources of oak reproduction, their contribution to future

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stocking is often important even when their numbers are relatively small. Earlier studies have shown that the sprouting potential of oak stumps is inversely proportional to parent tree age and diameter at breast height (DBH), and directly proportional to site quality (Roth and Hepting 1943; Johnson 1977).

Parent tree age, stump diameter, and site index were important predictors of oak stump sprouting in Missouri 1 year after the parent tree was harvested or killed by fire (Johnson 1977). Stump diameter was the significant predictor of sprouting potential five growing seasons after harvest for those stumps that had a live sprout after one growing season (Johnson 1977). Based on data collected from northern lower Michigan, Bruggink (1988) showed that parent tree age and stump diameter were important predictors of white (*Quercus alba* L.) and black (*Quercus velutina* Lam.) oak stump sprouting 5 years after clear-cutting; they were also important predictors for the presence of vigorous stump sprouts 5 years after harvest. Both Johnson and Bruggink used logistic regression for modeling. In these two studies, no preharvest or predeath data were collected.

Stump sprouting for northern red (*Quercus rubra* L.) and northern pin (*Quercus ellipsoidalis* E.J. Hill) oaks was not related to stump diameter, while stump sprouting for white oak was related to stump diameter in northern lower Michigan (Lynch and Bassett 1987). Smaller white oaks tended to sprout more frequently than larger stumps. Site index also produced mixed results for the three species. Northern red oak sprouting was independent of site index. White oak tended to sprout more frequently on poorer sites as did northern pin oak except on the very poor sites where northern pin oak sprouted less frequently. Tree age did influence sprouting for all three oaks with the very oldest stumps producing the fewest sprouts.

In Tennessee, Mann (1984) reported that white, black, and northern red oaks sprouted less frequently with increasing DBH. Smaller and larger chestnut oak sprouted less frequently than trees 15–30 cm DBH. These results were based on a total sample size of less than 100 trees.

In Missouri 6 years after girdling, stump sprouting response was inversely related to DBH for blackjack oak (*Quercus marilandica* Muenchh.) (Clark and Liming 1953). Smaller diameter blue oaks (*Quercus douglasii* Hook. & Arn.) in California were more likely to stump sprout than larger diameter blue oaks (McCreary et al. 1991). In West Virginia, Wendel (1975) reported stump sprouting percentages for 10 years but provided no information on DBH. The mean age of the parent stands was about 55 years. The proportion of stumps with sprouts was over 85% for red, white, and chestnut oaks 10 years after harvest. However, these reports did not use logistic regression for modeling. Results were presented at the macroscopic level in terms of percentages of sprouting stumps, some by age and (or) by DBH. Furthermore, the data collected were single-time measurements. Such data prevent researchers from making judgments about predictors of sprouting success in a competitive environment in longer terms beyond first-year sprouting.

The objectives of the present study were to determine the likelihood that an oak stump with defined characteristics would (*i*) have at least one live sprout 1 year after the parent tree is cut, and (*ii*) sprout and be competitively successful after 5 and 10 years.

Methods

Study area

The study was conducted on the Hoosier National Forest, in the Shawnee Hills and Highland Rim Sections (Keys et al. 1995) of southern Indiana (38°30′N, 86°30′W). The forest contains areas ranging from steep, sharply dissected slopes to gently rolling slopes. Elevations for the study areas ranged between 150 and 250 m above mean sea level. The mean annual temperature for the area is 12°C with a January mean of –2°C and a July mean of 25°C. Mean annual precipitation for the area is 118 cm, distributed evenly throughout the year.

Nine stands scheduled to be clear-cut were selected. To ensure a broad range of age-classes, three stands were selected in each of three age-classes: 71–90, 91–110, and 110+ years. Clear-cutting was completed between October 1987 and May 1989. Because it was not possible to separate those stumps harvested during the growing season from those harvested during the dormant season, time of harvest was not evaluated as a predictor of sprouting and competitive success in the subsequent building of predictive models.

Measurements

Within each stand, 0.04-ha plots were located on a systematic basis. From these plots, 1371 white oaks, 180 chestnut oaks (*Quercus prinus* L.), 399 black oaks, 130 scarlet oaks (*Quercus coccinea* Muenchh.), and 108 northern red oaks >4 cm DBH were measured and tagged to facilitate subsequent relocation and remeasurement (Table 1). For each species, preharvest measurements included DBH (cm), stump diameter 15 cm above ground (cm), and heights of selected trees for site index determination. Post-harvest measurements were made 1, 5, and 10 years after clear-cutting. First-year measurements included determining the age of the parent tree at time of harvest and noting the presence or absence of living sprouts. Fifth- and tenth-year measurements included counting the number of living sprouts, the height of the tallest sprout (cm), and the height of the tallest woody competitor (cm) within 1 m of the stump.

To compute mean height of dominant competitors and site index, we divided each stand into relatively homogeneous site units based on aspect and slope position. We defined two aspect categories: north (315°–135° azimuth) and south (136°–314° azimuth) (Hannah 1968). The defined slope position categories were ridge, upper slope, lower slope, and bottom. Thus, the mean heights of dominant competitors at the time of 5- and 10-year measurements were calculated for each slope–aspect combination within each stand. This value, referred to as the competition height, thus established the success criterion within each site unit within each stand. If a stump sprout equaled or exceed 80% of the competition height, it was deemed competitively successful.

Site index was calculated for each site unit within each stand based on the ages and heights of dominant and codominant site index trees, and a common site index value was then assigned to all stumps within each unit. Site index was based on the black oak curves (base age 50 years) of Carmean et al. (1989). Observed site index ranged from 15 to 25 m.

Statistical analysis

Logistic regression is useful for modeling binary outcome data (e.g., "success" or "failure") (Loftsgaarden and Andrews 1992). In our study, the binary outcome represented a "success" when a living stump sprout was (*i*) present 1 year after the parent tree was cut or (*ii*) 5 or 10 years after the parent tree was cut, a living sprout was present that equaled or exceeded 80% of the competition height defined previously. Six logistic models were derived from the data to predict the likelihood of sprouting or the likelihood of sprouts' competitive success. Each model was applicable to one of the two oak groups (white or red oaks) measured at one of the three times after clear-cutting.

The model-building approach suggested by Hosmer and Lemeshow (1989) was used to develop logistic regression models. The approach involved four steps: (1) perform descriptive analyses of all predictors and a series of univariate logistic regressions, each based on a continuous predictor; (2) develop a preliminary multivariate model using meaningful and significant predictors from step 1; (3) fit alternative multivariate models to data; and (4) compare the performance of the alternative models with that of the preliminary multivariate model in terms of the models' overall significance, interpretability and statistical significance of each predictor, goodness-of-fit statistics, predictive power, accuracy of prediction, and diagnostic results. Alternative models, in step 3, may be derived from the preliminary multivariate model by (*i*) adding two-way, three-way, etc., interactions of significant main predictors; (*ii*) creating polynomial trends from continuous predictors; (*iii*) performing nonlinear transformations, such as log, square root, etc., of continuous predictors; or (*iv*) removing unimportant or statistically insignificant predictors from the model. We used the maximum likelihood (ML) method implemented in PROC LOGISTIC of SAS version 6.12 (SAS Institute Inc. 1997) to perform the logistic modeling.

The independent variables considered in the present study included species, parent tree age, DBH, natural log of DBH, site index, natural log of site index, and interactions between two or more of these independent variables. The dependent variable for year 1 data was the presence of a sprout 1 year after the parent stem was harvested. For years 5 and 10, the dependent variable was the presence of a sprout that met or exceeded 80% of the competition height 5 or 10 years after the parent stem was harvested. Therefore, this criterion reflected the sprouting capacity, sprout survival, and the competitive status of sprouts. Moreover, these probability estimates were not conditioned on stump sprouting status at a previous measurement.

Preliminary analyses indicated that all species differed significantly from white oak ($p < 0.05$). Because of the smaller sample size of chestnut, black, scarlet, and northern red oaks, we grouped the stumps into two species groups: the white oaks and the red oaks. The white oaks consisted of white and chestnut oaks, and the red oaks consisted of black, scarlet, and northern red oaks. We used dummy coding to test for differences among species within each species group (Pedhazur 1982).

Table 1. Number of sampled stumps by diameter class, species, and parent tree age.

		Parent tree age-class			
DBH class (cm)	Species group	50	70	90	110
Red oak					
10	Black oak	30	2	0	0
	Scarlet oak	3	0	0	0
	Northern red oak	11	0	0	0
	Total	44	2	0	0
20	Black oak	41	32	2	0
	Scarlet oak	10	13	1	0
	Northern red oak	11	15	1	0
	Total	62	60	4	0
30	Black oak	22	52	20	5
	Scarlet oak	4	34	5	1
	Northern red oak	4	13	11	3
	Total	30	99	36	9
40	Black oak	8	30	38	27
	Scarlet oak	1	24	12	4
	Northern red oak	0	8	10	7
	Total	9	62	60	38
50	Black oak	3	17	11	28
	Scarlet oak	1	7	3	1
	Northern red oak	0	0	3	5
	Total	4	24	17	34
60	Black oak	0	5	3	11
	Scarlet oak	0	0	2	1
	Northern red oak	0	1	1	4
	Total	0	6	6	16
70	Black oak	0	2	2	8
	Scarlet oak	0	1	0	2
	Northern red oak	0	0	0	0
	Total	0	3	2	10
White oak					
10	White oak	207	51	4	1
	Chestnut oak	3	1	0	0
	Total	210	52	4	1
20	White oak	87	161	79	17
	Chestnut oak	5	7	14	0
	Total	92	168	93	17
30	White oak	27	60	148	100
	Chestnut oak	0	7	41	10
	Total	27	67	189	110
40	White oak	2	28	116	159
	Chestnut oak	0	2	26	31
	Total	2	30	142	190
50	White oak	1	8	24	73
	Chestnut oak	0	2	6	18
	Total	1	10	30	91
60	White oak	0	1	5	12
	Chestnut oak	0	1	1	5
	Total	0	2	6	17
70	White oak	0	0	0	0
	Chestnut oak	0	0	0	0
	Total	0	0	0	0

Results

Red oak group

Year 1 sprouting probabilities

Preliminary analyses indicated that northern red oak and scarlet oak did not differ statistically ($p > 0.05$) based on the selected predictors. Therefore, the scarlet and red oak observations were treated as one species and compared with black oak. The model-building strategy mentioned above was then used to identify the best model for the grouped data (Table 2, model 1). Three predictors were statistically significant: species, the interaction of age with DBH, and site index. The parameter estimates for the three predictors differed significantly from zero ($p < 0.05$).

Evaluation of model 1

How effective was model 1 in accounting for sprouting probabilities for red oak data at year 1? To answer this question, we performed (*i*) the overall evaluation of the model, (*ii*) statistical tests of individual predictors, and (*iii*) test of goodness-of-fit statistics.

Overall model evaluation

The overall statistical significance of model 1 was examined by the χ^2 test of the log-likelihood. The test statistic yielded a value of 146.964 which was significant at $p < 0.0001$. This means that the logistic model was a significant improvement over the intercept-only model.

Statistical tests of individual predictors

As mentioned before, the three predictors included in model 1 were statistically significant at $p < 0.05$ indicating the need to include them in the model.

Test of goodness-of-fit statistics

Goodness-of-fit statistics assess the fit of a logistic model against actual outcome, i.e., the presence or absence of a sprout. One inferential goodness-of-fit test, presented in Table 2, is the Hosmer–Lemeshow (H–L) test that yielded a χ^2 value of 13.611, which was insignificant ($p = 0.0925$, df = 8). In other words, the null hypothesis of a good model fit to data was not rejected.

According to model 1, the stump-sprouting probabilities for red oaks were inversely related to the interaction of parent tree age and DBH, and positively related to site index. In other words, if site index were held constant, older and larger red oaks were less likely to sprout than younger and (or) smaller red oaks. If age and DBH were held constant, red oaks on the better sites were more likely to sprout than on poor sites. The highest sprouting probability for scarlet – northern red oaks was 0.88 (parent tree age, 50 years; parent tree DBH, 10 cm; and site index, 22 m). The highest sprouting probability for black oak (0.80) similarly occurred (parent tree age, 50 years; parent tree DBH, 10 cm; and site index, 22 m) (Figs. 1A and 1B). For site indices of 18 and 22 m, probabilities declined with increased parent tree age and DBH. The estimated stump sprouting probability for the oldest and largest black oak observed was only 0.05 (parent tree age, 110 years; DBH, 65 cm; and site index, 18 m), whereas for scarlet – northern red oaks, probabilities were only slightly higher (0.09) for the same parent tree age, DBH, and site index.

The degree to which high and low predicted probabilities derived from model 1 matched with actual outcomes (sprouting versus not sprouting) is expressed in Table 3. The cutoff for distinguishing between high and low probabilities was set by SAS at 0.5 using a reduced-bias algorithm. According to Table 3, the overall correct classification rate based on model 1 was 68.4%, an improvement over the chance level. The model correctly classified stumps that sprouted more frequently than those that did not. This observation was supported by the magnitude of sensitivity (77.7%), compared with that of specificity (58.4%). Sensitivity measures the proportion of correctly classified stumps with one or more live stems at year 1, whereas specificity measures the proportion of correctly classified unsprouted stumps, i.e., those with no live stems. Both false positive and false negative rates were about 30%

Year 5 competitive success probabilities

The three red oak species differed from each other ($p < 0.05$) at the end of year 5 based on dummy coding for species effects. The predictors identified in model 1 also produced the best model (model 2), i.e., species, the interaction of parent tree age and DBH, and the natural log of site index (Table 2).

Evaluation of model 2

As was done with model 1, model 2 was assessed in terms of (*i*) the overall statistical test, (*ii*) the significance tests of all predictors, and (*iii*) the goodness-of-fit of the model against data. The χ^2 test of the overall model equaled 166.458, significant at $p < 0.0001$. Three predictors in the model were each statistically significant at $p < 0.05$. The goodness-of-fit of model 2 was confirmed by the insignificant H–L test of 13.782 ($p = 0.0876$). These indices indicated that model 2 fitted the data well and was statistically significant.

When parent tree age, DBH, and site index were held constant, the lowest competitive success probabilities occurred in black oak (Fig. 1C) and the highest in scarlet oak (Fig. 1E). Although scarlet oak probabilities for small-diameter parent trees were similar for years 1 and 5, with increased diameter the sprouting success rates were higher for year 1 than for year 5. In northern red and black oaks, the probability of competitive success declined uniformly from year 1 to year 5 regardless of parent tree age or DBH.

The models indicated that site index became increasingly less important as a determinant of competitive success with increased age of the parent tree. When parent tree age and DBH were held constant, the difference in estimated probabilities between site indices 18 and 22 m at year 5 was nominally less than that at year 1. Nevertheless, higher site index values remained associated with higher competitive success at year 5.

According to Table 3, the overall correct classification rate based on model 2 was 72.4%, which was an improvement over the chance level. Model 2 correctly classified stumps that did not sprout more frequently than those that did. This observation was supported by the magnitude of sensitivity (67.4%), compared with that of specificity (75.9%). Both false positive and false negative rates were at or below 30%.

Year 10 competitive success probabilities

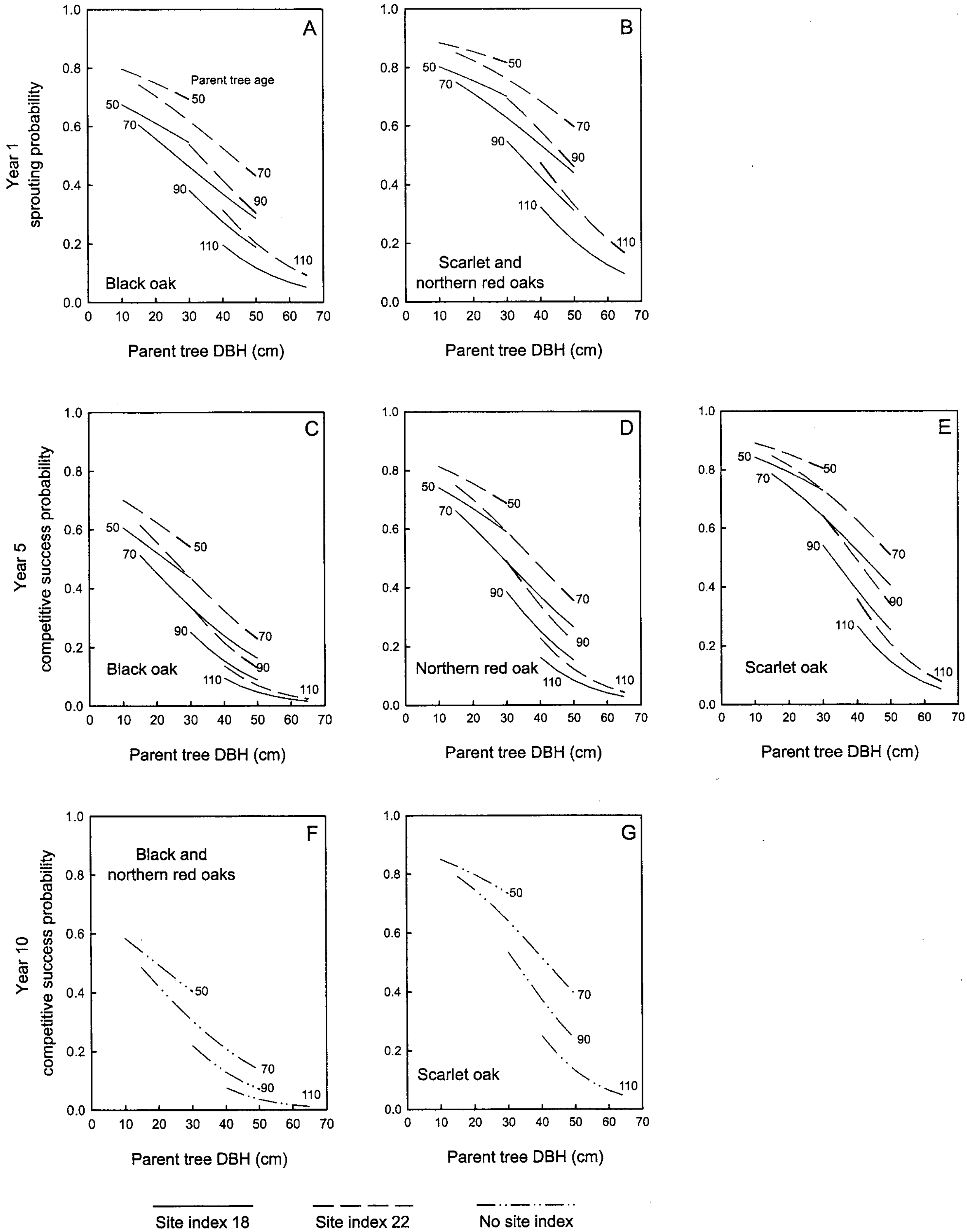
At year 10, competitive success probabilities for black oak and northern red oak did not differ significantly ($p > 0.05$). However, they did different significantly from scarlet oak ($p < 0.05$). Consequently, the two species were combined during the model-building process. After 10 years, the effect of site index was no longer a significant predictor of competitive success. By that time, the only significant predictors were species and the interaction of parent tree age with DBH (Table 2, model 3).

Table 2. Logistic regression models for estimating the probability that an oak stump will have at least one living sprout 1 year or that a sprout will meet or exceed 80% of the competition height 5 or 10 years after the parent tree is cut.

Model		Parameter estimates[a,b]								Model evaluation statistics	
No.	Species and year	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	χ^2	H–L[d]
1	Black oak, 1	−8.1468			−0.000 55			3.1679		146.964	13.611
	Red and scarlet oaks, 1	−7.4793			−0.000 55			3.1679		($p < 0.0001$)	($p = 0.0925$)
					(0.000 064)[c]			(0.6947)[c]			
2	Black oak, 5	−5.2843			−0.000 69			2.0970		166.458	13.782
	Scarlet oak, 5	−4.0317			−0.000 69			2.0970		($p < 0.0001$)	($p = 0.0876$)
	Red oak, 5	−4.6603			−0.000 69			2.0970			
					(0.000 077)[c]			(0.7100)[c]			
3	Black and red oaks, 10	0.7049			−0.000 73					150.434	7.3708
	Scarlet oak, 10	2.1114			−0.000 73					($p < 0.0001$)	($p = 0.4972$)
					(0.000 084)[c]						
4	White oak, 1	−53.6225		−1.7003		−0.005 34		25.7155	−0.2913	627.958	15.505
	Chestnut oak, 1	−50.4940		−1.7003		−0.005 34		25.7155	−0.2913	($p < 0.0001$)	($p = 0.0500$)
				(0.2937)[c]		(0.001 52)[c]		(7.3013)[c]	(0.0917)[c]		
5	White oak, 5	0.1048	−0.0883			−0.007 63	0.1182			619.144	15.178
	Chestnut oak, 5	3.1680	−0.0883			−0.007 63	0.1182			($p < 0.0001$)	($p = 0.0558$)
			(0.0162)[c]			(0.001 78)[c]	(0.0306)[c]				
6	White oak, 10	−75.6086			−0.001 48		−1.9945	38.8899		422.176	11.152
	Chestnut oak, 10	−73.2321			−0.001 48		−1.9945	38.8899		($p < 0.0001$)	($p = 0.1932$)
					(0.000 107)[c]		(0.5315)[c]	(10.6257)[c]			

[a]Regression models are of the form $P = [1 + e^{-(b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_6 + b_7X_7)}]^{-1}$, where P is the estimated probability that a cut tree will produce a stump sprout: X_1 is the DBH in centimetres; X_2 is the natural log of DBH in centimetres; $X_3 = (X_1 \times \text{tree age})$ where age is in years at stump height; $X_4 = (X_2 \times \text{tree age})$; X_5 is black oak site index in metres (where site index is derived from Carmean et al. 1989); X_6 is the natural log of site index; and $X_7 = (X_5 \times X_6)$.
[b]All parameter estimates differ significantly from zero at $p < 0.05$.
[c]Numbers in parentheses are standard errors of estimate.
[d]Hosmer–Lemeshow goodness-of-fit test (Hosmer and Lemeshow 1989).

Fig. 1. The estimated probability that a black, northern red, or scarlet oak will have at least one living sprout 1 year after the parent tree is cut or that a stump will produce a sprout that attains ≥80% of the competition height 5 or 10 years after the parent tree is cut in relation to parent tree age, DBH, and black oak site index.



Evaluation of model 3

The overall significance of model 3 reached a χ^2 value of 150.434, significant at $p < 0.0001$. The two predictors were each significant at $p < 0.05$. The goodness-of-fit of model 3 was confirmed by the insignificant H–L test (χ^2 = 7.3708, p = 0.4972).

Among species, scarlet oak produced the highest competitive success probabilities (Fig. 1G). These probabilities declined slightly from year 5 to year 10 for a given parent tree age and DBH. Differences in estimated competitive success probabilities for scarlet oak and black – northern red oak ranged from 0.17 (parent tree age = 110) to 0.32 (parent tree age = 90) for the smallest DBH. At the largest DBH (Figs. 1F and 1G), the same differences for scarlet oak versus black and northern red oaks, ranged from 0.03 (parent tree age 110) to 0.33 (parent tree age 50). All differences favored scarlet oak. Estimated competitive success probabilities for black and northern red oak that were 25 cm DBH or larger were all below 0.45 (Fig. 1F). For 50-year-old scarlet oak parent trees, competitive success probabilities were 0.70 or larger. Estimated probabilities for older scarlet oaks (age 110) were never greater than 0.25.

The overall correct classification rate based on model 3 was 72.5%, an improvement over the chance level (Table 3). Model 3 correctly classified stumps that did not sprout more frequently than those that did. This observation was supported by the magnitude of sensitivity (45.2%), compared with that of specificity (85.9%). False positive and false negative rates were 38.7 and 23.9%, respectively.

White oak group

Year 1 sprouting probabilities

This predictive model was the most complex of the six models developed. It included five predictors: species, the natural log of DBH, the interaction of the natural log of DBH with parent tree age, the natural log of site index, and the interaction of site index with the natural log of site index (Table 2, model 4).

Evaluation of model 4

The overall significance of model 4 reached a χ^2 value of 627.958, significant at $p < 0.0001$. The six predictors were each significant at $p < 0.05$. The goodness-of-fit of model 4 was confirmed by the marginal H–L test (χ^2 = 15.505, p = 0.0500).

For white oak, estimated sprouting probabilities decreased more sharply with increased DBH than for any other species. This suggests that DBH had a greater influence on the sprouting probabilities of white oak than on those of the other species observed. For example, sprouting probabilities for a 50-year-old white oak parent trees growing on site index 22 m ranged from 0.95 to 0.43 depending on DBH. In contrast, probabilities for chestnut oak ranged from near 1 to 0.95 (Figs. 2A and 2B).

According to model 4, chestnut oak sprouting probabilities were the highest among the five species observed. Chestnut oaks less than 90 years of age were associated with sprouting probabilities greater than 0.80. Only the oldest and largest chestnut oak stumps on the poorest sites had sprouting probabilities below 0.50. In comparison, all white oaks with 25 cm or greater DBH were associated with sprouting probabilities below 0.50 and many drop below 0.10 (Fig. 2A).

Table 3. The percent of matched observations between high and low predicted probabilities and actual outcomes.

Model	Correct	Sensitivity	Specificity	False positive	False negative
1	68.4	77.7	58.4	33.0	29.4
2	72.4	67.4	75.9	33.6	23.3
3	72.5	45.2	85.9	38.7	23.9
4	80.3	65.0	87.7	28.0	16.2
5	83.0	58.8	91.1	31.4	13.0
6	85.0	29.2	96.1	40.5	12.8

Note: Predicted probabilities were defined for successful sprouting at year 1 (models 1 and 4) and for competitive sprouting success at years 5 and 10 (models 2, 3, 5, and 6). High and low predicted probabilities were distinguished by a cutoff of 0.50, set by SAS.

The overall correct classification rate was 80.3%, an improvement over the chance level (Table 3, model 4). The model correctly classified stumps that did not sprout more frequently than those that did. This observation was supported by the magnitude of sensitivity (65.0%), compared with that of specificity (87.7%). False positive and false negative rates were 28.0 and 16.2%, respectively.

Year 5 competitive success probabilities

The final competitive success model (model 5) for year 5 contained four predictors: species, DBH, the interaction of age with the natural log of DBH, and site index (Table 2).

Evaluation of model 5

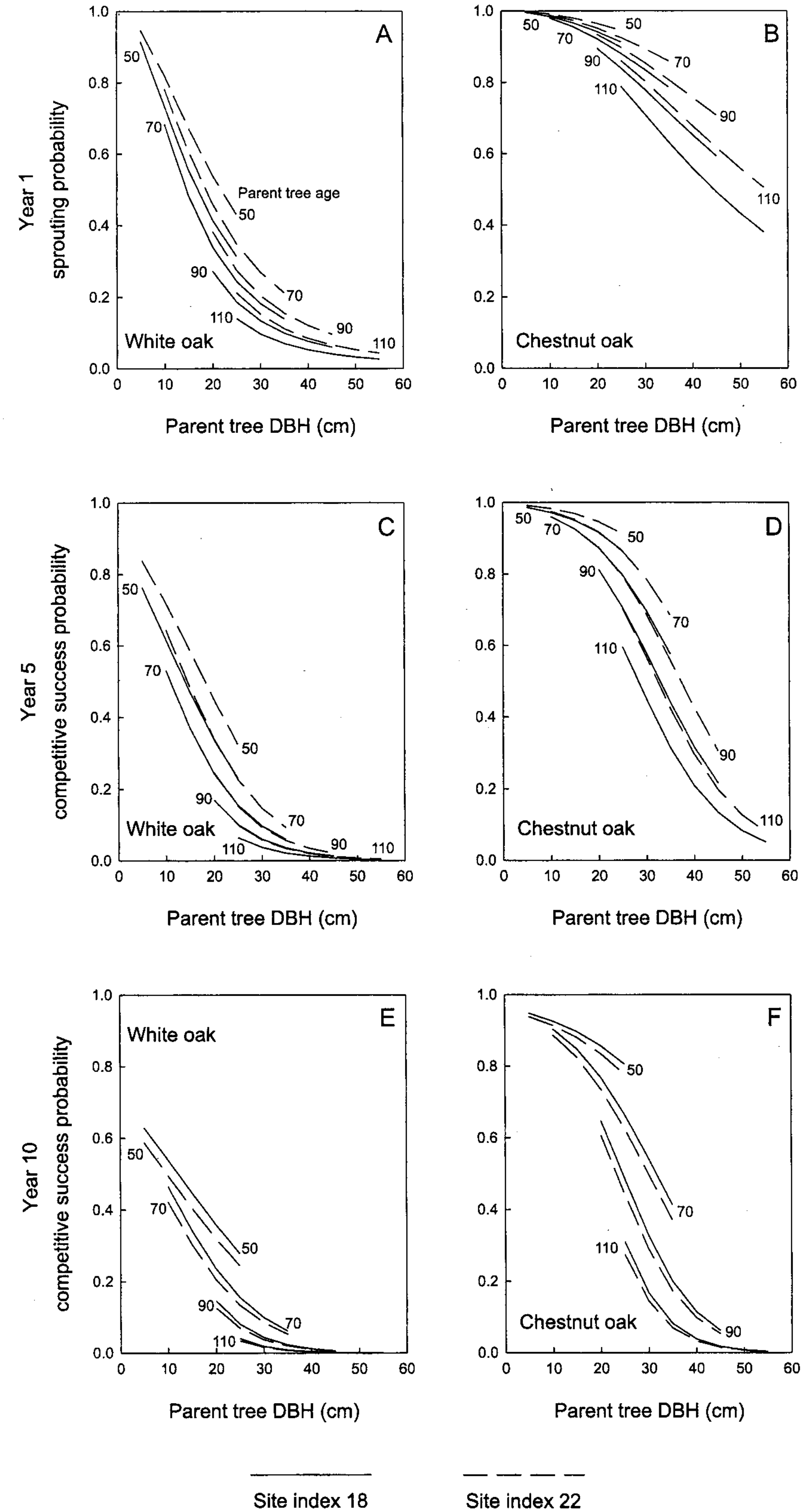
The overall significance of model 5 reached a χ^2 value of 619.144, significant at $p < 0.0001$. The four predictors were each significant at $p < 0.05$. The goodness-of-fit of model 5 was confirmed by the insignificant H–L test (χ^2 = 15.178, p = 0.0558).

Other factors held constant, year 5 competitive success probabilities were lower for white and chestnut oaks than year 1 sprouting probabilities. Like the year 1 model, chestnut oak was consistently associated with higher probabilities than white oak (Figs. 2C and 2D). For example, competitive success probabilities for chestnut oak sprouts originating from 50-year-old parent trees were greater than 0.90, whereas the probabilities for white oak were always 0.85 or less.

Stumps of white oak parent trees ≥25 cm DBH were associated with competitive success probabilities below 0.35, whereas similar probabilities for chestnut oak occurred in parent trees ≥45 cm DBH. The relation between site index and competitive success probability was positive when parent tree age and DBH were held constant, a finding consistent with the year 1 model.

The overall correct classification rate was 83.0%, which is an improvement over the chance level (Table 3, model 5). Model 5 correctly classified stumps that did not sprout more frequently than those that did. This observation was supported by the magnitude of sensitivity (58.8%), compared with that of specificity (91.1%). False positive and false negative rates were 31.4 and 13.0%, respectively.

Fig. 2. The estimated probability that a white or chestnut oak will have at least one living sprout 1 year after the parent tree is cut or that a stump will produce a sprout that attains ≥80% of the competition height 5 or 10 years after the parent tree is cut in relation to parent tree age, DBH, and black oak site index.



Year 10 competitive success probabilities

The best year-10 model (model 6) for the white oak group included four predictors: species, the interaction of parent tree age with DBH, site index, and the natural log of site index (Table 2).

Evaluation of model 6

The overall significance of model 6 reached a χ^2 value of 422.176, significant at $p < 0.0001$. The four predictors were each significant at $p < 0.05$. The goodness-of-fit of model 6 was confirmed by the insignificant H–L test ($\chi^2 = 11.152$, $p = 0.1932$).

However, other factors being equal, competitive success probabilities for year 10 were lower than those for years 1 and 5. Chestnut oak had greater predicted sprout success than white oak across the three time intervals investigated in this study. The competitive sprouting success rate for old white oak parent trees (90 years or older) with DBH greater than 35 cm approached zero (Fig. 2E). For chestnut oak, only trees that were at least 110 years old with DBH greater than 45 cm were associated with probabilities near zero (Fig. 2F). Unlike the other models, poorer sites were associated with higher competitive success probabilities for both white and chestnut oaks.

The overall correct classification rate was 85.0%, an improvement over the chance level. The model correctly classified stumps that did not sprout more frequently than those that did (Table 3, model 6). This observation was supported by the magnitude of sensitivity (29.2%), compared with that of specificity (96.1%). False positive and false negative rates were 40.5 and 12.8%, respectively.

Discussion

Parent tree age and DBH were significant predictors in all models. Sprouting probabilities decreased with increasing parent tree age and DBH. Site index was a significant predictor for all models, except for the red oak group at year 10. Site index contributed positively to sprouting probabilities, except for the white oak group at year 10. For this group, site index was inversely related to the likelihood of sprouts attaining 80% of the mean height of competitors.

The slopes of the probability curves differ among species. For example, year 1 probabilities for species in the white oak group begin to decline near values of 1, whereas those for the red oak group begin to decline in the 0.80–0.90 range. Chestnut oak was the only species to maintain competitive success probabilities above 0.90 for the three measurement periods investigated. Black, northern red, and white oaks showed the greatest decline in competitive success probabilities during the 10-year study period. Scarlet oak maintained roughly the same probabilities from year 1 to year 10 when parent tree age and DBH are held constant. Chestnut oak at age 50 likewise showed the same tendency in competitive success probability during the entire measurement period. This implies that for scarlet and young chestnut oak stumps, a successful sprout developed at year 1 will very likely remain competitive for the next 10 years. However, this was not the case for black, northern red, white, or older (70 years or more) chestnut oaks. The declining probabilities from year 1 through year 10 suggested they were unable to remain competitive and either died or were overtopped.

All six models indicate that sprouting probabilities decrease with increasing parent tree age and DBH. These relations are consistent with previous findings. For example, the sprouting frequency of black oak and white oak stumps in Missouri clearcuts decreased with increasing stump diameter and parent tree age (Johnson 1977). The same relations were observed in black oak in 5-year-old clearcuts in Michigan (Bruggink 1988). Although the frequency of sprouting in white oak also decreased with increasing parent tree age, stump diameter was unrelated to the occurrence of sprouts.

Our findings also generally agree with other studies on the relation between stump sprouting and site quality. For example, sprouting probabilities increased with increasing site index in a Missouri study (Johnson 1977). However, in the present study, site index became increasingly less important over time in explaining the competitive success of sprouts. By year 10, site index was no longer significant as a predictor of competitive success in the red oak group. In the white oak group, decreasing site quality was actually associated with a greater likelihood of sprouting success. We propose the following possible explanation for the latter relation. During the first few years after clear-cutting, there is relatively little competition between oak stump sprouts and other vegetation, i.e., each sprout clump is relatively free to grow. However, by year 10, competition has intensified, especially on the better sites where rapidly growing nonoak competitors may outgrow oak stump sprouts. Thus, oak sprouts growing on poor sites may have a greater competitive advantage than those growing on better sites. The same general relation may apply to the red oaks, i.e., the initial advantage of a high site index becomes increasingly less important with time because of competition effects.

Predicting and evaluating the future stocking of even-aged oak stands after final harvest is important to forest managers. To meet this need, regeneration guides have been developed in some regions for evaluating the regeneration potential of oaks stands (e.g., Sander et al. 1984; Dey et al. 1996). These guidelines consider a stand's total oak regeneration potential including reproduction originating from advance reproduction and stump sprouts. The predictive models developed in the present study, thus, have potential value for contributing to the development of similar regeneration models for upland oak stands in Indiana and possibly ecologically similar areas of the Central Hardwood Region. However, the stump sprouting models presented herein are based on observations in clearcuts. Different regeneration methods, thus, may produce results different from those observed in this study. For example, oak sprouting and sprout development under shelterwoods or in stands where the single-tree selection method is applied may produce very different results because of overstory shading effects. Conversely, regenerating stands using the group selection method that creates openings >0.1 ha might be expected to produce results similar to those observed in the present study.

Logistic regression as used herein also facilitates a more dynamic ecological approach to modeling stump sprouting than that traditionally reported in stump sprouting studies (e.g., reporting numbers of sprouts per stump and the percentage of stumps with sprouts). For example, the method can be used to include time- and site-dependent competition effects and their influence on the competitive success of oak stump sprouts. The resulting probabilities also pertain to individual parent trees with quantitatively specifiable characteristics such as age and DBH, which in turn are useful in the development and practical application of regional or ecosystem-specific regeneration models. Moreover, the present study provides information on chestnut, northern red, and scarlet oaks that have not been studied or less intensively observed in previous sprouting studies.

Future research should focus on evaluating the use of logistic regression or similar approaches to modeling the sprouting potential of oaks in other areas of the Central Hardwood Region and (or) in relation to different regeneration methods. Additional research is also needed to assess the competitive success of oak stump sprouts beyond year 10, and their longer term contribution to the stocking of developing stands.

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