STUMP SPROUT DOMINANCE PROBABILITIES OF FIVE OAK SPECIES IN SOUTHERN INDIANA 20 YEARS AFTER CLEARCUT HARVESTING

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Abstract.—Oak (*Quercus* spp.) stump sprouts are vital to sustaining oak's presence and long-term dominance when regenerating oak or mixed-hardwood forests in southern Indiana. A study was initiated on the Hoosier National Forest in southern Indiana in 1987 to predict the sprouting potential and dominance probability of oaks. Before clearcut harvesting, we sampled 2,188 trees of five oak species and measured tree age and diameter at breast height along with site index to develop sprouting and dominance probability models for subsequent follow-ups at years 1, 5, 10, 15, and 20. For the current study a dominant oak was one that had one or more competitively successful sprouts per stump 20 years after clearcutting. Two species were in the white oak group—white oak (*Q. alba* L.) and chestnut oak (*Q. prinus* L.)—and three in the red oak group—black oak (*Q. velutina* Lam.), scarlet oak (*Q. coccinea* Muenchh.), and northern red oak (*Q. rubra* L.). We used logistic regression to develop preharvest predictive models for sprouting potential and dominance probabilities as well as postharvest models for dominance probabilities of the five species. The 20-year results will be compared to results obtained 1, 5, 10, and 15 years after harvest (Weigel and Peng 2002, Weigel and others 2006). Managers can use our models to anticipate regeneration failures before harvesting or sprout success after harvest.

INTRODUCTION

Oaks are important for timber, wildlife food, and stand biodiversity. Oak regeneration continues to be a problem (Lorimer 1983, 1989). Oak advanced reproduction has been considered the main source of stems for the future forest (Sander and others 1976, 1984). One component of the future stand that is often overlooked is oak stump sprouts. The contribution of stump sprouts is overlooked in part because of the limited information about the percent of oak stumps that sprout and produce competitively successful sprouts. Thus, predicting the success or dominance of stump sprouts following overstory removal is important for understanding the role of stump sprouts in regenerating oaks.

Early research showed that parent tree age, diameter, and site quality were significant predictors of stump sprouting (Roth and Hepting 1943, McGee 1978). In Missouri, parent tree age, stump diameter, and site index were important predictors of oak stump sprouting (Johnson 1977, Dey and others 1996). In northern lower Michigan, parent tree age and stump diameter were important predictors of stump sprouting for white oak (*Quercus alba* L.) and black oak (*Q. velutina* Lam.) (Bruggink 1988). Diameter at breast height (d.b.h.) was a significant predictor for white, black, northern red (*Q. rubra* L.), and chestnut oak (*Q. prinus* L.) in

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Tennessee (Mann 1984). In Pennsylvania, species and d.b.h. were significant predictors at year 1 for white, black, northern red, and chestnut (Gould and others 2007). These prior studies were primarily concerned with short-term success of oak species in certain regions, not necessarily with the sustained dominance of sprouts in other locations (such as southern Indiana) at longer time intervals, such as 20 years.

Thus, our objectives were to determine significant predictors of oak stump sprouting in southern Indiana and to develop dominance probability models for oaks at year 20 that permit the forest manager to make an informed prediction of the approximate number of dominant or codominant oak stump sprouts in future stands. Two different types of models were developed to provide the forest manager with the ability to predict dominance probability when either preharvest or postharvest data are available.

STUDY AREAS

The study was conducted on the Hoosier National Forest in south-central Indiana. Nine stands scheduled to be clearcut were selected for measurement. There were three stands in each of three age classes: 71-90, 91-110, and 110+ years. Harvesting was done between October 1987 and May 1989. In any given year, it was not possible to determine what season (growing or dormant) individual stems were harvested, because harvesting occurred over two seasons. For a complete discussion of the study sites, measurements, model building, and data analysis, see Weigel and Peng (2002).

METHODS

MEASUREMENTS

Prior to harvest, 0.04-ha plots were established along transects in the nine stands. We inventoried and tagged 1,371 white oak, 180 chestnut oak, 399 black oak, 130 scarlet oak (*Q. coccinea* Muenchh.), and 108 northern red oak > 4.0 cm d.b.h. on the plots. Measurements included d.b.h. on all trees and heights and ages of selected trees used for site index determination. Postharvest measurements were completed 1, 5, 10, 15, and 20 years after clearcutting. First-year measurements included determining parent-tree age by counting rings on the stump surface and noting whether any sprouts were present. At years 5, 10, 15, and 20, we remeasured surviving oak stump sprouts and recorded the number of sprouts and the height of the tallest sprout. Tenth-, fifteenth-, and twentieth-year measurements included recording the crown class. Fifteenth- and twentieth-year measurements included d.b.h. of the tallest sprout.

Each stand was subdivided into smaller units that were uniform in aspect (north, 315°-135°; south, 136°-314°) and slope (ridge, upper slope, lower slope, and bottom). The mean height of the competition was computed for each of these units by averaging the heights of measured dominant or codominant competition within 1 m of selected stumps. The mean height of competition was used to determine whether a stump sprout at years 5 and 10 was competitively successful; successful competition was achieved if the sprout's height equaled or exceeded 80 percent of the mean height of the competition for the individual unit. This approach was taken because stand crown closure does not happen in the first 10 years, so the traditional concept of crown class (Smith and others 1997) is not useful in determining the social position, or competitiveness, of tree reproduction. At ages 15 and 20, oak sprout success was determined by its crown class position. This measure of sprout potential, success, or competitiveness is embodied in the concept of dominance probability (Spetich and others 2002). By year 15, crown closure had occurred; therefore, the use of crown class would provide meaningful success rates.

DATA ANALYSIS

We used logistic regression to model the dominance probability of oak stump sprouts based on the above definition of a successful, competitive, or dominant sprout, i.e., that the main sprout was at least 80 percent of the mean competition height at stand ages 5 and 10, or that the oak sprout was in the dominant or codominant crown class at ages 15 and 20. We used logistic regression because the outcome variable, success, is dichotomous and not continuous, as with the usual linear regression model.

The five-step model building approach suggested by Hosmer and Lemeshow (2000) was used. We used the maximum likelihood method implemented in PROC LOGISTIC of SAS version 9.1.3 (SAS Institute Inc., Cary, NC, 2004) to perform the logistic modeling.

Two different types of models were developed. The first type of model used preharvest measurements and therefore was not dependent on sprouting success at years 1, 5, 10, 15, or 20. The second type of model did not use preharvest data and consequently was dependent on sprouting success at years 1, 5, 10, 15, or 20.

Because the first type of model does not depend on stump sprouting status at years 1, 5, 10, 15, or 20, the model is useful when preharvest measurements can be made. Thus, probability estimates for year 20 can be obtained for the stand before harvest. The same dependent variable and independent variables for year 20 were used as in the 1-, 5-, 10-, or 15-year models (Weigel and Peng 2002, Weigel, Dey, and Peng 2006). The dependent variable was presence of a dominant or codominant stump sprout 20 years after the parent stem was harvested. The independent variables were species, parent tree age, d.b.h., natural log of d.b.h., site index, natural log of site index, and interactions between two or more of these independent variables.

Previous research emphasized developing preharvest models, which are not useful for evaluating regeneration after harvesting. To accommodate the need for predicting oak stump sprout performance after harvest, the postharvest models were developed in the present study. Postharvest models estimated dominance probabilities of stems at age 20 from stumps that had at least one live sprout at age 1, 5, 10, or 15. These models used the same dependent variable as in the preharvest models, but the number of independent variables was reduced so that only stump diameter, species, and site index were considered. These models were developed with the understanding that foresters would be examining the harvested stands at 1, 5, 10, or 15 years after harvest, and thus they would not have preharvest tree age or d.b.h. information.

The species were grouped into the white oak group and the red oak group for both types of models. The white oak group consisted of white and chestnut oaks, and the red oak group consisted of northern red, black, and scarlet oaks.

RESULTS

PREHARVEST TO AGE 20-YEAR MODELS

White Oak Group

Chestnut oak had higher dominance probabilities than white oak for a given tree age, d.b.h., and site quality (Fig. 1). For example, when age, d.b.h., and site index were held constant at 50 years, 10 cm, and 18 m, respectively, 92 percent of chestnut oak stumps are expected to produce a dominant sprout compared to only 54 percent of white oak stumps at stand age 20 years. Also, lower-quality sites (site index 18 m) had higher

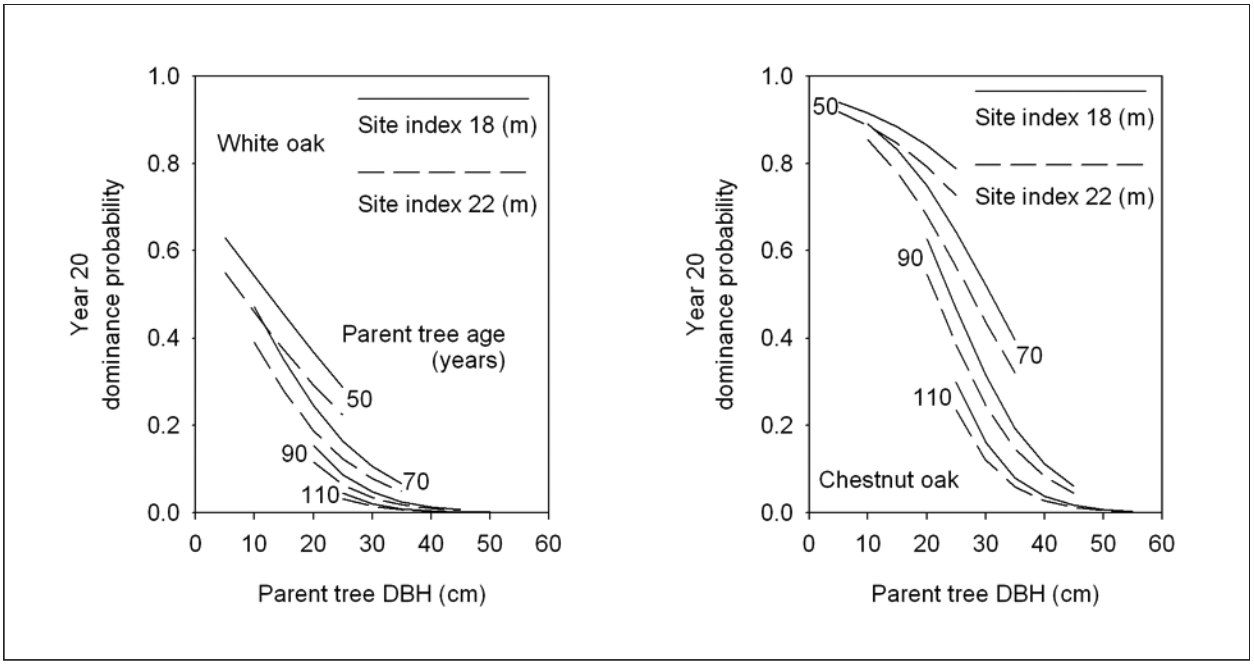

Figure 1.—Estimated dominance probability that a white oak or chestnut oak stump will produce a sprout that is either dominant or codominant 20 years after the parent tree is cut in a clearcut regeneration harvest based on parent age, d.b.h., and black oak site index.

dominance probabilities than higher-quality sites (site index 22 m). For instance, the dominance probability for white oak was 54 percent at site index 18 m, compared to 46 percent at site index 22 m. This influence of site quality on sprout dominance has been reported for 10-year- and 15-year-old stands (Weigel and Peng 2002, Weigel and others 2006). As in previous years, dominance probabilities decreased as oak trees became older and larger in diameter.

The best preharvest model (model 1 in Table 1) included four predictors: species, the interaction of parent tree age with d.b.h., site index, and the natural log of site index. The rationales for identifying the best model were explained in Weigel and Peng (2002); hence, they are not repeated here.

Table 1.—Preharvest Models: logistic regression models for estimating the probability that an oak stump sprout will be dominant or codominant at year 20.

		Parameter estimates[a,b]				Model evaluation statistics	
Model No.	Species	b_0	b_1	b_2	b_3	X^2	H-L[c]
1	White oak	-72.0747	-0.00144	-1.9628	37.4688	404.7816	12.1489
	Chestnut oak	-69.8599	-0.00144	-1.9628	37.4688	($p < 0.0001$)	($p=0.1447$)
2	Red & black oaks	0.2260	-0.00060			124.9196	14.2244
	Scarlet oak	1.7408	-0.00060			($p < 0.0001$)	($p=0.2441$)

[a]Regression models are of the form $P = [1+e^{-(b0+b1X1+b2X2+b3X3)}]^{-1}$, where P is the estimated probability that a cut tree will produce a successful (dominant or codominant) stump sprout at age 20: $X1$ = (dbh in centimeters x tree age); $X2$ is black oak site index in meters (where site index is derived from Carmean and others 1989); $X3$ is the natural log of site index.

[b]All parameter estimates differ significantly from zero at $p < 0.05$.

[c]Hosmer-Lemeshow goodness-of-fit test (Hosmer and Lemeshow 2000).

The overall significance of model 1 reached a likelihood ratio chi-square value of 404.7816, which was significant at $p < 0.0001$ with 4 degrees of freedom. The four predictors were each significant at $p < 0.05$. The goodness-of-fit of model 1 was confirmed by the insignificant Hosmer-Lemeshow (H-L) test (chi-square =12.1489, p =0.1447) (Table 1) (Hosmer and Lemeshow 2000).

The overall correct classification rate based on model 1 was 84.3 percent, which was a significant and meaningful improvement over the chance level. Model 1 was more successful in classifying stumps that did not produce a dominant or codominant stump sprout (specificity) than those that did (sensitivity). This observation was supported by the magnitude of specificity (91.9 percent), compared with that of sensitivity (45.3 percent). False positive and false negative rates were 47.7 percent and 10.5 percent, respectively.

Red Oak Group

In general, scarlet oak trees had higher stump sprout dominance probabilities than northern red oak and black oak combined (Fig. 2). Overall dominance probabilities continued to decline from year 1 (Weigel and Peng 2002) to year 20. The continued decline in dominance probability indicated that the three species were not able to compete with the surrounding vegetation. Scarlet oak had higher dominance probabilities at smaller d.b.h. and younger ages than northern red and black oak (81 percent at age 50 and 10 cm d.b.h. versus 48 percent at age 50 and 10 cm d.b.h., respectively).

The dominance probabilities for northern red oak and black oak did not differ ($p > 0.05$) at year 20. They did, however, differ from scarlet oak ($p < 0.05$). Therefore, the two species were combined in subsequent analysis. Similar to the white oak model, the best red oak year-20 model (model 2 in Table 1) included the same variables as those in the year-15 dominance probability model presented by Weigel and others (2006). Species and the interaction of parent tree age with d.b.h. were significantly related to future dominance probability in red oak group stump sprouts.

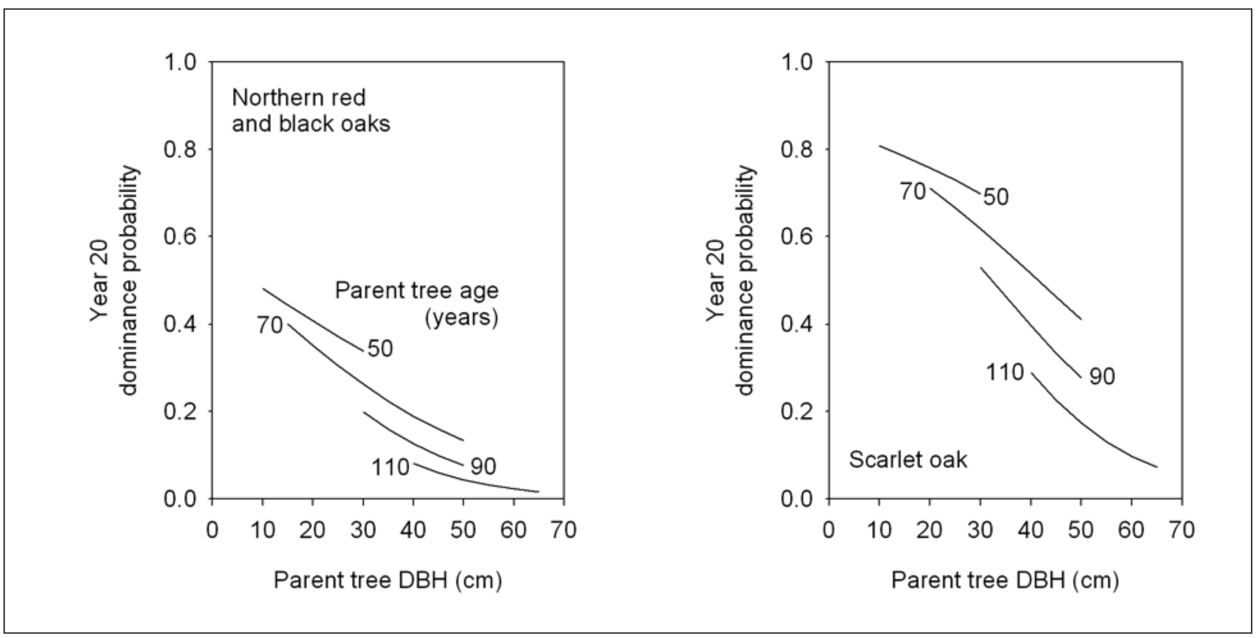

Figure 2.—Estimated dominance probability that a black oak or northern red oak, or scarlet oak, stump will produce a sprout that is either dominant or codominant 20 years after the parent tree is cut in a clearcut regeneration harvest based on parent age and d.b.h.

The overall significance of model 2 reached a likelihood ratio chi-square value of 124.9196, which is significant at $p < 0.0001$ with 2 degrees of freedom. The two predictors were each significant at $p < 0.05$. The goodness-of-fit of model 2 was confirmed by the insignificant H-L test (chi-square = 14.2244, $p = 0.0761$) (Table 1).

The overall correct classification rate based on model 2 was 65.0 percent which was a significant and meaningful improvement over the chance level. Model 2 correctly classified stumps that produced a dominant or codominant stump sprout more frequently than those that did not. This observation was supported by the magnitude of sensitivity (83.7 percent), compared with that of specificity (57.0 percent). False positive and false negative rates were 54.7 percent and 10.8 percent, respectively.

POSTHARVEST TO AGE 20 MODELS

The after-harvest models allow foresters to enter a harvested stand 1, 5, 10, or 15 years after harvest to determine the dominance probability at year 20 for those stumps that have sprouts at 1, 5, 10, or 15 years.

White Oak Group

Year 1—Oaks were more likely to produce dominant or codominant stems at year 20 on lower-quality sites than on higher-quality sites (Fig. 3). Dominance and codominance probabilities also were greater for smaller-diameter stumps. The best results were for 10-cm diameter stumps with site index of 18 m (79 percent), while the lowest dominance probability was for sprouts on 60-cm diameter stumps with site index of 22 m (6 percent). The higher-quality sites most likely had more and faster growing competition. Consequently, the oaks were unable to compete as well on higher-quality sites as on lower-quality sites.

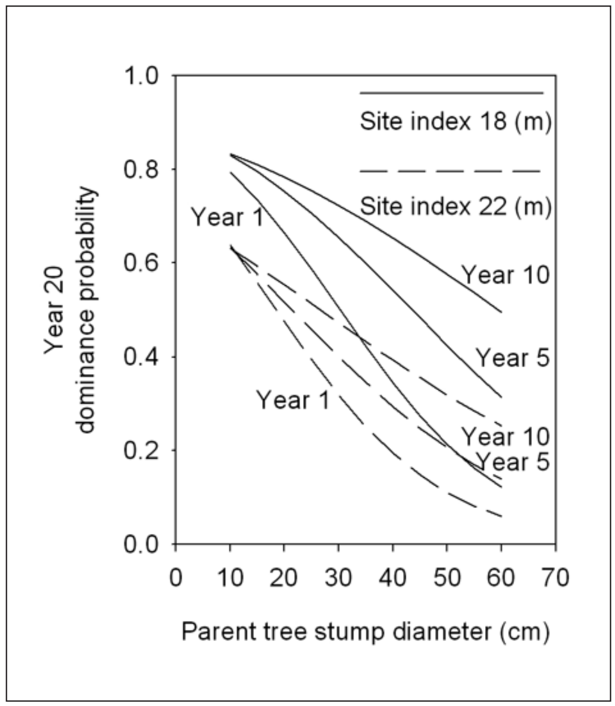

Figure 3.—Estimated dominance probability that a white or chestnut oak stump sprout that is present at year 1, 5, or 10 will produce a sprout that is either dominant or codominant 20 years after the parent tree is cut in a clearcut regeneration harvest based on parent tree stump diameter and site index.

At year 1, the success probabilities for white and chestnut oak were not statistically different, so they were combined ($p > 0.05$). The significant predictors were diameter at stump height and the interaction of site index with the natural log of site index (model 3 in Table 2).

The overall significance of model 3 reached a likelihood ratio chi-square value of 85.8272, which is significant at $p < 0.0001$ with 2 degrees of freedom. Both predictors were significant at $p < 0.05$. The insignificant H-L test (chi-square = 7.4618, $p = 0.3824$) confirmed the goodness-of-fit of model 3 (Table 2).

The overall correct classification rate based on model 3 was 66.0 percent, which was a significant and meaningful improvement over the chance level. Model 3 more correctly classified stump sprouts whose sprouts were dominant or codominant at year 20 (sensitivity) than those that were no longer dominant or codominant at year 20 (specificity). This observation was supported by the magnitude of sensitivity (74.4 percent), compared with that of specificity (58.1 percent). False positive and false negative rates were 37.3 percent and 29.4 percent, respectively.

Year 5—As in the year-1 model, the smallest stumps on lower quality sites had the highest dominance rates (Fig. 3). The dominance probabilities decreased with increasing parent tree stump diameter and increasing site index.

Table 2.—Postharvest Models: logistic regression models for estimating the dominance probability that an oak stump sprout will be in either the dominant or codominant crown class at year 20 when sprouts were present at year 1, 5, 10, or 15 after clearcutting.

		Parameter estimates[a,b]			Model evaluation statistics	
Model No.	Species and year	b_0	b_1	b_2	X^2	H-L[c]
3	White & chestnut oaks, 1	4.5566	-0.0664	-0.0489	85.8272 (*p* < 0.0001)	7.4618 (*p*=0.3824)
4	White & chestnut oaks, 5	5.4713	-0.0474	-0.0655	57.6083 (*p* < 0.0001)	9.7525 (*p*=0.2828)
5	White & chestnut oaks, 10	5.4129	-0.0325	-0.0669	44.9576 (*p* < 0.0001)	6.1552 (*p*=0.6299)
6	White & chestnut oaks, 15	5.7753		-0.0779	47.5109 (*p* < 0.0001)	10.5270 (*p*=0.1606)
7	Black & red oaks, 1	3.5918	-0.0321	-0.0422	63.8500 (*p* < 0.0001)	6.9883 (*p*=0.5379)
	Scarlet oak, 1	5.5106	-0.0321	-0.0422		
8	Black & red oaks, 5	4.3213		-0.0632	51.2045 (*p* < 0.0001)	2.4795 (*p*=0.9286)
	Scarlet oak, 5	5.7665		-0.0632		
9	Black & red oaks, 10	4.1130		-0.0568	41.9118 (*p* < 0.0001)	0.9743 (*p*=0.9952)
	Scarlet oak, 10	5.6756		-0.0568		
10	Black & red oaks, 15	4.2917		-0.0531	28.7678 (*p* < 0.0001)	1.1007 (*p*=0.9930)
	Scarlet oak, 15	5.9057		-0.0531		

[a]Regression models are of the form $P = [1+e^{-(b0+b1X1+b2X2+b3X3)}]^{-1}$, where *P* is the estimated dominance probability that a cut tree will produce a stump sprout that is successful (dominant or codominant crown class) at age 20: *X*1 = stump diameter in centimeters 15 centimeters above ground level; *X*2 is black oak site index in meters x natural log of site index (where site index is derived from Carmean and others 1989); *X*3 is the natural log of site index.
[b]All parameter estimates differ significantly from zero at $p < 0.05$.
[c]Hosmer-Lemeshow goodness-of-fit test (Hosmer and Lemeshow 2000).

Two predictors for model 4 were significant ($p < 0.05$): diameter at stump height and the interaction of site index with the natural log of site index (model 4 in Table 2).

The overall significance of model 4 reached a likelihood ratio chi-square value of 57.6083, which is significant at $p < 0.0001$ with 2 degrees of freedom. The goodness-of-fit of model 4 was confirmed by the insignificant H-L test (chi-square = 9.7525, $p = 0.2828$) (Table 2).

The overall correct classification rate based on model 4 was 68.6 percent, which was a significant and meaningful improvement over the chance level. Model 4 more correctly classified stump sprouts that were dominant or codominant at year 20 than those that were no longer dominant or codominant at year 20. This observation was supported by the magnitude of sensitivity (78.0 percent), compared with that of specificity (54.4 percent). False positive and false negative rates were 28.0 percent and 37.8 percent, respectively.

Year 10—As with year 1 and 5 models, the smallest stumps on lower-quality sites were more likely to produce dominant or codominant stems at year 20 than stumps on higher-quality sites. The dominance or codominance probabilities at year 20 were best predicted by the presence of a stump sprout at year 10, followed by that at year 5, then that at year 1 (Fig. 3).

As with years 1 and 5, the same two predictors once again were significant in year 10 ($p < 0.05$): diameter at stump height and the interaction of site index with the natural log of site index (model 5 in Table 2).

The overall significance of model 5 reached a likelihood ratio chi-square value of 44.9576, which is significant at $p < 0.0001$ with 2 degrees of freedom. The goodness-of-fit of model 5 was confirmed by the insignificant H-L test (chi-square = 6.1552, $p = 0.6299$) (Table 2).

The overall correct classification rate based on model 5 was 68.3 percent, which was a significant and meaningful improvement over the chance level. Model 5 more correctly classified stump sprouts that were dominant or codominant at year 20 than those that were no longer dominant or codominant at year 20. This observation was supported by the magnitude of sensitivity (90.2 percent), compared with that of specificity (26.9 percent). False positive and false negative rates were 30.0 percent and 41.0 percent, respectively.

Year 15—The year-15 model was very simple with only one predictor. Similar to the other white oak group models, the year-15 model predicted higher probabilities for lower-quality sites and lower probabilities for higher-quality sites (Table 3).

Table 3.—The estimated dominance probability that a white or chestnut oak stump sprout present at year 15 will produce a sprout that is either dominant or codominant 20 years after the parent tree is cut.

	Site index	
Initial year and species	18	22
Year 15 white & chestnut oaks	0.848	0.556

Only one predictor was significant in year 15 ($p < 0.05$): the interaction of site index with the natural log of site index (model 6 in Table 2).

The overall significance of model 6 reached a likelihood ratio chi-square value of 47.5109, which is significant at $p < 0.0001$ with 1 degree of freedom. The goodness-of-fit of model 6 was confirmed by the insignificant H-L test (chi-square = 10.5270, $p = 0.1606$) (Table 2).

The overall correct classification rate based on model 6 was 75.8 percent, which was a significant and meaningful improvement over the chance level. Model 6 more correctly classified stump sprouts that were dominant or codominant at year 20 than those that were no longer dominant or codominant at year 20. This observation was supported by the magnitude of sensitivity (88.2 percent), compared with that of specificity (41.9 percent). False positive and false negative rates were 19.4 percent and 43.5 percent, respectively.

Red Oak Group

Year 1—Scarlet oak stump sprouts present at year 1 had much higher probabilities of being dominant or codominant at year 20 than did northern red or black oak (Fig. 4). Scarlet oak's probabilities ranged from 95 percent (10-cm stump diameter, 18-m site index) to 71 percent (70-cm stump diameter, 22-m site index), compared to 75 percent and 27 percent for the combined northern red and black oak over the same range. Stump sprouts on lower-quality sites had higher probabilities for dominance or codominance than those on higher-quality sites. Similar to the white oak group (Fig. 3), red oak group stump sprouts (Fig. 4) were able to compete better on the lower-quality sites than on the higher-quality sites. However, the difference between lower-quality and higher-quality sites was not as great for the red oak group as it was for the white oak group (Fig. 4 vs. Fig. 3).

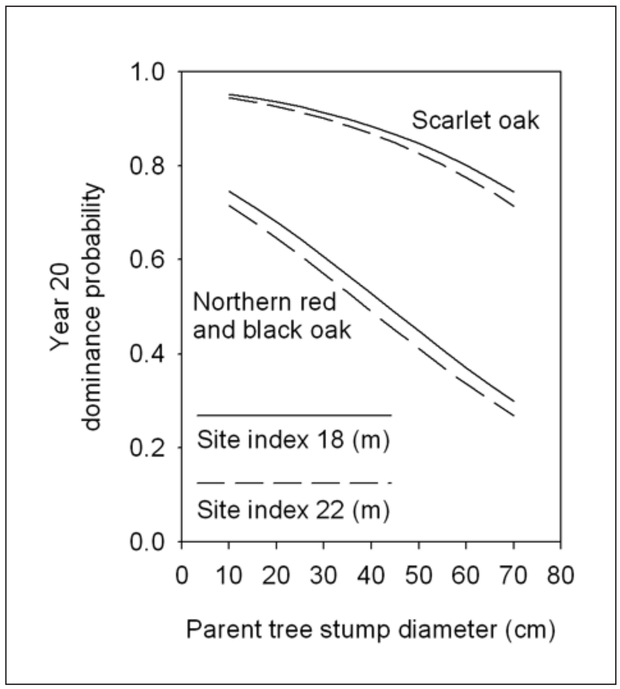

Figure 4.—Estimated dominance probability that a black oak or northern red oak, or scarlet oak, stump sprout that is present at year 1 will produce a sprout that is either dominant or codominant 20 years after the parent tree is cut in a clearcut regeneration harvest based on parent tree stump diameter and site index.

Scarlet oak was significantly different ($p < 0.05$) from black and northern red oak and thus was modeled separately. The significant predictors ($p < 0.05$) besides species were: diameter at stump height and the natural log of site index (model 7 in Table 2).

The overall significance of model 7 reached a likelihood ratio chi-square value of 63.6104, which is significant at $p < 0.0001$ with 3 degrees of freedom. The goodness-of-fit of model 7 was confirmed by the insignificant H-L test (chi-square = 10.5321, $p = 0.2296$) (Table 2).

The overall correct classification rate based on model 7 was 66.0 percent, which was a significant and meaningful improvement over the chance level. Model 7 more correctly classified stump sprouts that were dominant or codominant at year 20 (sensitivity) than those that were no longer dominant or codominant at year 20 (specificity). This observation was supported by the magnitude of sensitivity (85.2 percent), compared with that of specificity (42.3 percent). False positive and false negative rates were 35.5 percent and 30.0 percent, respectively.

Year 5—While diameter at stump height was no longer a significant predictor, the simplified model 8 still predicted higher probabilities for scarlet oak than for northern red or black oaks combined (Table 4). And again, lower-quality sites resulted in higher probabilities for sprout's dominance or codominance than higher-quality sites.

Scarlet oak differed significantly ($p < 0.05$) from black and northern red oaks. The other significant predictor ($p < 0.05$) was the interaction of site index with the natural log of site index (model 8 in Table 2).

The overall significance of model 8 reached a likelihood ratio chi-square value of 51.2045, which is significant at $p < 0.0001$ with 2 degrees of freedom. The goodness-of-fit of model 8 was confirmed by the insignificant H-L test (chi-square = 2.4795, $p = 0.9286$) (Table 2).

The overall correct classification rate based on model 8 was 72.7 percent, which was a significant and meaningful improvement over the chance level. Model 8 more correctly classified stump sprouts that were dominant or codominant at year 20 than those that were no longer dominant or codominant at year 20. This observation was supported by the magnitude of sensitivity (87.4 percent), compared with that of specificity (44.4 percent). False positive and false negative rates were 24.9 percent and 35.3 percent, respectively.

Year 10—Similar to model 8, model 9 was very simple, predicting higher probabilities for scarlet oak than for northern red and black oaks combined (Table 4). Stump sprouts on lower-quality sites performed better than those on higher-quality sites. The probabilities for dominance or codominance increased from model 8 to model 9 for any given species and site index. This is a reasonable and predictable finding because model 9 was based on a shorter time span than model 8 (until year 20). Consequently, the predicted probability that stump sprouts would survive was higher and more accurate.

Table 4.—The estimated dominance probability that a black, red, or scarlet oak stump sprout present at year 5, 10, or 15 will produce a sprout that is either dominant or codominant 20 years after the parent tree is cut.

	Site index	
Initial year and species	18	22
Year 5		
scarlet oak	0.923	0.813
northern red & black oaks	0.738	0.506
Year 10		
scarlet oak	0.938	0.860
northern red & black oaks	0.761	0.562
Year 15		
scarlet oak	0.959	0.908
northern red & black oaks	0.822	0.664

Similar to year 1 and year 5, scarlet oak differed ($p < 0.05$) from black and northern red oak. The other significant predictor ($p < 0.05$) was the interaction of site index with the natural log of site index (model 9 in Table 2).

The overall significance of model 9 reached a likelihood ratio chi-square value of 41.9118, which is significant at $p < 0.0001$ with 2 degrees of freedom. The goodness-of-fit of model 9 was confirmed by the insignificant H-L test (chi-square = 0.9743, $p = 0.9952$) (Table 2).

The overall correct classification rate based on model 9 was 74.3 percent, which was a significant and meaningful improvement over the chance level. Model 9 more correctly classified stump sprouts that were dominant or codominant at year 20 than those that were no longer dominant or codominant at year 20. This observation was supported by the magnitude of sensitivity (87.4 percent), compared with that of specificity (43.0 percent). False positive and false negative rates were 21.3 percent and 41.4 percent, respectively.

Year 15—Like models 8 and 9, model 10 was again very simple, predicting higher probabilities for scarlet oak than northern red and black oaks combined (Table 4). Stump sprouts on lower-quality sites had higher probabilities than stump sprouts on higher-quality sites. Dominance or codominance probabilities continued to increase from year-5 and year-10 models.

As in years 1, 5, and 10, scarlet oak differed ($p < 0.05$) from black and northern red oak. The other significant predictor ($p < 0.05$) was the interaction of site index with the natural log of site index (model 10 in Table 2).

The overall significance of model 10 reached a likelihood ratio chi-square value of 28.8108, which is significant at $p < 0.0001$ with 2 degrees of freedom. The goodness-of-fit of model 10 was confirmed by the insignificant H-L test (chi-square = 1.0406, $p = 0.9941$) (Table 2).

The overall correct classification rate based on model 10 was 76.8 percent, which was a significant and meaningful improvement over the chance level. Model 10 more correctly classified stump sprouts that were dominant or codominant at year 20 than those that were no longer dominant or codominant at year 20. This observation was supported by the magnitude of sensitivity (87.4 percent), compared with that of specificity (37.3 percent). False positive and false negative rates were 16.2 percent and 55.8 percent, respectively.

DISCUSSION

Across all 10 models, stump sprouts were more successful on lower-quality sites than on higher-quality sites. Additionally, stump sprouts from younger parent trees had higher success probabilities than stump sprouts of older parent trees. In the white oak group, chestnut oak did better than white oak in the preharvest model, but in the postharvest models there was no difference. In the red oak group, however, scarlet oak always performed better in both preharvest and postharvest models than did northern red and black oaks. Site index was the most important predictor. It was present in all models except for the red oak group preharvest model. In the two preharvest models the interaction of parent tree age and d.b.h. was also an important predictor. In the postharvest models stump diameter was an important predictor for the white oak group while species was an important predictor for the red oak group.

The 10 models presented in this paper are valuable for predicting the contribution of stump sprouts to forest regeneration. The models allow forest managers to predict the percent of competitive oak stump sprouts 20 years after an even-aged timber harvest. Models 1 and 2 can be used to predict the likelihood of dominant and codominant stump sprouts 20 years after clearcut harvest based on preharvest information. These models also permit forest managers to assess the contribution of stump sprouts to the desired stocking of oak advanced reproduction and to adjust stand prescriptions to promote oak advance reproduction by reducing the vigor and abundance of major woody competitors.

The remaining eight models, models 3 to 10, predict the likelihood of dominant and codominant stump sprouts at year 20 based on their presence at year 1, 5, 10, or 15. Forest managers are then able to assess the need for crop tree release or another type of precommercial thinning to maintain desired stocking of oak. Forest modelers can use these models to better predict and describe the influence of oak stump sprouts on future stands and stand stocking.

Our study differs from many other stump sprout studies by using logistic regression to predict the contribution of stump sprouts to the future stand and hence the sustainability of oak in that stand. Our model incorporates data regarding whether a stump produces sprouts, whether those sprouts survive and grow, and how competitive these sprouts are relative to competing vegetation. Another unique quality of this study is that it provides a long-term understanding of stump sprouts. We examined the fate of oak stump sprouts at age 20, when crown closure and differentiation are occurring, providing a better indication of the reproduction assuming dominance.

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