



Stump Sprouting Potential of Oaks in Missouri Ozark Forests Managed by Even- and Uneven-aged Silviculture

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Abstract.—We evaluated the stump sprouting potential of white oak, black oak, and scarlet oak in relation to tree age, stem diameter, and overstory density in Ozark forests managed by even-aged and uneven-aged silvicultural systems. In eastern North America, few studies have evaluated the influence of a forest canopy on the potential of hardwood stumps to sprout and contribute to regeneration. The Missouri Ozark Forest Ecosystem Project (MOFEP) gave us an opportunity to study oak stump sprouting in relation to tree characteristics and residual overstory density resulting from various regeneration methods.

One growing season after the clearcut, single-tree, and group selection harvests implemented on MOFEP sites in 1996, we measured sprout growth on 701 stumps of white oak (*Quercus alba* L.), scarlet oak (*Q. coccinea* Muenchh.), and black oak (*Q. velutina* Lam.). Stumps were selected from plots (primarily on Ecological Landtypes 17 and 18) within uneven- and even-aged compartments. Stumps averaged 9.3 in. (23.6 cm) in diameter (range 1.7 to 33.3 in. [4.3 to 84.5 cm]) and 61 years in age (range 38 to 169 years). By the end of the first growing season after harvest, 78 percent of the oak stumps had produced a live sprout. Stump sprout frequency was high for small diameter and young trees, regardless of species. However, sprouting probability declined more rapidly with increasing stump diameter or age for white oak than it did for scarlet oak and black oak. Scarlet oak and black oak produced more sprouts (mean = 12) per stump than white oak (mean = 8). Overstory density (e.g., clearcut vs. single-tree gaps) had no detectable effect on oak stump sprouting probability or on the number of sprouts per stump. However, increasing overstory density reduced the height of the tallest stem in each stump sprout clump. The tallest stem within a sprout clump averaged 2.8 ft (0.85 m) in the single-tree selection treatment compared to 4.0 ft (1.2 m) in the clearcut treatment. Sprouting potential, height of the dominant sprout, and sprout clump density decreased with increasing stump diameter and tree age for all species regardless of overstory density.

In Missouri Ozark forest ecosystems, the composition and structure of the overstory and

advance reproduction present before regeneration disturbances largely determines the composition of the future forest (Dey *et al.* 1996). Large advance reproduction and stump sprouts are the most competitive sources of oak reproduction. Their development is greatest where light intensities exceed 50 percent of full sunlight (Gottschalk 1994) because most oaks are intermediate in shade tolerance (e.g., white oak (*Quercus alba* L.), black oak (*Q. velutina* Lam.), and northern red oak (*Q. rubra* L.)) or are shade intolerant (e.g., post oak (*Q. stellata* Wangenh.))

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and scarlet oak (*Q. coccinea* Muenchh.)). Therefore, regeneration methods such as clearcutting and shelterwood harvesting have been recommended to managers of oak forests, and methods such as single-tree selection have not been considered appropriate for sustainable management of oak ecosystems (Marquis and Johnson 1989, Sander and Clark 1971, Sander and Graney 1993). Ironically, some interest groups are advocating uneven-aged silvicultural systems (e.g., single-tree selection) to preserve forest aesthetics and for other reasons. Consequently, Federal and State forest managers are now applying regeneration methods to create uneven-aged forests in the Ozarks, despite the uncertainty that these methods can sustain desired forest composition and conditions. Forest managers and scientists do not fully understand the dynamics of oak regeneration and recruitment that result from uneven-aged harvest methods, especially when they are applied to mature, fully stocked forests in the Ozarks.

Sustainable recruitment of oak into the overstory in stands managed by uneven-aged silvicultural systems depends on sufficient numbers of large oak reproduction in the understory (Larsen *et al.* 1999). This reproduction can arise from advance reproduction as seedling sprouts or from stump sprouts created by harvesting. Foresters must manage stand density and structure carefully because understory light levels, which are directly related to the forest canopy, affect development of oak reproduction.

Long-term survival of oak advance reproduction (i.e., seedling sprouts) is low beneath closed-canopied forests, especially on productive sites where subcanopies of shade tolerant species reduce understory light levels to as low as 1 percent of full sunlight, far below the light compensation point of oaks (Dey and Parker 1996, Hanson *et al.* 1987, Loftis 1990). Forest managers and scientists have long recognized the important relationship between the occurrence of abundant large oak advance reproduction as seedling sprouts and overstory density (Carvell and Tryon 1961). More recently, Larsen *et al.* (1997) found in Ozark forests that the chance of having abundant large oak advance reproduction was improved when overstory density was maintained at relatively low stocking (i.e., 58 percent stocking according to Gingrich 1967). In contrast, there is less known about the persistence and competitiveness of

oak stump sprouts that develop in single-tree gaps and in small group openings. Most studies of oak stump sprouting have dealt with how sprouts develop in clearcuts, or large openings (Cobb *et al.* 1985, Johnson 1977, Lynch and Bassett 1987, Ross *et al.* 1986, Weigel and Johnson 1998, Wendel 1975).

The purpose of this study was to determine the effect of overstory density, forest canopy crown cover, and individual tree characteristics on the sprouting potential and growth performance of sprouts arising from oak stems cut by chainsaw in a timber harvest operation. We present an assessment of sprouting capacity and growth performance for white oak, black oak, and scarlet oak in Missouri Ozark forests harvested by the clearcut, group selection, or single-tree selection regeneration method. Longer term monitoring will provide valuable insight into the persistence of stump sprouts growing under a partial forest canopy and their recruitment potential in small canopy gaps.

METHODS

We monitored stump sprouting of oak trees in stands harvested by the clearcut, group selection, or single-tree selection regeneration method as part of the Missouri Ozark Forest Ecosystem Project (MOFEP). MOFEP is described in Brookshire and Shifley (1997), Shifley and Brookshire (2000), and other papers in this volume. Timber harvesting was completed in the fall of 1996 and was immediately followed by slashing (i.e., cutting) of unmerchantable stems in the winter of 1996-1997. A total of 70 vegetation plots (0.5-ac [0.2 ha]) were used to sample oak stumps in stands harvested by clearcutting (21 plots from sites 3, 5, and 9) and in stands harvested by uneven-aged methods (i.e., group selection and single-tree selection) (49 plots from sites 2, 4, and 7) on Ecological Landtypes 17 and 18 (Brookshire *et al.* 1997). All plots that were clearcut were sampled, and approximately 50 percent of the more accessible uneven-aged management plots were sampled. On each vegetation plot, oak stumps were randomly selected and spatially referenced to a plot or subplot center. At each plot or subplot center, no more than 5 stumps were chosen for each species. A total of 701 stumps were selected to represent the range of stump diameters present on MOFEP harvest units (table 1).

Table 1.—*Distribution of oak stumps by species and harvest treatment sampled on Missouri Ozark Forest Ecosystem Project sites*

Species	Clearcut	Group selection	Single-tree selection	Total
White oak	155	97	124	376
Scarlet oak	67	26	55	148
Black oak	71	46	60	177
Total	293	169	239	701

During the winter of 1996-1997, before sprouting occurred, a 0.5- to 2-in. (1 to 5 cm)-thick disc was cut from the top of each of the 701 oak stumps to determine tree age. Stumps were tagged, the diameter of each stump was measured, and stumps were referenced to plot or subplot center by azimuth and distance. Stumps averaged 9.3 in. (23.6 cm) in diameter (range 1.7 to 33.3 in. [4.3 to 84.6 cm]) and 61 years in age (range 38 to 169 years). In the spring of 1998, one growing season after harvest, stumps were revisited to count the number of sprouts and measure the height of the tallest sprout.

In the summer of 1995 (before timber harvesting) and again in the summer of 1997 (after logging and slashing operations), ocular estimates of forest canopy crown cover were made on each 0.5-ac (0.2-ha) vegetation plot according to procedures outlined in Grabner (2000). Crown cover was measured above each ground

flora quadrat and above each plot and subplot center, resulting in a total of 21 observations per vegetation plot. These were averaged to give an estimate of crown cover for each 0.5-ac (0.2-ha) plot in which stump sprouts were monitored. In 1998, basal area and trees per acre for trees ≥ 4.5 in. (11.4 cm) d.b.h. were determined for each 0.5-ac (0.2-ha) circular permanent vegetation plot according to procedures outlined by Jensen (2000). Pre- and post-harvest stand conditions are summarized in table 2.

The probability of an oak stump producing at least one live sprout at the end of the first growing season was modeled using logistic regression (SAS Institute Inc. 1995). Independent variables considered included stump diameter, tree age, species, and measures of stand density and forest crown cover. For a subset of stumps that sprouted, regression analysis (SAS Institute Inc. 1991) was used to evaluate relationships between the response

Table 2.—*Average pre-harvest and post-harvest stand density and crown cover^a by harvest treatments for the Missouri Ozark Forest Ecosystem Project plots used in this study*

Harvest treatment	Basal area ^b Feet ² /acre	Trees per acre ^b	Crown cover Percent
Pre-harvest			
Even-aged	84 $\pm$ 6	149 $\pm$ 17	85 $\pm$ 2
Uneven-aged	85 $\pm$ 1	157 $\pm$ 18	84 $\pm$ 4
Post-harvest			
Even-aged	7 $\pm$ 6	9 $\pm$ 9	3 $\pm$ 4
Uneven-aged	62 $\pm$ 16	122 $\pm$ 39	58 $\pm$ 17

^a The pre-harvest inventory was conducted in 1995. Post-harvest crown cover was measured in 1997, and stand density was determined in 1998.

^b 1 ft²/ac = 0.2296 m²/ha; 1 tree/ac = 2.47 trees/ha.

variables (number of sprouts and height of the tallest sprout) and an array of independent tree and stand variables similar to those used in the logistic regression analysis.

RESULTS

Survival

By the end of the first growing season after harvest, 78 percent of the oak stumps had produced at least one live sprout. One of the best models for predicting stump sprouting probability was:

$$P = [1 + \exp \{- (5.9991 - 0.2413SD - 0.0475AGE + 1.527OAK1 + 1.4122OAK2)\}]^{-1} \quad (1)$$

where: P = probability of producing at least one live sprout at the end of the first growing season,

SD = stump diameter (inches),
AGE = tree age at stump height (years),
OAK1 = 0 for white oak and black oak,
and 1 for scarlet oak, and
OAK2 = 0 for white oak and scarlet oak,
and 1 for black oak.

Other models (table 3) were significant (p-values < 0.001) and provided good fits to the data according to the Hosmer and Lemeshow (2000) test. Including a dummy variable (OAK1 and OAK2) for species resulted in the lowest Akaike's information criterion (AIC_c) (271 for the model in Equation (1)), which was adjusted for small sample sizes according to Burnham and Anderson (1998). In the first set of nested models (i.e., the upper group of models) in table 3, adding species to the model substantially improved model performance as indicated by ΔAIC_c . Models that have an AIC_c that is 7 to 10 units lower than any other model within a family of nested models are considered superior

Table 3.—Logistic regression models and diagnostic statistics for the probability that an oak stump will produce at least one live sprout at the end of the first growing season after being harvested by either clearcut, group selection, or single-tree selection harvesting

MODELS ^a (includes group opening data)	AIC _c	ΔAIC_c	Fit ^b
SD ^c	471	200	0.28
AGE ^c	292	21	0.94
SD ^c +AGE ^c	284	13	0.64
SD+AGE ^c +(SD x AGE)	286	15	0.59
SD ^c +OAK1 ^c +OAK2 ^c	441	170	0.48
AGE ^c +OAK1+OAK2	290	19	0.55
SD ^c +AGE ^c +OAK1 ^c +OAK2 ^c	271	0	0.41
SD+AGE+(SD x AGE)+OAK1 ^c +OAK2 ^c	273	2	0.76
MODELS (excludes group opening data)			
SD ^c +AGE ^c +OAK1 ^c +OAK2 ^c	271	0	0.69
SD ^c +AGE ^c +OAK1 ^c +OAK2 ^c +CC	273	2	0.75
SD ^c +AGE ^c +OAK1 ^c +OAK2 ^c +BA	273	2	0.71
SD ^c +AGE ^c +OAK1 ^c +OAK2 ^c +TPA	273	2	0.79
SD ^c +AGE ^c +OAK1 ^c +OAK2 ^c +BA+TPA	275	4	0.22
SD ^c +AGE ^c +OAK1 ^c +OAK2 ^c +BA+TPA+CC	276	5	0.16
SD ^c +AGE ^c +OAK1 ^c +OAK2 ^c +BA+TPA+(BA x TPA)	277	6	0.07
SD ^c +AGE ^c +OAK1 ^c +OAK2 ^c +BA+TPA+CC+(BA x TPA)	278	7	0.25

^a Where models are of the form: $P = [1 + \exp\{-(\beta_0 + \beta_1 X_1 + \dots + \beta_n X_n)\}]^{-1}$ and SD = stump diameter (inches); AGE = tree age at stump height (years); OAK1 = 0 for white and black oak, and 1 for scarlet oak; OAK2 = 0 for white oak and scarlet oak, and 1 for black oak; TPA = trees per acre; BA = basal area (feet²/acre); and CC = crown cover of forest canopy (%).

^b Probability value for Hosmer and Lemeshow goodness-of-fit test (Hosmer and Lemeshow 2000).

^c Indicates significance of parameter ($P \leq 0.05$) based on Wald χ^2 statistic.



(Burnham and Anderson 1998). Both black oak and scarlet oak had higher sprouting probabilities in year 1 than white oak for a given stump diameter and tree age (fig. 1). For all oak species, sprouting probabilities decreased with increasing stump diameter and age. As stump diameter and age increased, sprouting probabilities dropped more rapidly for white oak than for black oak or scarlet oak.

We evaluated the significance of stand density and crown cover on sprouting probability with the models presented in table 3. Inclusion of stand density or crown cover did not significantly improve model goodness of fit, and parameters for stand density and crown cover were each judged insignificant based on the Wald χ^2 statistic, despite overall model significance. Again the model with the lowest AIC_c was Equation (1). It does not appear that a partial forest canopy affects stump sprouting and first-year sprout survival.

Height

Increasing overstory density significantly reduced height of the tallest sprout regardless of oak species (fig. 2). Stump sprouts in clearcuts, which had an average residual basal area of 7 ft²/ac (1.6 m²/ha), were about 1 foot taller (30 cm) on average than sprouts under a single-tree selection canopy, which had an average residual basal area of 62 ft²/ac (14.2 m²/ha). In clearcuts, white oak sprouts averaged 3.6 ft (1.1 m), scarlet oak 4.5 ft (1.4 m), and black oak 4.3 ft (1.3 m). Stand density measures (i.e., basal area and trees per acre and crown cover) were highly correlated with each other (Pearson correlation coefficients were consistently about 0.91 with p-values of <0.001). Models that contained combinations of basal area, trees per acre, and crown cover had serious multicollinearity problems as indicated by analysis of variance inflation factors, eigenvalues, condition index, and proportion of variance diagnostics (Neter *et al.* 1985, SAS Institute Inc. 1991). In addition, parameter estimates for these variables were individually non-significant where the overall model was highly significant. Consequently, we present three height models, each containing

only one measure of stand density or overstory crown cover, that express the relationship between sprout height, and tree and stand characteristics (table 4).

Black oak and scarlet oak sprouts were significantly taller (about 0.7 and 1.0 ft taller [0.2 and 0.3 m], respectively, on average) than those of white oak for given tree diameter, age, and stand condition (table 4). Both tree diameter and age were negatively related to height of the tallest sprout for all oak species (fig. 2).

Sprout Numbers

Including measures of stand density and crown cover did not improve our ability to explain variation in sprout clump density (based on adjusted R²), nor were parameter estimates of these variables significant. Sprout clump density was similar in clearcuts and single-tree selection harvest units. However, tree age and diameter were negatively related to the number of sprouts per stump after the first year regardless of oak species (fig. 3). Numbers of sprouts per stump were significantly different among the red and white oak groups (scarlet oak = black oak > white oak), and the following model was selected as the best fit ($F = 8.14$, $p\text{-value} = <0.0001$, $R^2_{\text{adj}} = 0.10$):

$$S = 17.09666 + 3.8806\text{OAK1} + 3.93426\text{OAK2} - 0.03101\text{SD} - 0.15368\text{AGE} \quad (2)$$

where: S = number of sprouts per stump at the end of the first growing season,
SD = stump diameter (inches),
AGE = tree age at stump height (years),
OAK1 = 0 for white and black oak, and 1 for scarlet oak, and
OAK2 = 0 for white oak and scarlet oak, and 1 for black oak.

Black oak and scarlet oak stumps each produced about 4 more sprouts per stump than white oaks across the range of stump diameters and tree ages observed in this study. On average, black oak and scarlet oak stumps each produced 12 sprouts per stump compared to 8 sprouts for white oak.

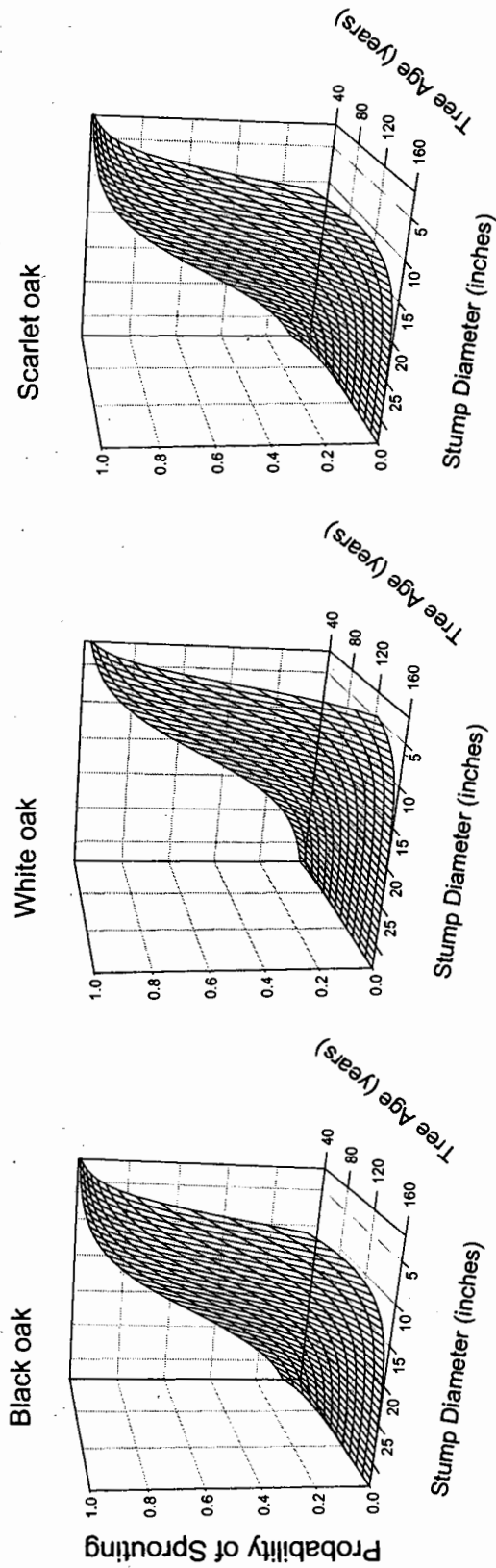


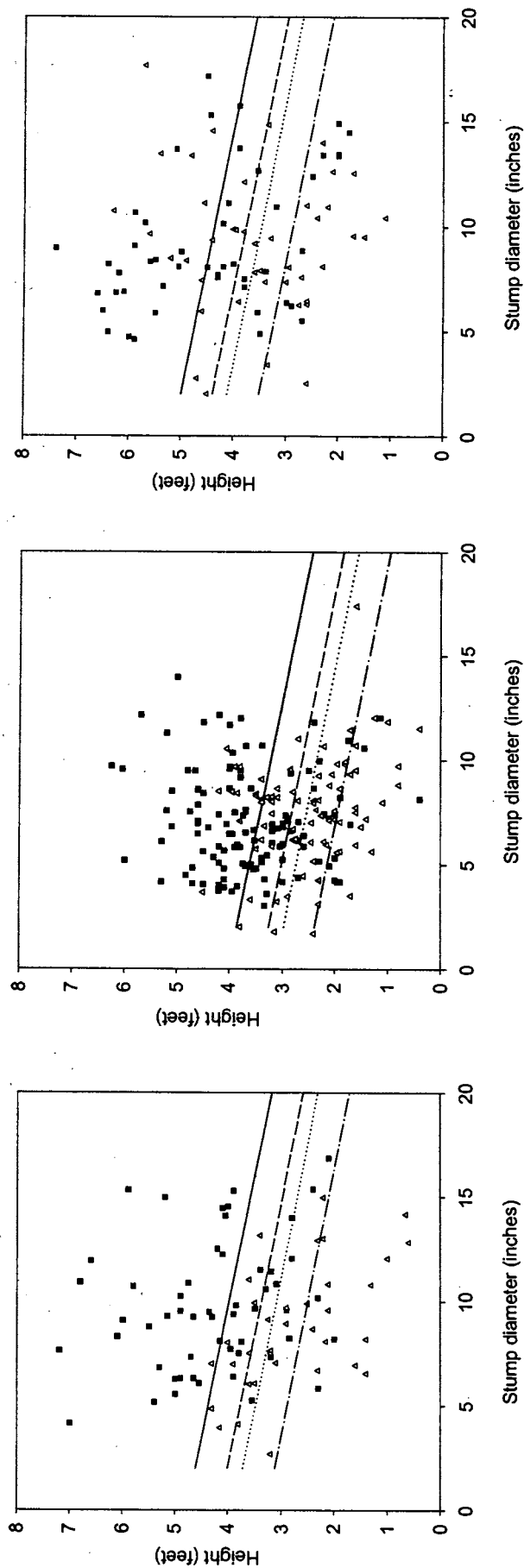
Figure 1.—Probability of producing at least one live sprout at the end of the first growing season in relation to stump diameter and tree age for black oak, white oak, and scarlet oak. Plotted lines are based on Equation (1). 1 inch = 2.54 cm.



Black oak

White oak

Scarlet oak



- Basal Area = 7 ft²/ac; Age = 60 years
- Basal Area = 62 ft²/ac; Age = 60 years
- Observed Sprouts in Clearcuts
- ▲ Observed Sprouts in Selection Cuts
- Basal Area = 7 ft²/ac; Age = 100 years
- Basal Area = 62 ft²/ac; Age = 100 years

Figure 2.—First-year height of the dominant stump sprout for black oak, white oak, and scarlet oak in relation to stump diameter, tree age, and overstory density. Plotted lines are based on the equations presented in table 4. 1 inch = 2.54 cm; 1 foot = 0.3048 m; 1 ft²/ac = 0.2296 m²/ha.

Table 4.—Regression models of first-year height of tallest sprout in relation to tree species, diameter and age, and stand density

Model	Regression model ^a	Overall model F-value (p-value)
1	$HT = 5.12483 + 1.08725OAK1 + 0.73658OAK2 - 0.0741SD - 0.01751AGE - 0.00771TPA$	20.16 (<0.001)
2	$HT = 5.03427 + 1.13404OAK1 + 0.74591OAK2 - 0.07888SD - 0.015AGE - 0.01605BA$	19.65 (<0.001) [*]
3	$HT = 5.13286 + 1.08193OAK1 + 0.73915OAK2 - 0.07647SD - 0.01704AGE - 0.01795CC$	21.53 (<0.001)

^a Where: HT = height (feet) of the tallest sprout at the end of the first growing season,
SD = stump diameter (inches),
AGE = tree age at stump height (years),
OAK1 = 0 for white and black oak, and 1 for scarlet oak,
OAK2 = 0 for white oak and scarlet oak, and 1 for black oak,
TPA = trees per acre,
BA = basal area (feet²/acre), and
CC = crown cover of forest canopy (%).

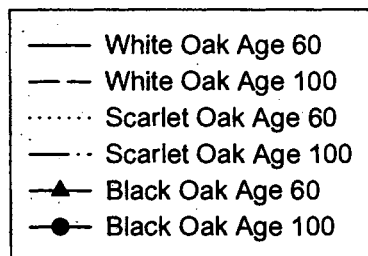
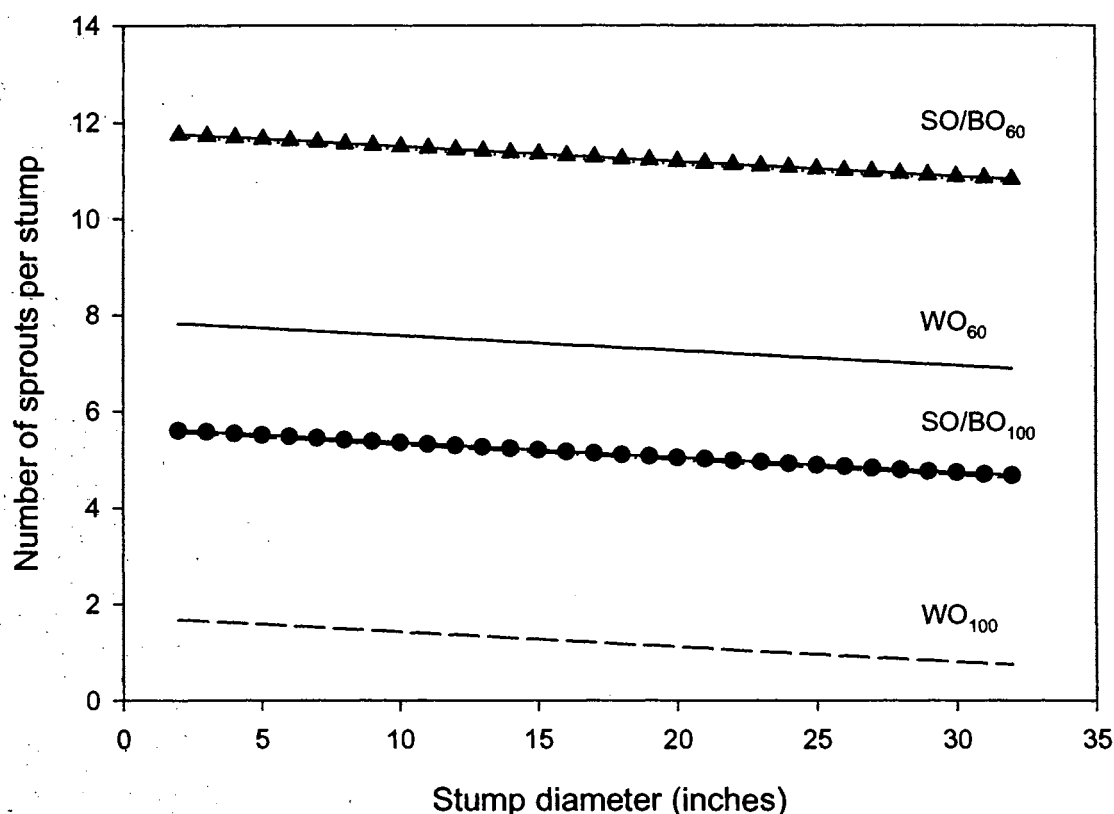


Figure 3.—Predicted sprout clump density 1 year after harvesting by stump diameter and for selected ages of scarlet oak, black oak, and white oak. Plots are based on Equation (2). 1 inch = 2.54 cm.



DISCUSSION

For all oak species in our study, sprouting probability decreased with increasing diameter and age. Similarly, declines in sprouting frequency with increasing diameter and age have been reported for black oak, scarlet oak, white oak, and northern red oak (Johnson 1975, 1977; Lynch and Bassett 1987; Weigel and Johnson 1998), and pin oak (*Quercus palustris* Muenchh.), cherrybark oak (*Q. falcata* var. *pagodifolia* Ell.), and willow oak (*Q. phellos* L.) (Kabrnick and Anderson 2000). These studies sampled oak stumps over a wide range of diameters and ages. In some research studies, oak sprouting frequencies were high and there were low correlations between tree age and (1) sprouting frequency, (2) height and diameter of the dominant sprout, and (3) number of sprouts per stump (Gardiner and Helmig 1997, Kabrnick and Anderson 2000, Lynch and Bassett 1987, Wendel 1975). These results usually occurred when the sample oaks were relatively young and uniformly small in diameter (e.g., 28-year-old water oak (*Quercus nigra* L.)).

The sprouting probabilities of black oak and scarlet oak were similar, and both species were more likely to sprout than white oaks of similar size and age. Similarly, Johnson (1977) observed that scarlet oak and black oak had greater sprouting probabilities than white oak after 1 year in Missouri Ozark clearcuts. We found that black oak and scarlet oak exhibited greater sprouting probabilities at larger diameters and greater ages than white oak (fig. 1). Similar species differences in sprouting probability were also observed by Weigel and Johnson (1998) in southern Indiana clearcuts. They also found that sprouting probability decreased more rapidly in white oak than it did in black oak, scarlet oak, and northern red oak as stem diameter and age increased.

Overstory density, as measured by basal area, stems per acre, or forest canopy crown cover, did not significantly affect the probability of producing at least one live sprout the first year after harvesting for white oak, black oak, or scarlet oak. Stumps in clearcuts were as likely to sprout as trees of similar sizes and ages in single-tree selection or group selection openings. However, increasing overstory density and canopy cover significantly reduced the height of the tallest sprout by the end of the first growing

season in all oak species. In contrast, a partial forest overstory did not affect the initial sprout density.

Gardiner and Helmig (1997) studied the development of water oak stump sprouts in a 28-year-old plantation that had been thinned from below to 40 percent or 60 percent basal area. They found that overstory density was not related to the probability of sprouting because all stumps produced sprouts in this young oak stand. In a mature bottomland oak forest in southeast Missouri, Kabrnick and Anderson (2000) reported that stumps of pin oak, cherrybark oak, and willow oak in single-tree gaps sprouted as readily as stumps of upland oaks in clearcuts (Johnson 1977, Weigel and Johnson 1998). Their sprouting frequencies were also comparable to open-grown stump sprouts in this study.

In our study, scarlet oak produced the tallest dominant sprouts at the end of the first year, followed closely by black oak. Sprouts of these species were significantly taller than those of white oak (fig. 2). Sprout heights in clearcuts were slightly higher than those reported by Johnson (1977) for upland oaks in the Missouri Ozarks and by Weigel and Johnson (1998) for oaks in southern Indiana. Stump sprouts under a single-tree selection canopy were slightly taller than 1-year sprouts of pin oak, willow oak, and cherrybark oak growing in single-tree gaps in a bottomland forest in southeast Missouri (Kabrnick and Anderson 2000).

Black oak and scarlet oak stump sprout clump densities were similar (mean = 12 sprouts per stump), and both species produced more sprouts per stump than white oak (mean = 8 sprouts per stump) (fig. 3). In southeast Missouri, pin oak, cherrybark oak, and willow oak averaged 9, 16, and 20 sprouts per stump, respectively, for stumps in single-tree gaps (Kabrnick and Anderson 2000). Johnson (1977) reported sprout clump densities for upland white oak and black oak (mean = 8 sprouts per stump) and scarlet oak (mean = 12 sprouts per stump) in Missouri Ozark clearcuts that were similar to those in our study.

Even though stand density and canopy cover did not affect initial stump sprouting probability or sprout density, they may affect stump sprout long-term survival and recruitment into the

overstory. Oak advance reproduction is more likely to accumulate and grow large when understory light intensities are 50 percent or more of full sunlight (Gottschalk 1994). Single-tree selection harvest in mature, closed-canopied hardwood forests may not appreciably increase light levels at the forest floor (Fischer 1979, Marquis 1988). Thus, low light levels may limit oak advance reproduction, including stump and seedling sprouts, under a moderate to heavy overstory. Overstory density is important for developing large oak advance reproduction in Missouri Ozark (Larsen *et al.* 1997) and Lower Peninsula of Michigan (Johnson 1992) oak ecosystems, where the probability of having large oak reproduction was greatest at stocking levels between 30 and 60 percent (according to Gingrich 1967). Larsen *et al.* (1999) recommended maintaining overstory density at 63 ft²/ac (14.5 m²/ha) on average over a 20-year cutting cycle to favor oak recruitment in forests managed to produce an uneven-aged structure in the Missouri Ozarks. However, the effect of an overstory on stump sprout potential in oaks is not well known and few studies address this situation. Most recently, Gardiner and Helmig (1997) and Kabrick and Anderson (2000) studied stump sprouting under a bottomland overstory. These studies were too short-term to provide any indication of the ability of stump sprouts to survive and develop under a forest overstory. The overstory in our single-tree selection stands (mean basal area = 62 ft²/ac [14.2 m²/ha]) did reduce the height of the tallest stump sprout. The long-term survival and recruitment success of these sprouts remains unknown.

SUMMARY

Oak stump sprouts are important in obtaining adequate oak regeneration. In young stands, stump sprouting may account for most of the reproduction. In older stands, stump sprouts can supplement advance reproduction populations to ensure the adequacy of oak in the new forest. Managers need to be able to predict the contribution of stump sprouts to the overall population of oak reproduction to judge whether (1) reproduction is adequate, (2) artificial regeneration by planting or direct seeding is needed to supplement natural reproduction, (3) competition control is needed to maintain oak in a free-to-grow state, or (4) harvesting should be delayed to give time for the development of large advance reproduction.

The contribution of oak stump sprouts to oak regeneration potential is predictable, and estimates based on tree, stand and site characteristics can be made before harvesting. In this study, we demonstrated that stem diameter and age are primary factors that determine the probability of sprouting, density of sprouts, and height growth of the dominant sprout for individual trees. We also noted that sprouting potential and sprout growth vary by oak species.

Overstory density is important in determining long-term survival of oak stump sprouts and success of oak recruitment into the overstory. Further monitoring of stump sprouts in this study will provide valuable information on their contribution to oak regeneration in stands managed by uneven-aged management, and it will provide a quantitative basis for assessing the fate of oak stump sprouts developing under a partial forest overstory. Managers can use these results to help determine when uneven-aged management is appropriate and to manipulate stand stocking to promote oak reproduction and recruitment.

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