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Stump sprout dynamics in response to reductions in stand density for nine upland hardwood species in the southern Appalachian Mountains

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ABSTRACT

Much about stump sprout dynamics of upland hardwood trees species has been obtained in clearcuts. Information on the response of stump sprouts to alternative silvicultural treatments, including treatments that manipulate stand density and stand structure is lacking. In this study we examined the influence of harvest season and levels of basal area reduction on the probability of sprouting and subsequent sprout growth in the southern Appalachian Mountains. In 2009, 24 – 0.1 ha plots were established in fully-stocked mixed-hardwood forests near Asheville, North Carolina, USA. Basal area was mechanically reduced from below by 10%, 20%, 30%, or 40% between January and February, 2009 (dormant season) and again between July and August, 2010 (growing season), with each harvest season and level of basal area reduction combination randomly applied to three plots. For each stump, we recorded: (1) presence of live sprouts (yes/no); (2) height (m) of the dominant (i.e., tallest) sprout, and (3) area (m^2) occupied by individual sprout clumps. All measurements were conducted one, two, and three years post-harvest. We used logistic regression and ANOVA to analyze the probability that a stump sprouts one year post-harvest and annual stump survival (i.e., the presence of at least one live sprout), sprout height, and area.

Probability of sprouting was independent of dbh for red maple, dogwood, sourwood, hickory spp., chestnut oak, yellow-poplar, and sweet birch. For sweet birch the probability of sprouting was affected by harvest season, with 54% and 93% of stumps producing sprouts one year following growing and dormant season harvests, respectively. For blackgum and white oak, dbh was negatively correlated with the probability of sprouting. Stump survival varied by species and year. Third year stump survival was 38% lower for oak and hickory than sourwood and 32% lower than red maple. Dominant sprout height was significantly greater for red maple and sourwood than for oak and hickory, with the greatest height achieved under the 40% reduction in basal area treatment. By year three, dominant sprout height for both red maple and sourwood was 40% greater than for oak and hickory and 58% greater than other shade-tolerant midstory species. Our results suggest planning harvests to occur during a particular point in the year with the idea it will limit sprouting and subsequent sprout growth is ineffective and should not be considered a viable means of reducing the production or growth of stump sprouts.

1. Introduction

The role of stump sprouts in the regeneration of upland hardwood forests in the eastern United States is well documented (Elliott et al., 1997; Beck and Hooper, 1986; Cook et al., 1998). Due to the already developed root systems of parent trees, stump sprouts exhibit rapid growth following disturbance, and can, therefore, greatly influence post-disturbance species composition (Del Tredici, 2001). For example, 11 years after clearcutting mixed-oak stands in Kentucky, Arthur et al. (1997) report stump sprouts accounted for 50% of all stems, with flowering dogwood (*Cornus florida* L.) and red maple (*Acer rubrum* L.), both prolific sprouters (Buell, 1940; Fei and Steiner, 2009), comprising the greatest percentage of overall basal area. Similarly, Beck and Hooper (1986) found 86% of all dominant/co-dominant stems were comprised of stump sprouts 20 years after clearcutting in a southern Appalachian mixed hardwood stand. Sprouting potential varies by species (Kay et al., 1988a,b; Mann, 1984), and within a species can be influenced by a variety of factors, including tree size or age (e.g., Sands and Abrams, 2009). For many of the species considered desirable due to their ecological and/or economic importance (e.g., oak (*Quercus* spp.) and hickory (*Carya* spp.)), the likelihood of

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sprouting decreases as tree size or age increases, making mature overstory oak and hickory trees an unreliable source of stump sprouts (Mann, 1994; Weigel and Peng, 2002). In contrast, sprouting of less desirable species, which, in the southern Appalachian Mountains, are generally shade-tolerant midstory species (e.g., red maple, sourwood (*Oxydendrum arboretum* L.), blackgum (*Nyssa sylvatica* Marsh.), and flowering dogwood) appears to be less dependent on tree size (Kays et al., 1988a,b; Mann, 1994).

The rapid growth of stump sprouts from some of the less desirable shade-tolerant midstory species can hinder the establishment, growth, and recruitment of the more desirable oak and hickory species (Loftis, 1985; Beck and Hooper, 1986; Arthur et al., 1997; Elliott et al., 1997). Consequently, control of stump sprouts from undesirable tree species following silvicultural treatments is critical when managing for oak and hickory species. If sprouts of undesirable species are left untreated, growing space created by cutting is quickly re-captured making regeneration of desirable species difficult (McGee and Hooper, 1970; Loftis, 1985; Beck and Hooper, 1986). Control of stump sprouts can be accomplished via mechanical or chemical methods as well as through the use of prescribed fire. Although herbicide applications are effective at eliminating stump sprouts (Loftis, 1985), the cost in both material and labor, issues with chemical usage in ecologically sensitive areas, and/or public concern (e.g., Wagner et al., 1998; Shepard et al., 2004; Miller and Miller, 2004; Guynn et al., 2004) may limit where and when herbicide applications can be performed. In regards to mechanical treatment of stump sprouts, a variety of studies suggest cutting when root carbohydrate reserves are low (e.g., during the growing season) (Kays and Canham, 1991; Babeux and Mauffette, 1994; Belz, 2003) may reduce sprouting, stump survival, and/or subsequent sprout growth (Johansson, 1992a, 1992b; Hytönen, 1994). For example, in western North Carolina, Buell (1940) observed a decrease in the growth of flowering dogwood sprouts when trees were cut in July and early August versus late winter or early spring. Similarly, Belz (2003) recommends that to achieve at least 50% mortality of severed red alder (*Alnus rubra* Bong.) stumps, harvesting should be performed between 7 and 19 weeks after budbreak when root starch reserves are at their lowest levels.

Most of the information on stump sprout dynamics of upland hardwood tree species has been obtained following clearcutting (e.g., McGee and Hooper, 1970; Kays et al., 1988a,b; Weigel and Peng, 2002; Sands and Abrams, 2009). As such, information on how stump sprouts respond to alternative silvicultural treatments, including thinning, partial harvesting methods, and site-preparation activities similar in design to thinning treatments and implemented to promote the development of a robust oak and hickory advance reproduction pool (e.g., Loftis, 1990; Ward, 1992) is limited (Atwood et al., 2009) or altogether lacking. In one of the few studies to examine the effects of overstory density on stump sprout potential and growth in bottomland hardwood forests Gardner and Helmig (1997) found no effect of residual overstory on the percent of water oak (*Quercus nigra* L.) stumps that sprouted, but did document greater stump survival after heavy (60% reduction in basal area) versus light (40% reduction in basal area) thinning. In contrast, Lockhart and Chambers (2007) found no difference in either the proportion of cherrybark oak (*Quercus pagoda* Raf.) stumps that sprouted or stump survival following light and heavy thinnings.

Despite the role of stump sprouts in controlling species composition following stand-replacing disturbance in upland hardwood forests across the Central Hardwood Region (e.g., Beck and Hooper, 1986; Cook et al., 1998; Elliott et al., 1997; Arthur et al., 1997) little quantitative information exists regarding sprout dynamics following less than stand-replacing disturbances. Although not intended to regenerate stands, intermediate silvicultural treatments that reduce stand density have the potential to alter understory species composition and recruitment and, thereby, influence the future regeneration potential of the stand (e.g., Ward, 1992; Bailey and Tappeiner, 1998; Albrecht and McCarthy, 2006; Yeo and Lee, 2006). In this study, we manipulated stand density during two distinct time periods, the growing season and dormant season, to better understand stump sprout dynamics for some of the most common commercial and noncommercial tree species in the southern Appalachians. Specifically, this study was designed to test the hypotheses that species, reductions in stand density, the season of harvest or cutting along with their interactions have no significant effect on (a) the probability that any given cut tree sprouts; (b) the survival of cut stumps; (c) sprout height; and (d) the area occupied by individual sprouts over a three year time period in mixed-upland oak forests of the southern Appalachian Mountains.

2. Methods

2.1. Study area

This study was conducted on Bent Creek Experimental Forest in Asheville, North Carolina, USA (35.5°N, 82.6°W) located in the Blue Ridge Physiographic Province of the southern Appalachian Mountains. Altitudes range from approximately 600 to 1200 m. Winters are generally cool, with January temperatures averaging 2.3 °C, and summers are warm, with July temperatures averaging 22.3 °C (McNab et al., 2004). Total annual precipitation in the Bent Creek Watershed averages approximately 1200 mm, and is evenly distributed throughout the year.

2.2. Experimental design and data collection

In 2009, 24 – 0.1 ha plots were randomly established in mature fully-stocked upland, mixed-hardwood forest types on Bent Creek Experimental Forest (Table 1). Based on documents describing the disturbance history of Bent Creek along with early study files, ages of stands used in this study were estimated to be between 80 and 100 years. Plots were primarily of mixed-oak species composition, with oaks comprising approximately 52% (range 29–74%) of the overall basal area. At the time of plot establishment, diameter at 1.37 m above ground line (dbh; cm) and species of all live trees $\geqslant$2.5 cm dbh were recorded. Basal area was mechanically reduced from below by 10%, 20%, 30%, or 40% between January and February, 2009 (dormant season) and again between July and August, 2010 (growing season), with each harvest season and basal area reduction combination randomly applied to three plots. Stumps were cut to an approximate height of 30 cm. Following thinning, basal area ($m^2\ ha^{-1}$) averaged (standard deviation) 32.7 (7.2), 23.9 (3.7), 23.8 (3.4), and 21.5 (3.2) in the 10, 20, 30, and 40% thinning levels, respectively.

On each cut stump, we recorded: (1) the presence of live sprouts (yes/no); (2) height (m) of the dominant sprout in each clump, and (3) the maximum horizontal diameter (m) of the widest axis of the sprout clump (measured across the center of the stump) and the diameter (m) perpendicular to this axis. All sprout measurements were conducted one, two, and three growing seasons post-harvest. Diameter data were then used to calculate the average area of sprouts clumps, with area modeled as an ellipse.

2.3. Statistical analyses

For nine species in which sample size (Table 2) was adequate (red maple, sweet birch, hickory, flowering dogwood, yellow-poplar, blackgum, sourwood, white oak (*Quercus alba* L.), and chestnut oak (*Quercus prinus* L.)), hierarchical logistic regression implemented with PROC GLIMMIX (SAS Institute Inc., 2011) was utilized to individually model the probability of sprouting one year post-

Table 1
Stand attributes of plots prior to basal are reduction treatments. Trees ha^{-1} and basal area were calculated using all trees $\geqslant$ 2.5 cm diameter at breast height (dbh). Quadratic mean diameter was calculated using all trees $\geqslant$ 12.7 cm dbh.

Attribute	Mean	Standard deviation	Minimum	Maximum
Trees ha^{-1}	805	295	240	1320
Basal area (m^2 ha^{-1})	33.9	5.9	22.0	46.2
Quadratic mean diameter (cm)	32.7	4.2	26.5	46.4

Table 2
Number of cut stumps sampled (*n*) and size distribution of parent trees prior to treatment.

Species	Diameter at breast height (cm)				
	n	Mean	Standard deviation	Minimum	Maximum
Red maple*	596	9.7	6.9	2.3	37.0
Sweet birch*	40	7.4	4.2	2.8	18.8
Serviceberry	3	7.7	4.3	2.7	10.5
Hickory*	30	12.9	5.2	3.3	21.9
Dogwood*	53	7.5	3.4	2.6	16.1
American beech	6	7.7	7.0	2.5	21.3
American holly	8	4.9	1.7	3.0	8.0
Yellow-poplar*	21	15.6	10.3	2.5	37.3
Cucumber tree	8	9.1	7.0	4.9	25.6
Fraser magnolia	12	7.2	6.1	2.8	19.6
Blackgum*	77	11.4	5.6	4.3	33.1
Sourwood*	399	11.0	6.8	2.3	35.4
Scarlet oak	6	18.2	5.7	12.5	26.3
Northern red oak	9	19.1	12.2	3.2	35.9
Black oak	4	31.3	9.7	18.1	39.3
White oak*	26	22.5	9.2	3.2	38.9
Chestnut oak*	53	21.9	8.0	3.0	38.2
Black locust	2	20.0	5.4	16.1	23.8
Sassafras	13	5.7	4.0	2.5	16.2

* Indicates sample size was of sufficient size ($n \geqslant 15$) to analyze the effects of parent tree dbh, harvest season, and thinning level on the probability of stump sprouting.

harvest as a function of (a) parent tree dbh, (b) harvest season (dormant season versus growing season), and (c) basal area reduction (10%, 20%, 30%, 40%). The logistic model had the form:

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

where $P(S)$ is the probability of sprouting, β_0, β_1, β_2, and β_3 are the model coefficients, and X_1, X_2 and X_3 are dbh, season of harvest, and basal area reduction, respectively. Adequate sample size was defined as those species where the number of observations was greater than five times the number of independent predictor variables (Vittinghoff and McCulloch, 2006). In the model, dbh was a continuous variable and harvest season and thinning level were categorical variables. Due to the limited sample sizes for some individual species, we did not test the significance of interactions in the probability of sprouting model. The hierarchical nature of the data (i.e., cut stumps nested within plots) was accounted for by including plot as a random effect in the probability of sprouting model (Dai et al., no year).

Average annual height of the dominant sprout, average area (m^2) of individual sprout clumps, and percent stump survival (i.e., percentage of stumps with at least one live sprout) were analyzed as a completely random split-plot repeated measures design (Proc Mixed SAS Institute Inc., 2011). The main plot factor was a factorial combination of harvest season and basal area reduction, the split-plot factor was species group (5 levels), and year (one, two, and three years post-harvest) was the repeated factor. An unstructured covariance matrix (UN) was used to account for the correlation due to repeated measurements as this structure resulted in the lowest AICC (others tested included, VC, AR(1), CS, and HF). A stump was considered alive if it had at least one live sprout. Species groups were: (a) oak/hickory; (b) red maple; (c) sourwood; (d) other shade-tolerant midstory species, which included blackgum (*N. sylvatica* Marsh.), American holly (*Ilex opaca* Ait.), flowering dogwood, sassafrass (*Sassafrass albidum* L.), American beech (*Fagus grandifolia* Ehrh.), DC.), and serviceberry (*Amalanchier arborea* (Michx. F.) Fern); and (e) shade-intolerant species, which included sweet birch (*Betula lenta* L.), yellow-poplar (*Liriodendron tulipifera* L.), black locust (*Robinia pseudoacacia* L.), cucumber tree (*Magnolia accuminata* L.), and fraser magnolia (*Magnolia fraseri* Walt.). Stump survival data were weighted by sample size to account for unequal representation of stumps per species groups in each of the plots.

Significant interactions were examined using the SLICE option in PROC MIXED (SAS Institute Inc., 2011). Following significant *F*-tests or partitioned *F*-tests, differences in Least Squares Means were compared using Bonferroni's adjusted LSD, where α = (0.05/number of comparisons). Weighted stump survival data were square root transformed and dominant sprout height and area data were ln-transformed to achieve normality and homoscedasticity (assessed graphically). The means and standard errors reported are from the raw and untransformed data. All analyzes were significant at $\alpha = 0.05$ unless noted.

3. Results

3.1. Probability of sprouting

Within the range of parent tree diameters observed in this study (Table 2), the relationship between the probability of sprouting one year post-harvest and dbh was not statistically significant ($P > 0.05$) for red maple (95% sprout rate), dogwood, (88% sprout rate), sourwood (98% sprout rate), hickory spp. (77% sprout rate), chestnut oak (86% sprout rate), yellow-poplar (91% sprout rate), and sweet birch (73% sprout rate). For only blackgum and white oak, we observed a negative relationship between parent tree dbh ($P < 0.05$) and the probability of stump sprouting. For blackgum, the parameter estimates (SE) associated with the intercept and dbh were 5.5798 (1.3881) and −0.2011 (0.0757), respectively. For white oak, the parameter estimates (SE) associated with the intercept and dbh were 4.7135 (1.9363) and −0.2347 (0.0898), respectively. White oak experienced a particularly precipitous decrease in sprouting as dbh increased (Fig. 1a). As white oak trees exceeded 20 cm dbh, the probability of sprouting fell below 50% while when dbh exceeded 30 cm dbh, it was less than 10%. In contrast, for blackgum, the probability of sprouting did not drop below 50% until trees surpassed 30 cm dbh (Fig. 1). Only for sweet birch was the probability of sprouting significantly affected by the harvest season ($P = 0.0365$), with trees harvested during the growing season less likely to sprout (54% sprout rate) than trees harvested during the dormant season (93% sprout rate). Basal area reduction was not a significant predictor ($P > 0.1$) of the probability of sprouting one year post-harvest for any of the nine species analyzed.

3.2. Stump survival

Stump survival was significantly affected by basal area reduction, species group, year, and the interaction between species group and year (Table 3). Although the main effect of basal area reduction was significant, after controlling for the Type-I error-rate via the Bonferonni-adjusted LSD tests, no differences in stump survival were detected. Stump survival (averaged across species groups, harvest season, and years) in the 10%, 20%, 30%, and 40% reduction levels averaged (SE), 83% (4), 80% (3), 89% (2), and 90%

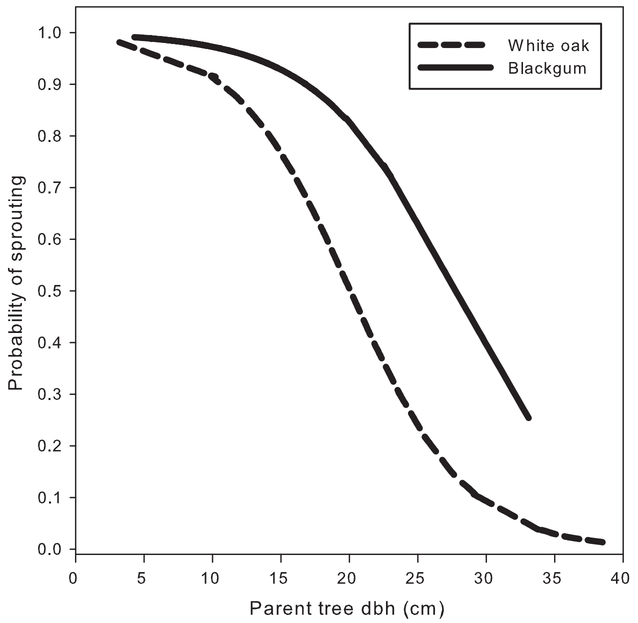

Fig. 1. Relationship between parent tree diameter at breast height (dbh) and probability of sprouting one year post-harvest for white oak and blackgum based on model coefficients presented in Section 3.

(2), respectively. The species∗year interaction used partitioned *F*-tests to reveal several significant differences in stump survival between the species groups at one, two, and three years post-harvest. At one year post-harvest, stump survival was 22% lower for the oak/hickory species group than for sourwood (Table 4). Stump survival in the oak/hickory group dropped to 65% two years post-harvest. Consequently, stump survival for the oak/hickory group was 33% and 28% lower than for sourwood and red maple, respectively. Third year stump survival was 38% and 32% lower for the oak/hickory group than for sourwood and red maple, respectively. In addition, by the third year post-harvest, sourwood possessed stump survival rates 19% greater than in the other tolerant midstory species group.

3.3. Sprout height and area

Dominant sprout height was affected by basal area reduction, species group, year, the interaction between basal area reduction and year, and the interaction between species group and year (Table 3). Regardless of year, the height of dominant red maple sprouts (averaged over thinning level and harvest season) was significantly greater than in the oak/hickory and other tolerant midstory species groups (Fig. 2a). By the second year, the average height of the dominant sprout in the sourwood, red maple, and intolerant species groups were similar, and were significantly taller than the dominant sprout in both the oak/hickory and other tolerant midstory species groups. There was a trend of increasing height with years since harvest. However, regardless of year, dominant sprout height (averaged across species groups, harvest season, and years) in the 10% and 20% basal area reduction levels was significantly less than in the 30% and 40% basal area reduction levels (Fig. 2b).

Area of individual sprout clumps was affected by species group, basal are a reduction, year, and the interaction between harvest season and year (Table 3). The season∗year interaction used partitioned *F*-tests to reveal significant differences between the dormant season area (SE) of 2.0 (0.2) m^2 and the growing season area of 1.7 (0.2) m^2 (averaged across species groups and basal area reduction levels) two years post-harvest. Partitioned *F*-tests describing the interaction between harvest season and year one and three years post-harvest were not significant ($P > 0.05$). Aver-

Table 4
Mean (SE) stump survival (%) by species group and year post-harvest (averaged over basal area reduction levels and harvest season). Means followed by different letters indicate significant differences in stump survival among species within a given year at a Bonferonni-adjusted $\alpha = 0.0050$.

	Stump survival (%)
One year post-harvest	
Intolerant	88 (8)^{ab}
Oak/hickory	76 (5)^{a}
Red maple	93 (2)^{ab}
Sourwood	98 (1)^{b}
Other tolerant	91 (2)^{ab}
Two years post-harvest	
Intolerant	86 (9)^{ab}
Oak/hickory	65 (7)^{a}
Red maple	93 (2)^{b}
Sourwood	98 (1)^{b}
Other tolerant	81 (5)^{ab}
Three years post-harvest	
Intolerant	85 (9)^{ac}
Oak/hickory	60 (7)^{bc}
Red maple	92 (2)^{ad}
Sourwood	98 (1)^{a}
Other tolerant	79 (5)^{dc}

Table 3
Results of the split-plot repeated measures ANOVA, with the main plot factor a factorial combination of basal area reduction (10%, 20%, 30%, and 40%) and harvest season (dormant versus growing season) and the split-plot factor species group (oak/hickory, red maple, sourwood, other tolerant, intolerant).

Effect	df	*F*-value Stump survival	*P*-value	*F*-value Height	*P*-value	*F*-value Area	*P*-value
Season	1	2.37	0.1430	1.92	0.1831	2.54	0.1386
Reduction	3	3.60	0.0362	12.30	0.0002	9.31	0.0023
Season x reduction	3	0.78	0.5226	0.31	0.8181	0.34	0.7952
Species	4	9.54	<0.0001	53.33	<0.0001	37.74	<0.0001
Season x species	4	1.37	0.2591	0.60	0.6623	0.49	0.7419
Reduction x species	12	1.51	0.1543	1.78	0.0770	0.83	0.6183
Season x reduction x species	12	1.94	0.0536	1.37	0.2130	0.89	0.5669
Year	2	6.68	0.0023	570.84	<0.0001	86.69	<0.0001
Season x year	2	1.20	0.3072	2.00	0.1450	11.80	<0.0001
Reduction x year	6	0.89	0.5083	3.45	0.0046	0.92	0.4857
Season x reduction x year	6	0.76	0.6027	1.59	0.1621	1.26	0.2880
Species x year	8	2.23	0.0326	11.82	<0.0001	1.32	0.2473
Season x species x year	8	1.45	0.1867	0.54	0.8200	1.10	0.3722
Reduction x species x year	24	0.88	0.6275	0.85	0.6665	0.60	0.9200
Season x reduction x species x year	24	0.69	0.8475	1.25	0.2217	1.00	0.4767

Note: The model contained three error terms which were used by Proc Mixed to appropriately test the fixed effects.

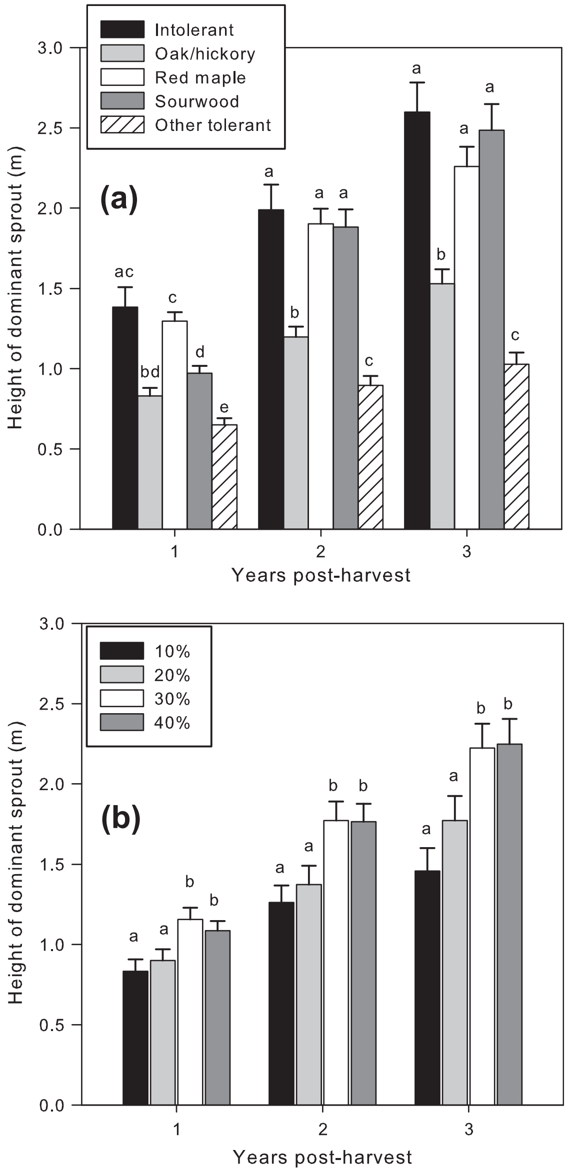

Fig. 2. Height (m) of the dominant sprout per clump (a) by species group (averaged across levels of basal area reduction and harvest season) and (b) basal area reduction level (averaged across species group and harvest season) one, two, and three years post-harvest. Means following by the same letter within a given year are not significantly different at a Bonferonni-adjusted $\alpha = 0.0050$ for (a) and $\alpha = 0.0083$ for (b). Error bars represent ± 1 standard error.

aged across basal area reduction levels, harvest season, and years, the area occupied by individual red maple and sourwood sprout clumps averaged 2.3 m^2 (Fig. 3a). This was significantly greater than the area occupied by individual sprout clumps in the oak/hickory and other midstory tolerant species groups, which averaged 1.4 m^2 and 0.6 m^2, respectively. Averaged across species groups, harvest season, and years, the area occupied by sprout clumps was significantly 83% greater in the 30% than 10% basal area reduction treatment and almost twice as large in the 40% than in the 10% basal area reduction treatment (Fig. 3b). No difference in growing space occupied was observed between the 20% and 30% and 30% and 40% reduction levels. However, area occupied by sprout clumps was 72% greater in the 20% than 40% reduction levels. To put the area of sprouts into perspective, by the third year post-harvest, growing space occupied by sprout clumps, as a percentage of the 0.1 ha plot area (acknowledging some overlap between individual sprout clumps), averaged 6%, 12%, 22%, and 25% in the 10%, 20%, 30%, and 40% reduction levels, respectively.

4. Discussion

The probability that an individual tree sprouts varies by species (Weigel and Peng, 2002), geographic location (Johansson, 1992b; Babeux and Mauffette, 1994), parent tree size (Harrington, 1984; Sands and Abrams, 2009), age (Šplíchalová et al., 2012), site quality (Kays et al., 1988a,b), overstory density (Atwood et al., 2009), and harvest season (Johansson 1992a, 1992b). In this study, the probability of sprouting for red maple, sweet birch, sourwood, chestnut oak, dogwood, hickory, and yellow-poplar was independent of parent tree dbh, thinning level, and, with the exception of sweet birch, harvest season. Sprouting probabilities for commercial oak species are well documented, with sprouting negatively related to parent tree size (Johnson, 1977; Ross et al., 1986; Weigel and Peng, 2002). An exception appears to be chestnut oak where rates of sprouting are high (86% in this study) regardless of tree size (Mann, 1984; Kays et al., 1988a,b; Sands and Abrams, 2009). Although quantitative data describing the probability of sprouting for red maple, sourwood, dogwood, and yellow-poplar are limited, results from this study suggest these less desirable and, in most cases non-commercial species, sprout readily following harvest regardless of parent tree dbh (Mann, 1984; Kays et al., 1988a,b; Fei and Steiner, 2009). It should be noted that because this study examined the effects of different levels of basal area reduction from below, the results of the study are limited in scope to the range of parent tree diameters observed in this study (Table 2).

Sprouting and subsequent sprout growth is dependent, in part, on the parent tree root reserves (Kozlowski et al., 1991). In general, carbohydrate reserves are at or near their lowest levels during the growing season (i.e., at full leaf-expansion but prior to cessation of aboveground growth) (Kays and Canham, 1991). Consequently, timing timber harvests or intermediate treatments during this period when root reserves are at their lowest levels has been suggested as a means to deter the sprouting or decrease the competitiveness of less desirable species (e.g., Buell, 1940; Johansson, 1992a; Hytönen, 1994; Belz, 2003). In this study the probability of sprouting of only sweet birch was reduced by harvesting in the growing season (54%) rather than in the dormant season (93%). Although this represents a substantial decline in sprouting, management of seed-origin sweet birch following silvicultural activities is more of a management concern than stump sprouts in these forests (Beck and Hooper, 1986; Schuler and Miller, 1995; Johnson et al., 1998). We did find a significant effect of harvest season on sprout area, but this was only significant during the second year post-harvest. Furthermore, the differences in sprout area we report (2.0 m^2 two years following dormant season harvest vs. 1.7 m^2 two years following growing season) are likely biologically not very meaningful. Overall, this study confirms the results from other studies that suggest that even if an initial reduction in sprout growth following growing season versus dormant season harvests occurs, over time, differences are negligible and do not have any significant management implications (Kays and Canham, 1991; Johansson, 1992b; Ducrey and Turrel, 1992).

We found no significant effect of harvest season on stump survival. Although some studies have reported significant effects of harvest season on stump survival, in the long-term, these differences are likely of little practical importance. For example, Xue et al. (2013) found 3-year stump survival of Chinese cork oak (*Quercus variabilis*), was 89% when trees were severed in May versus 83% when severed in December. Similarly, Babeux and Mauffette (1994) report red maple stump mortality rates of 53% and 65% one year following harvest in May and June, respectively.

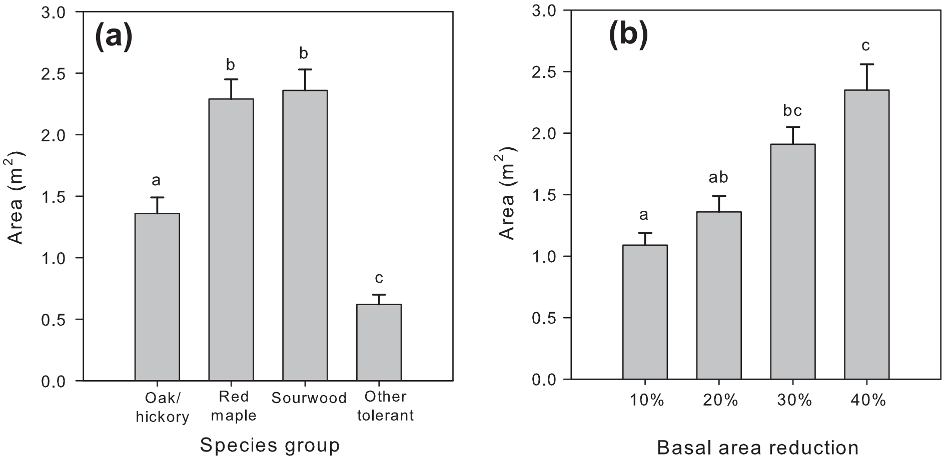

Fig. 3. Area (m^2) occupied by individual sprout clumps by (a) species group (averaged across levels of basal area reduction, harvest season, and years) and (b) basal area reduction level (averaged across species group, harvest season, and years). Means following by the same letter are not significantly different at a Bonferonni-adjusted $\alpha = 0.0050$ for (a) and $\alpha = 0.0083$ for (b). Error bars represent ± 1 standard error.

However, the authors report by the second year post-harvest, the initial differences in stump mortality between the cutting dates were absent. Based on the findings in this study, we conclude that harvesting during the growing season, as defined in this study, does little to decrease stump survival of undesirable species. The one factor significantly affecting stump survival in this study was species.

We found no evidence that the relatively light reductions in basal area (10% to 40%) affected the probability that an individual tree sprouts or stump survival. This is in contrast to a study by Atwood et al. (2009) who found partial harvesting systems resulted in lower rates of sprouting than clearcutting. It should be noted, however, the authors sampled 9–11 year-old stands where substantial sprout mortality may have already occurred (Johnson, 1975; Gardiner and Helmig, 1997; Lockhart and Chambers, 2007), and did not control for parent tree size in their analysis; a factor known to influence sprouting. In contrast, our findings appear to support those that suggest the percent of stumps that produce sprouts does not differ between light and heavy thinnings (Gardiner and Helmig, 1997; Lockhart and Chambers, 2007), low and high density shelterwood treatments (Rong et al., 2013), or single-tree selection and clearcutting regeneration methods (Dey and Jensen, 2002).

The response of sprouts in terms of height (Fig. 2) and area occupied (Fig. 3) under the various levels of basal area reduction was as expected, with aggressive sprouting shade-tolerant species, such as sourwood and red maple, out-performing the less shade-tolerant oaks and hickories under all levels of basal are reduction. The effects of overstory density on stump sprout growth presented here are similar to those found across a variety forest types and species. For example, O'hara et al. (2007) found height growth of coastal redwood (*Sequoia sempervirens* (D. Don) Endl.) stump sprouts following thinning was largely a function of overstory density and resultant light conditions. Similarly, Gardiner and Helmig (1997) report significant reductions in the height of water oak stump sprouts under increasing overstory density. Silvicultural treatments that reduce stand density to levels used in this study do not appear to benefit desirable species and may, over time, decrease the relative dominance of oak and hickory species as undesirable shade-tolerant species have quickly re-occupied growing space under all levels of basal area reduction. In regards to the height and area values reported in this study, it should be noted that all plots were surrounded by mature and undisturbed forest. In many situations, treated buffers, equivalent to one tree height in length, are installed to reduce or eliminate any potential edge effect on response variables. Because all plots possessed an untreated buffer, any potential edge effect would have been similar across plots. The untreated buffer and corresponding edge effect may have resulted in an underestimation of absolute sprout height and sprout area. However, the relative and statistical differences across treatments should not be affected as all plots were surrounded by similar untreated buffers.

5. Conclusions

In upland hardwood forests, sprouting of less desirable species, such as red maple and other midstory shade-tolerant species can interfere with the establishment, growth, and recruitment of more desirable species, such as oak and hickory species (Loftis, 1983, 1985; Beck and Hooper, 1986). Planning harvests or cuttings to occur during a particular point in the year with the idea it will limit sprouting and subsequent sprout growth of some of the most prominent undesirable (e.g., red maple) species (e.g., Kays and Canham, 1991; Hytönen, 1994; Belz, 2003) is ineffective and should not be considered a viable means of reducing the production of stump sprouts or reducing sprout growth and development in upland hardwood forests. Whether implementing regeneration harvests, thinning treatments, or site-preparation activities prior to regeneration harvests (e.g., Loftis, 1985, 1990), it is clear the rapid growth of stump sprouts, if not controlled through further manual or chemical methods, may determine, in large part, future species composition.

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