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Stump sprouting of 19 upland hardwood species 1 year following initiation of a shelterwood with reserves silvicultural system in the southern Appalachian Mountains, USA

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Abstract Models that quantify the probability of stump sprouting P(s) and sprout characteristics for predominant tree species in the southern Appalachian Mountains, USA are lacking. In this study, 375 plots (0.01 ha) were installed across five stands in eastern Tennessee and western North Carolina. Trees $\geq$3.8 cm diameter at 1.37 m above groundline (dbh) were tagged, and dbh and species recorded. Stands were regenerated using a two-aged silvicultural system (residual basal area (BA) <6.3 m^2 ha^{-1}). One growing season post-harvest, we recorded (1) sprouting (yes/no), (2) the number of sprouts per stump (sprout density), and (3) dominant (tallest) sprout height. Sprout density, sprout height, and P(s) were modeled as function of dbh, site index (SI), and BA. For white (*Quercus alba* L.), black (*Quercus velutina* Lam.), scarlet (*Quercus coccinea* Muenchh.), and northern red (*Quercus rubra* L.) oaks, and sweet birch (*Betula lenta* L.), yellow buckeye (*Aesculus flava* Aiton), and red maple (*Acer rubrum* L.), P(s) was inversely related to dbh. Sprout density was positively related to (1) dbh for red maple, yellow buckeye, sourwood (*Oxydendrum arboreum* L. (DC)), silverbell (*Halesia tetraptera* Ellis), and white basswood (*Tilia heterophylla* Vent.), and (2) SI for scarlet oak. For eight species, sprout height was influenced by dbh, SI, dbh and SI, or dbh and BA. Because stump sprouts are a primary source of regeneration, the information on stump sprouting produced for these 19 species can be used to quantify and predict early stand dynamics following regeneration harvests in these diverse southern Appalachian hardwood stands.

Keywords Oak · Non-oak species · Probability of sprouting · Regeneration · Shelterwood with reserves

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Introduction

Stump sprouts, with an already-developed root system, exhibit rapid growth following disturbance and, therefore, greatly influence post-disturbance species composition and stand structure (Del Tredici 2001; Dietze and Clark 2008; Fei and Steiner 2009). In upland hardwood forests of the Central Hardwood Region of the USA, stump sprouts play a particularly important role in shaping stand-level structure and composition following both natural (Peterson and Pickett 1991; Peterson 2000, 2007; Dietze and Clark 2008) and silvicultural disturbances (Cook et al. 1998; Elliott et al. 1997). For example, 11 years after clearcutting mixed-oak (*Quercus* L.) stands in Kentucky, Arthur et al. (1997) reported stump sprouts comprised 50 % of all stems. Similarly, 20 years following clearcutting in a southern Appalachian mixed-hardwood stand, Beck and Hooper (1986) found 86 % of all dominant and co-dominant stems were of stump sprout origin. Following the creation of experimental gaps designed to emulate small- to intermediate-windthrow events common in upland hardwood forests of the southern Appalachian Mountains, Dietze and Clark (2008) observed recruitment from stump sprouts comprised up to 87 % of gap regeneration and was the primary source of regeneration for sourwood (*Oxydendrum arboreum* L. (DC)) and flowering dogwood (*Cornus florida* L.).

The propensity of a tree to sprout following cutting is dependent on several factors, including species (Mann 1984; Kays et al. 1988; Rydberg 2000), age (Weigel and Peng 2002; Šplíchalová et al. 2012), tree size (Johnson 1977; Sands and Abrams 2009; Keyser and Zarnoch 2014), site quality (Johnson 1977; Cook et al. 1998), and season of harvest (Kays et al. 1988; Belz 2003). Tree size is consistently the most influential (e.g., Johnson 1977; Weigel and Peng 2002) and easily measured variable affecting sprouting for a variety of upland hardwood tree species. Although there is an abundance of information describing, in general terms, the relationship between tree size and sprouting for individual species, few predictive equations are available for the diverse suite of species commonly found in upland hardwood forest types across the Central Hardwood Region, with most equations specific to economically desirable species. For example, because of the difficulty in regenerating ecologically and commercially-valuable oak species (Loftis and McGee 1993; Cook et al. 1998), equations that quantify the probability of sprouting for oak species are abundant (Dey et al. 1996; Weigel and Peng 2002; Gould et al. 2007; Sands and Abrams 2009). In contrast, for species of lower commercial value- species that often interfere with successful oak regeneration (e.g., Loftis 1983; Loftis 1985)- predictive sprouting equations are, for the most part, lacking, or are applicable to only certain stand conditions, size ranges, or management activities (e.g., Keyser and Zarnoch 2014).

The number of sprouts produced by a cut stump (i.e., sprout density), as well as subsequent sprout growth and development, is often influenced by many of the same factors that affect the probability of sprouting, including species (Sands and Abrams 2009), tree size (Kays and Canham 1991; Lockhart and Chambers 2007; Sands and Abrams 2009), age (Harrington 1984), and site quality (Johnson 1975). For example, unimodal relationships between tree size and/or age and sprout density and sprout height have been described for a variety of oak species, including cherrybark oak (*Quercus pagoda* Raf.) (Lockhart and Chambers 2007), northern red oak, (*Quercus rubra* L.) (Johnson 1975), white oak (*Quercus alba* L.), and black oak (*Quercus velutina* Lam.) (Johnson 1977; Sands and Abrams 2009). Similar to the probability of sprouting, however, quantitative relationships that describe sprout characteristics, including sprout density and sprout height, during the early years post-harvest are largely limited to some of the most valuable (e.g., oaks) or abundant [e.g., red maple (Fei and Steiner 2009)] tree species.

The temperate forests of the southern Appalachian Mountains possess some of the highest levels of tree species diversity outside of the tropics (Trani Greip and Collins 2013). Maintaining diversity following silvicultural activities is a primary management objective in these upland hardwood forest stands. Because stump sprouts are a potential source of regeneration for a variety of species (e.g., Beck and Hooper 1986), models and/or basic information that quantifies the response of stump sprouts of both commercial and non-commercial forest tree species to management are needed to adequately describe and predict early stand dynamics. In this study, we test the hypotheses that tree size, overstory density, and site quality have no significant effects on (a) the probability that any given cut tree sprouts; (b) sprout density (i.e., the number of sprouts per cut stump); and (c) sprout height following regeneration harvests in efforts to more effectively model sprouting and post-harvest sprout development for 19 commercial and non-commercial tree species common to upland hardwood forests in the southern Appalachian Mountains.

Methods

Study area

This study was conducted on five stands located on the Wayah, Cheoah, and Appalachian Ranger Districts of the Nantahala and Pisgah National Forests in western North Carolina, USA and the Nolichucky and Watauga Ranger Districts of the Cherokee National Forest in eastern Tennessee, USA. Stands were comprised of mature (>80 years), fully-stocked, second-growth forests located within the Blue Ridge Physiographic Province of the southern Appalachian Mountains. Like most forest stands in the southern Appalachian Mountains, the stands used in this study likely originated from the widespread exploitive logging that occurred during the early 20th century. Elevations ranged from approximately 760 to 1,070 m above sea level. Climate in the Blue Ridge Physiographic Province is considered Hot Continental, with an annual temperature in Bryson City, NC (35.429°N 83.438°W- an area within proximity of all stands used in this study) averaging 13.1 °C (http://www.ncdc.noaa.gov/cdo-web/). Annual precipitation across the region, which ranges from 1,000 to 1,500 mm, increases with elevation and is evenly distributed throughout the year (McNab 2011). Geology is predominantly felsic to mafic high-grade metamorphic biotite and granitic gneisses (Hadley and Nelson 1971). Soils are Inceptisols and Ultisols that are shallow to very deep, well drained, moderately to extremely acid, and range in texture from coarse-loamy to clayey (Greenberg and Mcnab 1998). Site productivity throughout the region varies with topography, with productivity, as measured by site index (SI), generally decreasing as landform changes from cove to slope to ridgetop locations (McNab 1992).

Data collection

In 2000 and 2001, between 41 and 108 plots (0.01 ha) were installed throughout the five stands planned and marked to receive a shelterwood with reserves (i.e., two-aged) regeneration harvest. The initial plot within each stand was randomly established, with subsequent plots located at random azimuths between 23 and 31 m apart. All stands were upland hardwood forest types. One of the five stands sampled was dominated by mixed-mesophytic species, including silverbell (*Halesia tetraptera* Ellis), sugar maple (*Acer saccharum* Marsh), white basswood (*Tilia heterophylla* Vent.), yellow buckeye (*Aesculus* *flava* Aiton), and sweet birch (*Betula lenta* L.). The remaining four stands were dominated by oak species, with northern red, black, white, scarlet (*Quercus coccinea* Muenchh.), and chestnut (*Quercus prinus* L.) oaks comprising between 41 and 91 % of pre-harvest stand basal area. SI (upland oak, base-age 50), determined using a method outlined by McNab and Loftis (2013), varied from 16.2 m in stands dominated by dry oak species (e.g., scarlet oak, black, and chestnut oaks) to 33.3 m in the stand dominated by mixed-mesophytic species (Table 1). In general, preferred retention trees in the shelterwood with reserves prescription were trees of wildlife value, including oak and hickory species. All harvest operations were conducted during the dormant season. Site preparation activities, including herbicide treatments and the removal of non-merchantable material were not conducted prior to or during the sampling period.

Prior to harvest, individual trees $\geq$3.8 cm diameter at 1.37 m above groundline (dbh) within each plot were permanently tagged, with dbh (cm) and species of each tagged individual recorded. One growing season post-harvest, plots were revisited, and for each relocated cut tree, we recorded (1) the presence of live sprouts (yes/no), (2) the total number of sprouts originating from each cut stump (i.e., sprout density), and (3) height (m) of the dominant (i.e., tallest) sprout. Using a tally of uncut trees recorded during the post-harvest inventory, stand-level basal area following harvesting was estimated to vary between 1.4 m^2 ha^{-1} and 6.3 m^2 ha^{-1}. At the plot-level, residual basal area was more variable, and across all stands ranged from a low of 0 m^2 ha^{-1} to a maximum of 55.5 m^2 ha^{-1} (Table 1).

Statistical analyses

The production of stump sprouts has a binary distribution (i.e., 0 = sprout(s) not present, 1 = sprout(s) present). Consequently, we used logistic regression with PROC GLIMMIX (SAS Institute Inc. 2011) to model the probability of an individual tree sprouting one growing season post-harvest as a function of parent tree dbh, plot-level SI, and plot-level residual basal area Eq (1). The logistic model had the form:

$$P(s) = \frac{1}{1 + \exp[-(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3)]} \qquad (1)$$

where P(s) is the probability of stump sprouting one growing season post-harvest, β_0, β_1, β_2, and β_3 are model coefficients, and X_1 is dbh (cm), X_2 is plot-level upland oak SI (m), and X_3 is residual plot-level basal area (m^2 ha^{-1}). All species where the number of observations was $\geq$15 (five times the number of independent variables) (Vittinghoff and

Table 1 Stand metrics, including site index (upland oak, base-age 50; m), post-harvest basal area (m^2 ha^{-1}), post-harvest trees ha^{-1}, and post-harvest quadratic mean diameter (Dq; cm). Values represent the mean (minimum, maximum)

Stand	Plots	Site index (m)	Basal area (m^2 ha^{-1})	Trees ha^{-1}	Dq (cm)
1	72	16.2 (10.0, 26.7)	1.6 (0, 30.3)	30 (0, 198)	22.2 (7.4, 62.5)
2	108	33.3 (15.6, 37.8)	2.0 (0, 55.5)	20 (0, 297)	32.2 (5.7, 84.6)
3	77	24.0 (17.0, 31.2)	6.3 (0, 32.4)	182 (0, 988)	20.2 (5.1, 47.5)
4	77	16.7 (9.4, 30.4)	1.4 (0, 50.3)	26 (0, 593)	24.6 (6.4, 80.5)
5	41	22.9 (15.7, 30.1)	1.6 (0, 17.0)	58 (0, 791)	17.3 (4.3, 33.1)

McCulloch 2006) were analyzed using Eq. (1) (Table 2). Trees whose cut stumps were partially or completed uprooted due to their proximity to skid roads or temporary logging roads were not included in the analyses. Backwards elimination of non-significant variables ($\alpha = 0.05$) was utilized to simplify the final predictive equation for each species. Of the 19 species listed in Table 2, the inclusion of both residual basal area and SI into Eq. (1) resulted in convergence issues for white basswood and American beech (*Fagus grandifolia* Ehrh.). Similarly, the inclusion of basal area into Eq. (1) led to convergence issues for sourwood and white oak. For these species, reduced forms (lacking SI and/or basal area) of the Eq. (1) were utilized in the probability of sprouting analysis. Mixed-effects multiple linear regression with PROC MIXED (SAS Institute Inc. 2011) was used to analyze the effects of dbh, plot-level SI, and plot-level residual basal area on both sprout density and dominant sprout height. Backwards elimination of non-significant independent variables ($\alpha = 0.05$) was conducted to simplify the final predictive equation for each species.

Data on stump sprouts were obtained from a hierarchical design, with the response variables (i.e., sprouting (yes/no), sprout density, and dominant sprout height) measured on cut stumps nested within plots (level-1). Two additional levels of hierarchy were present, including plots nested within a given stand (level-2) and stand (level-3). The effects of higher-level units were accounted for by including random intercepts related to level-2 and level-3 units in the models. Likelihood ratio $\chi 2$ tests (with one degree of freedom) using -2 log L values from species-specific 2- and 3-level empty means (i.e., intercept only) models were used to determine if the random intercepts related to both stand (level-3) and plot

Table 2 Species, number of cut stumps sampled (*n*), and size distribution of parent trees prior to harvest

		Diameter at breast height (cm)			
Species	*n*	Mean	Standard deviation	Minimum	Maximum
Striped maple (*Acer pennsylvanica* L.)	20	4.8	0.9	3.8	6.6
Red maple (*Acer rubrum* L.)	145	16.2	12.1	3.0	64.5
Sugar maple (*Acer saccharam* Marsh)	35	14.0	13.5	3.8	66.3
Yellow buckeye (*Aesculus flava* Aiton)	53	9.5	7.0	3.8	36.3
Sweet birch (*Betula lenta* L.)	47	20.0	11.7	4.1	46.7
Hickory species (*Carya* Nutt.)	38	15.5	7.3	4.3	33.5
American beech (*Fagus grandifolia* Ehrh.)	15	8.5	4.7	3.8	22.1
Silverbell (*Halesia tetraptera* Ellis)	65	14.9	10.3	3.8	45.5
Yellow-poplar (*Liriodendron tulipifera* L.)	64	36.2	15.3	3.8	66.8
Cucumbertree (*Magnolia accuminata* L.)	24	30.2	13.1	7.4	60.2
Fraser magnolia (*Magnolia fraseri* Walt.)	38	14.7	12.1	3.8	50.5
Blackgum (*Nyssa sylvatica* Marsh.)	57	25.5	15.4	3.8	58.4
Sourwood (*Oxydendrum arboreum* L. (DC))	33	18.5	11.5	4.3	47.8
White oak (*Quercus alba* L.)	36	22.6	19.2	4.6	73.2
Chestnut oak (*Quercus prinus I.*)	83	31.3	17.3	5.8	67.1
Scarlet oak (*Quercus coccinea* Muenchh.)	97	30.2	11.0	8.9	52.8
Northern red oak (*Quercus rubra* L.)	78	46.3	18.8	9.9	83.8
Black oak (*Quercus velutina* Lam.)	40	33.5	14.4	11.7	70.9
White basswood (*Tilia heterophylla* Vent.)	94	35.7	16.3	5.3	78.7

within stand (level-2) were required (Snijders and Bosker 1999). When a non-significant likelihood ratio test occurred ($P > 0.05$), only the random intercept related to plot within stand (level-2) was included, as the fixed effects were of primary interest. For one species, cucumbertree, the inclusion of level-2 random effects, with or without level-3 random effects, in analysis of dominant sprout height resulted in convergence issues. Consequently, dominant sprout height was not analyzed for this species. Data presented represent the marginal predicted values obtained using only the estimated fixed effects portion of the models (West et al. 2007).

Results

For white basswood and American beech, we were unable to test the effects of dbh, residual basal area, and SI simultaneously on the probability of sprouting due to convergence issues. However, when Eq. (1) included combinations of either dbh and SI or dbh and residual basal area, we found that neither SI nor residual basal area were significant ($P > 0.05$) predictors of sprouting for these two species. For sourwood and white oak, we were unable to test the effects of residual basal area on sprouting due to convergence issues. However, using the reduced (i.e., without basal area) form of Eq. (1), we found that SI was not a significant ($P > 0.05$) predictor of sprouting for these two species. For the 14 species analyzed with the full form of Eq. (1) (silverbell was unable to be analyzed due to a 100 % sprout rate), we found that neither SI nor residual basal area significantly affected the probability that a cut tree produced stump sprouts one growing season post-harvest. After backwards elimination of these non-significant variables, we found the probability of stump sprouting was not significantly correlated with dbh ($P > 0.05$) for the following species: striped maple (*Acer pennsylvanica* L.), sugar maple, hickory (*Carya* Nutt.), American beech, cucumbertree (*Magnolia accuminata* L.), Fraser magnolia (*Magnolia fraseri* Walt.), blackgum (*Nyssa sylvatica* Marsh.), sourwood, yellow-poplar, chestnut oak, and white basswood. Sprouting probabilities for these species ranged from 67 % for cucumbertree to 100 % for silverbell (Table 3).

For red maple (*Acer rubrum* L.), sweet birch, white oak, scarlet oak, northern red oak, black oak, and yellow buckeye, we observed a significant ($P < 0.05$) negative relationship between parent tree dbh and the probability of stump sprouting (Table 4). Of these species,

Table 3 Percentage of stumps with at least one sprout 1 year post-harvest for those species where the probability of stump sprouting was not correlated with diameter at breast height (dbh)

Species	Sprout rate
Striped maple	80
Sugar maple	74
Hickory	95
American beech	93
Yellow-poplar	80
Cucumbertree	67
Fraser magnolia	95
Blackgum	72
Sourwood	97
Silverbell[a]	100
Chestnut oak	78
White basswood	99

[a] species was unable to be analyzed with Eq. (1) due to a 100 % sprout rate

sweet birch and white oak experienced the most precipitous decline in the probability of sprouting as dbh increased. Red maple and northern red oak declined the least, with probability of sprouting remaining >40 % over the range of observed tree diameters (Fig. 1).

For individuals that possessed at least one sprout following harvest, sprout density was not significantly correlated with dbh, SI, or residual basal area ($P > 0.05$) for 13 species (Table 5). For these species, the average number of sprouts per stump ranged from 7 for blackgum to 52 for American beech. Backwards elimination of non-significant variables revealed significant and positive relationships between sprout density and parent tree dbh for red maple, yellow buckeye, sourwood, silverbell, and white basswood (Fig. 2). For one species, scarlet oak, sprout density (ln-transformed) was significantly and positively correlated with SI ($\beta_0 = 0.9204$, $\beta_1(\text{site index}) = 0.0936$).

For those individuals possessing at least one sprout following harvest, dominant sprout height was not significantly correlated with dbh, residual basal area, or SI ($P > 0.05$) for 10 of the species examined (Table 6). The average height of the dominant sprout one growing season post-harvest for these species ranged from 0.3 m for American beech to 1.4 m for chestnut oak. For silverbell, yellow-poplar, and white basswood significant ($P < 0.05$) positive relationships between parent tree dbh and dominant sprout height were observed, although relationships were relatively weak (Fig. 3). For northern red oak, dominant sprout height (square-root transformed) was negatively correlated with parent tree dbh and positively correlated with SI ($\beta_0 = 0.6571, \beta_1(\text{dbh}) = -0.0067, \beta_2(\text{site index}) = 0.0281$). For hickory, dominant sprout height (ln-transformed) was positively related to both dbh and SI ($\beta_0 = -1.1552, \beta_1(\text{dbh}) = 0.0289, \beta_2(\text{site index}) = 0.0415$). Although weak, significant ($P < 0.05$) and positive relationships between dominant sprout height and SI were observed for scarlet oak and black oak (Fig. 4). The only species to display a significant effect of residual basal area on dominant sprout height was red maple. For this species, dominant sprout height (square-root transformed) was positively related to parent tree dbh and negatively related with residual basal area ($\beta_0 = 1.2672, \beta_1(\text{dbh}) = 0.0053, \beta_2$ $(\text{residual basal area}) = -0.0133$).

Discussion

Of the 19 commercial and non-commercial tree species examined (Table 2), the probability of sprouting for seven species—northern red oak, scarlet oak, white oak, black oak, red maple, yellow buckeye, and sweet birch—was significantly and negatively related to

Table 4 Parameter estimates (standard error) fitted with Eq. (1) for those species in which a significant ($P < 0.05$) relationship between the probability of sprouting P(s) and diameter at breast height (dbh) was observed

Species	β_0	β_1
Yellow buckeye	6.0782 (1.9535)	−0.1767 (0.0751)
Red maple	3.6603 (0.5939)	−0.0614 (0.0204)
Sweet birch	3.2535 (1.0920)	−0.2000 (0.0584)
White oak	2.4608 (0.9741)	−0.1218 (0.0497)
Scarlet oak	3.8897 (0.9054)	−0.0900 (0.0254)
Northern red oak	3.2586 (0.9120)	−0.0441 (0.0165)
Black oak	3.1070 (1.1152)	−0.0838 (0.0322)

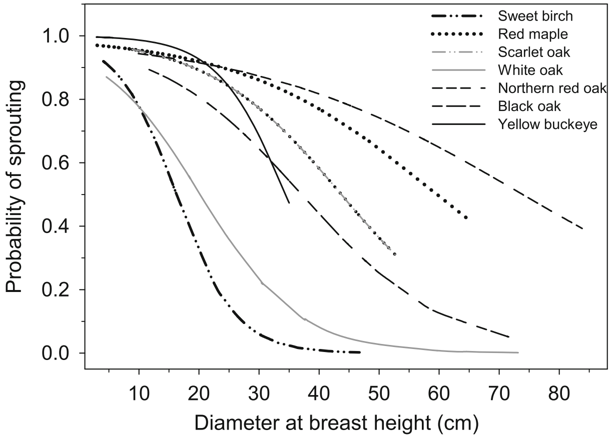


Fig. 1 Relationships between parent tree diameter at breast height (dbh) and probability of sprouting one growing season post-harvest for white oak, scarlet oak, northern red oak, black oak, sweet birch, yellow buckeye, and red maple based on model coefficients presented in Table 4

Table 5 Average, standard deviation, minimum, and maximum number of sprouts per stump one growing season post-harvest

Species	Mean	Standard deviation	Minimum	Maximum
Striped maple[a]	8	9	1	31
Red maple	21	19	1	128
Sugar maple[a]	10	10	1	42
Yellow buckeye	13	7	2	39
Sweet birch[a]	8	7	1	27
Hickory[a]	9	7	1	35
American beech[a]	52	46	1	155
Silverbell	18	14	1	72
Yellow-poplar[a]	13	13	1	65
Cucumbertree[a]	11	9	1	37
Fraser magnolia[a]	13	16	1	90
Blackgum[a]	7	5	1	17
Sourwood	30	24	1	79
White oak[a]	16	11	2	46
Chestnut oak[a]	22	18	1	93
Scarlet oak	13	16	1	77
Northern red oak[a]	19	17	1	89
Black oak[a]	8	7	1	25
White basswood	30	19	1	83

[a] Species for which non-significant ($P > 0.05$) relationships between sprout density and diameter at breast height (dbh), site index, or residual basal area were observed

parent tree size (Fig. 1). The relationships we observed between stump sprouting and tree size for the oak species (northern red, scarlet, black, and white oaks) are consistent with results from across the Central Hardwood Region (Ross et al. 1986; Dey et al. 1996;

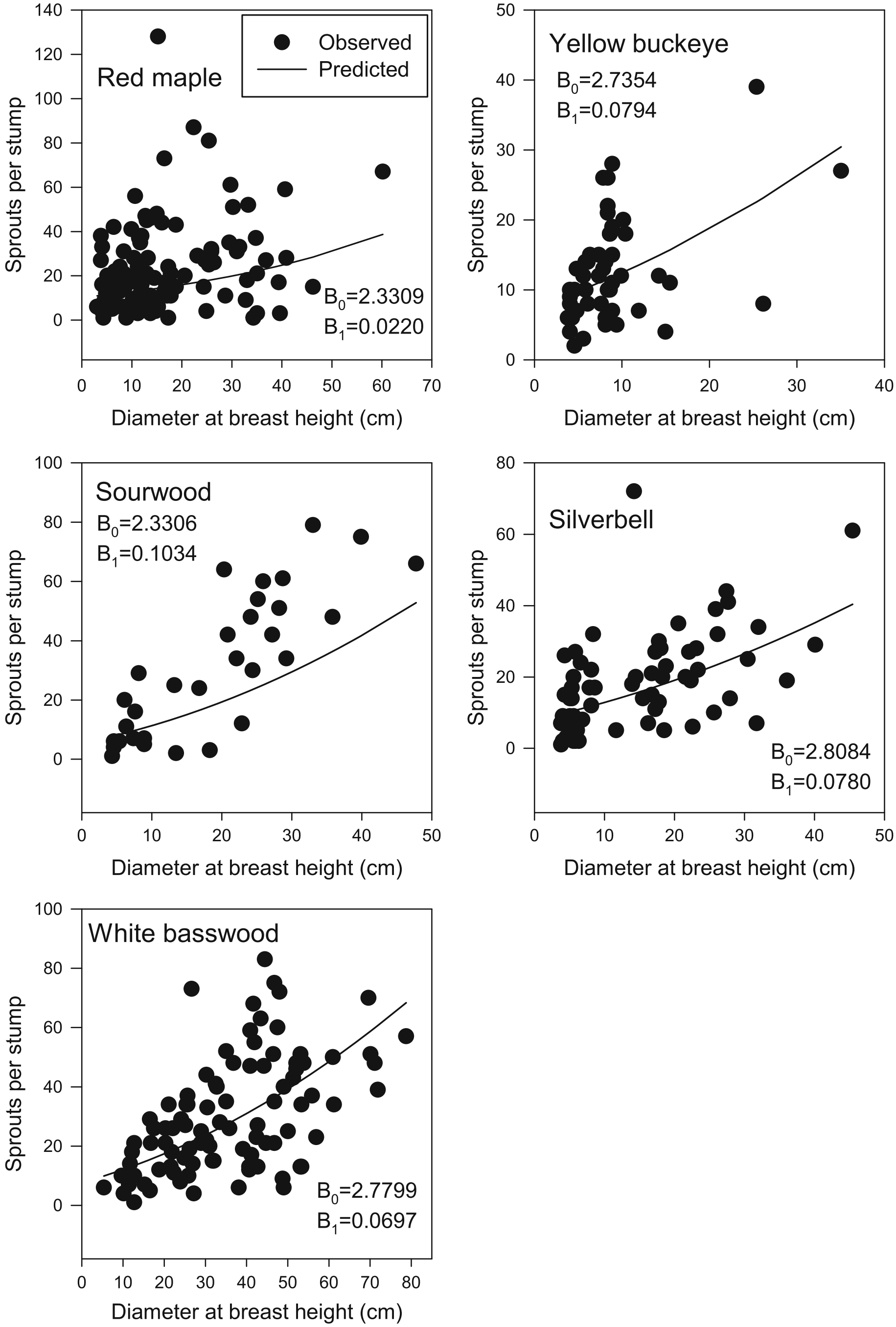


Fig. 2 Relationships between parent tree diameter at breast height (dbh) and sprout density one growing season post-harvest for red maple, yellow buckeye, sourwood, silverbell, and white basswood. Models for sprout density were developed using square-root transformed data for all species presented. Regression lines represent back-transformed values

Table 6 Average, standard deviation, minimum, and maximum dominant sprout height (m) one owing season post-harvest

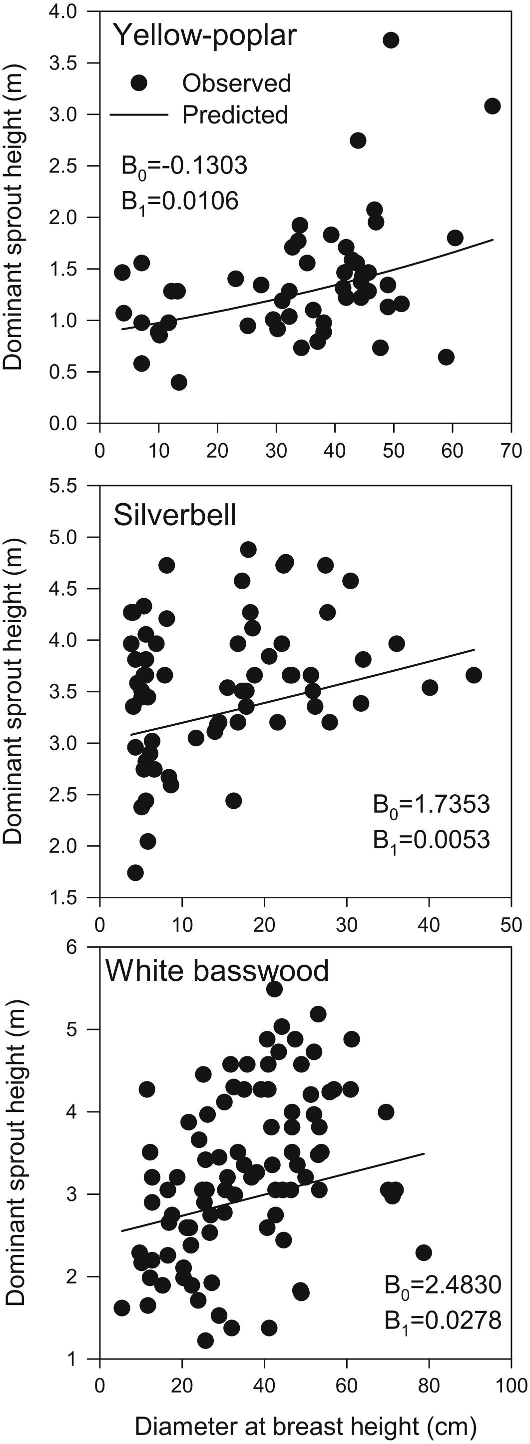
Species	Mean	Standard deviation	Minimum	Maximum
Striped maple[a]	1.1	0.5	0.1	2.0
Red maple	1.3	0.7	0.1	4.3
Sugar maple[a]	0.5	0.4	0.1	1.6
Yellow buckeye[a]	1.1	0.4	0.5	2.0
Sweet birch[a]	0.8	0.5	0.2	1.7
Hickory	1.5	1.1	0.5	3.7
American beech[a]	0.3	0.4	0.1	1.6
Silverbell	3.6	0.7	1.7	4.9
Yellow-poplar	1.4	0.6	0.4	3.7
Cucumbertree[b]	2.4	1.3	1.1	4.9
Fraser magnolia[a]	1.3	0.5	0.1	2.2
Blackgum[a]	0.9	0.6	0.1	3.0
Sourwood[a]	1.3	0.6	0.2	2.3
White oak[a]	0.9	0.3	0.2	1.4
Chestnut oak[a]	1.4	0.6	0.3	3.4
Scarlet oak	1.0	0.5	<0.1	2.3
Northern red oak	1.3	0.6	0.2	2.6
Black oak	1.2	0.7	0.1	2.6
White basswood	3.2	1.0	1.2	5.5

[a] Species for which non-significant ($P > 0.05$) relationships between dominant sprout height and diameter at breast height (dbh), site index, or residual basal area were observed. [b]Species was unable to be analyzed due to convergence issues

Weigel and Peng 2002). For example, in the Ozark Highlands of Missouri, Johnson (1977) found the probability of a scarlet oak stump possessing a living sprout 1 year after cutting was reduced from 99 to 15 % when stump diameter increased from 7.6 to 76.2 cm. For chestnut oak, the lack of a significant relationship between stump sprouting and tree size observed in this study (Table 3) and elsewhere (Kays et al. 1988; Sands and Abrams 2009; Keyser and Zarnoch 2014) suggests chestnut oak stump sprouts may be a more reliable source of regeneration than other oak species in mature, second-growth forest stands (Weigel and Peng 2002; Gould et al. 2007). The negative relationship between the probability of sprouting and tree size observed for red maple and sweet birch was unexpected. Although direct comparisons of results among studies may be confounded by differences in the diameter distributions of harvested trees, site quality, stand structure, and/or age, red maple stump sprout production is generally not correlated with tree size, with sprouting of red maple exceeding 90 % in hardwood forests of Pennsylvania (Fie and Steiner 2009) and North Carolina (Keyser and Zarnoch 2014).

For the majority of species sampled, no significant relationships between the probability of sprouting and tree size were observed (Table 3). Sprouts rates for these species were high and ranged from a low of 67 % for cucumbertree to 100 % for silverbell. For some of these species, such as silverbell, Fraser magnolia, white basswood, and cucumbertree, this is the only study, to our knowledge, to model the probability of sprouting as a function of

Fig. 3 Relationships between parent tree diameter at breast height (dbh) and dominant sprout height one growing season post-harvest for yellow-poplar (ln-transformed), silverbell (square-root transformed), and white basswood. For those species analyzed using transformed sprout density values, regression lines represent back-transformed values



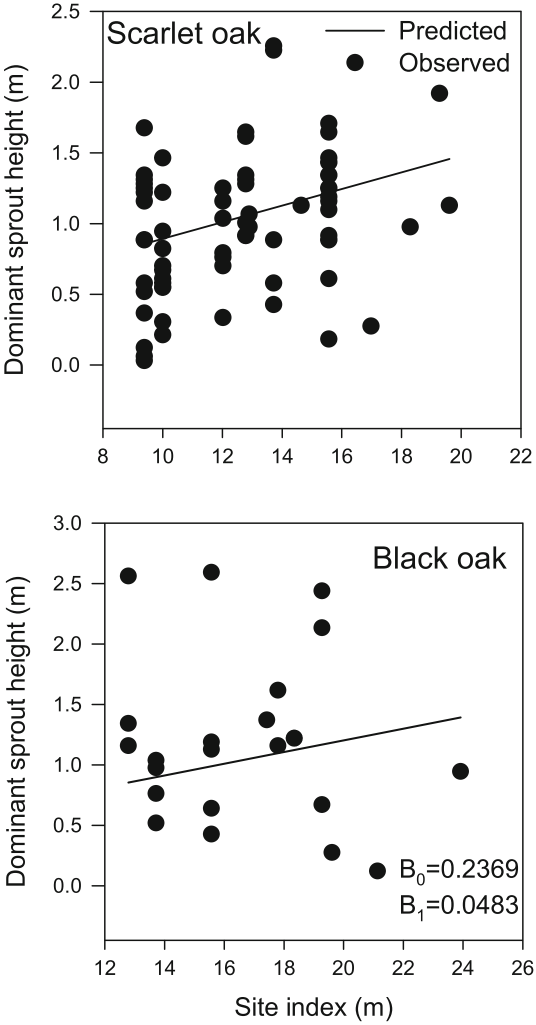


Fig. 4 Relationships between site index (m) and dominant sprout height one growing season post-harvest for scarlet oak and black oak (square-root transformed). For black oak, regression lines represent back-transformed values

tree size, SI, and/or post-harvest basal area for these largely noncommercial species. For many of these species, the propensity to sprout has been described only qualitatively in the literature (e.g., Della-Bianca 1971, 1983; Crow et al. 1991; Phillips and Shure 1990), or quantitative relationships are specific to other forest types and/or geographic areas (e.g., Nyland et al. 2006). For some species, such as sugar maple, this study contrasts results from northeastern North America where sprouting was found to decrease with increasing tree size (e.g., MacDonald and Powell 1983). Conflicting results emphasize the differences in sprouting that can occur within a given species and across broad geographic locations (Johansson 1992; Dietze and Clark 2008), and supports the development of local and/or regional sprouting models.

Although parent tree size if often the primary factor controlling stump sprout production for oak species, in particular (e.g., Weigel and Peng 2002), other factors can influence stump sprouting following harvest, including site quality. For example, Johnson (1977) found that sprouting of black oak and white oak was negatively related to parent tree dbh and positively related to SI in the Ozark Highlands of Missouri. Comparably, Weigel and Peng (2002) report 1 year sprout probabilities of five predominant oak species in Indiana—northern red, scarlet, black, chestnut, and white oaks—were lower on sites of low verses high SI. In this study, site quality (as measured by SI) was not a significant predictor of stump sprouting for either the oak or non-oak species sampled, suggesting, along with Wendel (1975) and Gould et al. (2007), that site quality may have less of an influence on stump sprout production in the southern and central Appalachian hardwood forests than in other parts of the Central Hardwood Region.

Quantitative information and/or models regarding the effects of overstory density (e.g., post-harvest residual basal area) on sprouting frequencies and probabilities for commercial and noncommercial species across the Central Hardwood Region are, for the most part, lacking. In central Appalachian hardwood stands, Atwood et al. (2009) reported lower rates of sprouting for oak species following partial harvests (e.g., shelterwood with reserves) than clearcutting. In that study, however, stump sprouts were sampled 9–11 years post-harvest, during which time sprout mortality may have already occurred (Johnson 1975; Beck 1977). In our study, the probability that any given tree produced a sprout did not vary across a broad range of residual basal areas (Table 1); a result consistent with others studies that demonstrate sprout production, at least in the short-term, is similar between light and heavy thinnings (Gardiner and Helmig 1997; Lockhart and Chambers 2007; Keyser and Zarnoch 2014) and low and high density shelterwood treatments (Gould et al. 2007; Rong et al. 2013). Over time, as initial carbohydrate reserves in parent root systems are depleted (Del Tredici 2001), overstory density may begin to affect sprouting frequency and the survival of sprout clumps (Rydberg 2000; Atwood et al. 2009).

Although tree size significantly influenced sprout density for red maple, yellow buckeye, sourwood, silverbell, and white basswood, the relationships were generally weak (Fig. 2). The lack of relationships between tree size and sprout density for the oak species contrasts results from Sands and Abrams (2009) who report greater sprout density in small (10– < 20 cm) versus large (20– < 50 cm) white oak in Pennsylvania while Johnson (1975) found sprout density increased with increasing diameter for northern red oak in the Driftless Area of the Upper Midwest. The relationships we report may be used to describe the immediate (e.g., 1 year post-harvest) effect of cutting on sprout density. However, these short-term results may not be indicative of longer-terms trends, as sprout clumps self-thin over time (Johnson 1975; Beck 1977; Retana et al. 1992). For example, Beck (1977) determined that when self-thinning of yellow-poplar stump sprouts ceases (between 6 and 24 years of age), 65 % of sprouting stumps will contain only one stem, 25 % will possess two stems, and only 10 % will contain three stems per stump. Similarly, for northern red oak, Johnson (1975), who reported that initial differences in sprout density among diameter classes disappeared by age 12, noted that by age 23, regardless of size, sprout density averaged four sprouts per stump.

Regarding post-harvest structure and composition, the height attained by stump sprouts is likely of more importance than the number of sprouts any given stump produces, as rapid sprout growth during the immediate years post-harvest can quickly overtop existing advance reproduction (e.g., Beck and Hooper 1986). Most of the species analyzed in this study displayed no significant relationships between dominant sprout height and tree size, SI, or residual basal area (Table 6). For yellow-poplar, silverbell, and white basswood, dominant sprout height was positively related to tree size (Fig. 3) while sprout height for northern red oak, hickory, and scarlet and black oak was influenced by SI (Fig. 4) and/or tree size. Interestingly, with the exception of red maple, a species tolerant of shade, residual basal area had no significant effect on dominant sprout height sprout. While Gracia and Retana (2004) found overstory density did not affect dominant sprout height of holm oak, shading did influence crown surface area; a variable not measured in this study. Other studies, however, have documented a decrease in dominant sprout height with increased residual basal area (Gardiner and Helmig 1997; Rydberg 2000; Keyser and Zarnoch 2014). The fact that residual basal area did not significantly affect dominant sprout height for 95 % of the species sampled in this study could be due to the short-term nature of our results. As sprouts age and carbohydrate reserves that support rapid height growth post-harvest are exhausted (Cobb et al. 1985; Del Tredici 2001), the influence of site quality and residual basal area on sprout height may increase among species of varying shade tolerance (Rydberg 2000; Gracia and Retana 2004; Keyser and Zarnoch 2014).

Conclusions

This study quantified the short-term stump sprouting response to partial harvests for the predominant oak species as well as many of the non-oak species common throughout southern Appalachian forests. The lack of any significant influence of either SI or residual basal area on the probability of stump sprouting one growing season post-harvest suggests the sprout rates (Table 3) and probability of sprouting equations (Table 4) produced in this study are robust and may be utilized to assess sprouting potential across a variety of stand structures and site qualities in the southern Appalachian hardwood forests (Table 1). Although the results describe only the short-term (i.e., one growing season post-harvest) response of stump sprouts, the information presented improves our knowledge of the immediate response of stump sprouts to management in second-growth upland hardwood forest types. Quantitative models that describe the long-term survival, growth, and competitiveness of stump sprouts (e.g., Gould et al. 2007; Fei and Steiner 2009) relative to other sources of hardwood regeneration, such as newly established seedlings and advance reproduction, are lacking and, as such, are necessary to improve our understanding and model the longer-term effects of management on species composition and stand development in these diverse southern Appalachian hardwood stands.

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References

Arthur MA, Muller RN, Costello S (1997) Species composition in a central hardwood forest in Kentucky 11 years after clear-cutting. Am Midl Nat 137:274–281

Atwood CJ, Fox TR, Loftis DL (2009) Effects of alternative silviculture on stump sprouting in the southern Appalachians. For Ecol Manage 257:1305–1313

Beck DE (1977) Growth and development of thinned versus unthinned yellow-poplar sprout clumps. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC, Res. Pap. SE-173, p 16

Beck DE, Hooper RM (1986) Development of a southern Appalachian hardwood stand after clearcutting. South J Appl For 10:168–172

Belz D (2003) Severing red alder: timing the cut to achieve the best mortality. West J Appl For 18:199–201

Cobb SW, Miller AE, Zahner R (1985) Recurrent shoot flushes in scarlet oak stump sprouts. For Sci 31:725–730

Cook JE, Sharik TL, Smith DWm (1998) Oak regeneration in the southern Appalachians: potential, problems, and possible solutions. South J Appl For 22:11–18

Crow TR, Mroz GD, Gale MR (1991) Regrowth and nutrient accumulations following whole-tree harvesting of a maple-oak forest. Can J For Res 21:1305–1315

Del Tredici P (2001) Sprouting in temperate trees: a morphological and ecological review. Bot Rev 67:121–140

Della-Bianca L (1971) Frothingham's hardwood cleaning at Looking-Glass Rock–43 years later. J For 69:100–102

Della-Bianca L (1983) Sixty years of stand development in a southern Appalachian cove-hardwood stand. For Ecol Manage 5:229–241

Dey DC, Johnson PS, Garrett HE (1996) Modeling the regeneration of oak stands in the Missouri Ozark Highlands. Can J For Res 26:573–583

Dietze MC, Clark JS (2008) Changing the gap dynamics paradigm: vegetation regeneration control on forest response to disturbance. Ecol Monogr 78:331–347

Elliott KJ, Boring LR, Swank WT, Haines BR (1997) Successional changes in plant species diversity and composition after clearcutting a Southern Appalachian watershed. For Ecol Manage 92:67–85

Fei S, Steiner KC (2009) Rapid capture of growing space by red maple. Can J For Res 39:1444–1452

Gardiner ES, Helmig LM (1997) Development of water oak stump sprouts under a partial overstory. New For 14:55–62

Gould PJ, Fei S, Steiner KC (2007) Modeling sprout-origin oak regeneration in the central Appalachians. Can J For Res 37:170–177

Gracia M, Retana J (2004) Effect of site quality and shading on sprouting patterns of holm oak coppices. For Ecol Manage 188:39–49

Greenberg CH, McNab WH (1998) Forest disturbance in hurricane-related downbursts in the Appalachian mountains of North Carolina. For Ecol Manage 104:179–191

Hadley JB, Neslon AE (1971) Geologic map of the Knoxville quadrangle, North Carolina, Tennessee and South Carolina. USDI Geological Survey, Washington, DC, Miscellaneous Geologic Investigations, Map I-654 (1:250,0000 scale)

Harrington CA (1984) Factors influencing initial sprouting of red alder. Can J For Res 14:35–361

Johansson T (1992) Sprouting of 10- to 50-year-old *Betula pubescens* in relation to felling time. For Ecol Manage 53:283–296

Johnson PS (1975) Growth and structural development of red oak sprout clumps. For Sci 21:413–418

Johnson PS (1977) Predicting oak stump sprouting and sprout development in the Missouri Ozarks. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN, Res. Pap. NC-149, p 11

Kays JS, Canham CD (1991) Effects of time and frequency of cutting on hardwood root reserves and sprout growth. For Sci 32:524–539

Kays JS, Smith DWm, Zedaker SM, Kreh RE (1988) Factors affecting natural regeneration of Piedmont hardwoods. South J Appl For 12:98–102

Keyser TL, Zarnoch SJ (2014) Stump sprout dynamics in response to reductions in stand density for nine upland hardwood species in the southern Appalachian Mountains. For Ecol Manage 391:29–35

Lockhart BR, Chambers JL (2007) Cherrybark oak stump sprout survival and development 5 years following plantation thinning in the lower Mississippi alluvial valley, USA. New For 33:183–192

Loftis DL (1983) Regeneration southern Appalachian mixed hardwood stands with the shelterwood method. South J Appl For 7:212–217

Loftis DL (1985) Preharvest herbicide treatment improves regeneration in southern Appalachian hardwoods. South J Appl For 9:177–180

Loftis DL, McGee CE (1993) Oak regeneration: serious problems, practical recommendations. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC, Gen. Tech. Rep., SE-84, p 319

MacDonald JE, Powell GR (1983) Relationships between stump sprouting and parent-tree diameter in sugar maple in the 1st year following clearcutting. Can J For Res 13:390–394

Mann LK (1984) First-year regeneration in upland hardwoods after two levels of residue removal. Can J For Res 14:336–342

McNab WH (1992) A topographic index to quantify the effect of mesoscale landform on site productivity. Can J For Res 23:1100–1107

McNab WH (2011) Subregional variation in upland hardwood forest composition and disturbance regimes of the Central Hardwood Region. In: Greenberg CH, Collins BS, Thompson FR II (eds) Sustaining young forest communities: ecology and management of early successional habitats in the Central Hardwood Region. Springer, New York, pp 11–26

McNab WH, Loftis DL (2013) A preliminary test of estimating forest site quality using species composition in a southern Appalachian watershed. In: Guildin JM (ed) Proceedings of the 15th biennial southern silvicultural research conference. USDA Forest Service, Southern Research Station, Asheville, NC, eGen. Tech. Rep., SRS-GTR-175, pp 95–102

Nyland RD, Bashant AL, Bohn KK, Verostek JM (2006) Interference to hardwood regeneration in northeastern North America: ecological characteristics of American beech, striped maple, and hobblebush. North J Appl For 23:53–61

Peterson CJ (2000) Damage and recovery of tree species after two different tornadoes in the same old growth forest: a comparison of infrequent wind disturbances. For Ecol Manage 135:237–252

Peterson CJ (2007) Consistent influence of tree diameter and species on damage in nine eastern North America tornado blowdowns. For Ecol Manage 250:96–108

Peterson CJ, Pickett STA (1991) Treefall and resprouting following catastrophic windthrow in an old-growth hemlock-hardwoods forest. For Ecol Manage 42:205–217

Phillips DL, Shure DJ (1990) Patch-size effects on early succession in southern Appalachian forests. Ecology 71:204–212

Retana J, Riba M, Castell C, Espelta JM (1992) Regeneration by sprouting of holm oak (*Quercus ilex*) stands exploited by selection thinning. Vegetatio 99–100:355–364

Rong L, Wenhui Z, Jingfeng H, Jianyun Z (2013) Survival and development of Liaodong oak stump sprouts in the Huanglong Mountains of China 6 years after three partial harvests. New For 44:1–12

Ross MS, Sharik TL, Smith DWM (1986) Oak regeneration after clear felling in southwest Virginia. For Sci 32:157–169

Rydberg D (2000) Initial sprouting, growth and mortality of European aspen and birch after selective coppicing in central Sweden. For Ecol Manage 130:27–35

Sands BA, Abrams MD (2009) Effects of stump diameter on sprout number and size for three oak species in a Pennsylvania clearcut. North J Appl For 26:122–125

SAS Institute (2011) SAS Version 9.3. SAS Institute Inc., Cary, NC

Snijders TAB, Bosker RJ (1999) Multilevel analysis: An introduction to basic and advanced multilevel modeling. Sage Publications, Newbury Park

Šplíchalová M, Adamec Z, Kadavý J, Kneifl M (2012) Probability model of sessile oak (*Quercus petraea* (Matt.) Liebl.) stump sprouting in the Czech Republic. Eur J For Res 131:1611–1618

Trani Griep M, Collins B (2013) Wildlife and forest communities. In: Wear DN, Greis, JG (eds) The Southern Forest Futures Project: technical report. USDA Forest Service, Southern Research Station, Asheville, NC Gen. Tech. Rep. SRS-178, pp 341–396

Vittinghoff E, McCulloch CE (2006) Relaxing the rule of ten events per variable in logistic and Cox regression. Am J Epidemiol 165:710–718

Weigel DR, Peng CYJ (2002) Predicting stump sprouting and competitive success of five oak species in southern Indiana. Can J For Res 32:703–712

Wendel GW (1975) Stump sprout growth and quality of several Appalachian hardwood species after clearcutting. USDA Forest Service, Northeastern Forest Experiment Station, Upper Darby, PA. Res. Pap. NE-329, p 9

West BT, Welch KB, Gałecki AT (2007) Linear mixed models: a practical guide using statistical software. Chapman & Hall/CRC, Boca Raton