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# Effects of alternative silviculture on stump sprouting in the southern Appalachians

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ABSTRACT

Stump sprouts are an important form of regeneration for a number of species in the southern Appalachians, especially the oaks (*Quercus* spp.). Alternative regeneration systems to clearcutting such as shelterwood and leave-tree systems are being implemented in many hardwood stands in the Appalachians. However, the effects of these alternative silvicultural systems on stump sprouts are not known. Therefore, we evaluated the impact of three silvicultural systems: a clearcut, leave-tree, and shelterwood on stump sprouting. These treatments were implemented in seven stands in Virginia and West Virginia in the Appalachian Plateau (AP) and Ridge and Valley (RV) physiographic provinces. The stands were even-aged oak dominated Appalachian hardwood stands with ages ranging from 62 to 100 years.

Species were placed into six groups: (1) red oak (*Quercus* spp.), (2) chestnut oak (*Q. prinus* L.), (3) white oak (*Q. alba* L.) and hickory (*Carya* spp.), (4) red maple (*Acer rubrum* L.), (5) mixed mesic, and (6) midstory groups. Partial harvesting also reduced the number of sprouts per stump for the red oak group and red maple. Sprouting probabilities were generally less in the Appalachian Plateau than the Ridge and Valley, particularly for the oaks (*Quercus* spp.). Partial harvesting systems decreased sprouting in both physiographic provinces. However, the sprouting in specific species groups varied between the two physiographic provinces. In the Ridge and Valley, the highest sprouting rates were in the clearcut for the red oak (60%), chestnut oak (77%), white oak–hickory (26%), and midstory (33%) species groups. Red maple sprouting was highest in the leave-tree (67%) in the Ridge and Valley. The mixed mesic and midstory groups were only reduced in the Ridge and Valley. Sprouting was negatively correlated with residual basal area for the red oak group, chestnut oak, and red maple. For the all oak species except white oak, sprouting was reduced by about 2% for every 1m$^2$/ha increase in residual basal area.

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## 1. Introduction

Over the past several decades, changes in forest management objectives have forced a change in silvicultural systems in the southern Appalachians. These objectives have become more diverse and complex catering to different wants and needs from both society and landowners. The move has been away from clearcutting towards alternative methods which retain variable numbers of stems to meet objectives related to improving aesthetics, providing structural elements from the previous stands for wildlife food and habitat, reducing alterations in the micro-climate, and preserving oak (*Quercus* spp.) ecosystem types (Smith et al., 1989; Loftis, 1990a; Franklin et al., 1997; Miller et al., 2006; McShea et al., 2007).

Maintaining oak forests and the critical functions which they serve in the southern Appalachians has proven to be difficult. Oak is considered a keystone species in the southern Appalachians. Its high commercial value has become important to the region and is recognized worldwide (Appalachian Hardwood Manufactures, 2007). After chestnut blight (*Cryphonectria parasitica*) eliminated American chestnut (*Castanea dentata* (Marsh.) Borkh.) as an overstory component in the southern Appalachians, oaks have become the most important hard mast producing species (McShea et al., 2007).

Oak regeneration originates from three sources: seedlings, advance regeneration, or stump sprouts. Newly established seedlings are frequently overtopped by faster growing competitors and rarely contribute to future stand composition at rotation age (Larsen and Johnson, 1998). In contrast, large advance oak regeneration can grow fast enough following harvest to remain in the upper canopy of the developing stand, thus contributing to

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merchantable volume in the future. Sander (1971, 1972), Sander et al. (1984), and Loftis (1990b) have described the ability of advance regeneration to perpetuate oak following harvest in the Missouri Ozarks and the southern Appalachians. However accumulation of advance oak regeneration is hindered by the development of tolerant midstory species in many stands in the southern Appalachians, which can in turn impede postharvest oak development (Loftis, 1985). Stump sprouts are an important source of regeneration for oak because stump sprouts will grow fast enough to successfully compete during the stem exclusion phase following canopy closure. Stump sprouts have a large established root system which often supports more rapid growth and multiple flushes from stored carbohydrates and an increased ability to obtain resources (Johnson et al., 2002). Stump sprouting has been found to be more important in the southern Appalachians than in other regions where these species are found (Cook et al., 1998). The quality of trees which result from stump sprouts equals other forms of oak regeneration if stands are properly harvested and stump heights are kept low (Groninger et al., 1998).

A concern in many mature Appalachian hardwood stands is that oak's sprouting ability has been shown to drastically decrease with increasing parent tree age and diameter in clearcuts. In a southern Indiana clearcut, Weigel and Johnson (1998) found large decreases in first year sprouting probabilities for white oak (*Q. alba* L.) once trees become older than 50 years or larger than 20 cm dbh. However there are important differences in sprouting abilities among species. Chestnut oak (*Q. prinus* L.) sprouting did not decrease until age 100 years or a dbh over 30 cm, while black oak (*Q. velutina* Lam.), northern red (*Q. rubra* L.), and scarlet oak (*Q. coccinea* Muenchh.) declined after 70 years or a dbh over 30 cm. Cook et al. (1998) also investigated a number of studies which showed regional variations in the initial sprouting probabilities for a number of oak species across size, age, site quality, and season of harvest. Generally stump sprouting decreases as site quality increases, and trees harvested during the dormant season have shown higher rates of sprouting (Johnson et al., 2002; Cook et al., 1998).

Clearcutting was promoted as the most effective and efficient form of timber management in this region in the 1960s (Roach and Gingrich, 1968). However frequently oak regeneration has been inadequate following clearcuts on higher quality sites (Beck and Hooper, 1986; Loftis, 1990b, Cook et al., 1996). This led to the development of alternative silvicultural systems to clearcutting designed to manipulate the light regime and foster the development of advance oak regeneration such as shelterwood and leave-tree systems (Loftis, 1990a). The shelterwood system involves multiple entries and depends on recruiting advance regeneration, which in most cases can take multiple years for proper implementation and success. The leave-tree system was developed to mimic clearcut conditions while leaving just enough residual trees to lessen the aesthetic impacts of clearcuts (Smith et al., 1989). However the effects of these alternative systems on stump sprouting is not known (Johnson et al., 2002). The objectives of this study were to quantify the effects of alternative silvicultural systems and different residual basal areas on stump sprouting percents and the number of sprouts per stump in the southern Appalachians. We predicted a greater proportion of stump sprouting in the treatments with fewer residuals trees, and stump sprouts would be more vigorous, in terms of the number of sprouts per stump, in the treatments with fewer residual trees.

## 2. Methods and materials

### 2.1. Study sites

Seven sites in the southern Appalachians were included in this study. These sites supported mature Appalachian hardwood stands

**Table 1**
Stand conditions by site and original overstory composition, basal area ($m^2/ha$) and density (stems/ha) of all stems >5 m in height, by species group.

| Site | County, State | Aspect (°) | Slope % | Average annual precipitation (cm) | Oak site index 50 (m) | Age years | Year of harvest completion | Age at measurement | Basal area ($m^2/ha$) | | | | | Density (stems/ha) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | All oak spp. | Red maple | Mesic mesic spp. | Midstory spp. | Total | All oak spp. | Red maple | Mesic mesic spp. | Midstory spp. | Total |
| BB1 | Montgomery, VA | 153 ± 19 | 16 ± 3 | 101.6 | 23 | 100 | 1995 | 11 | 24.2 | 1.3 | 1.8 | 1.2 | 28.6 | 187 | 73 | 506 | 200 | 966 |
| BB2 | Montgomery, VA | 151 ± 14 | 21 ± 3 | 101.6 | 22 | 99 | 1996 | 10 | 24.0 | 2.2 | 3.2 | 3.3 | 32.7 | 472 | 185 | 404 | 222 | 1283 |
| NC | Craig, VA | 150 ± 16 | 12 ± 4 | 113.6 | 18 | 62 | 1996 | 10 | 20.4 | 0.9 | | 2.5 | 23.7 | 360 | | 673 | 61 | 1094 |
| CL1 | Wise, VA | 149 ± 20 | 30 ± 3 | 124.5 | 18 | 100 | 1998 | 9 | 20.3 | 5.2 | 3.5 | 6.4 | 35.3 | 303 | 158 | 234 | 322 | 1017 |
| CL2 | Wise, VA | 108 ± 19 | 16 ± 3 | 124.5 | 20 | 76 | 1998 | 9 | 19.2 | 8.0 | 2.2 | 5.7 | 35.1 | 406 | 191 | 221 | 426 | 1244 |
| WV1 | Randolph, WV | 270 ± 7 | 38 ± 3 | 113.9 | 23 | 73 | 1997 | 10 | 12.8 | 6.4 | 6.8 | 4.0 | 30.0 | 474 | 307 | 153 | 360 | 1294 |
| WV2 | Randolph, WV | 129 ± 11 | 9 ± 4 | 113.9 | 24 | 63 | 1998 | 9 | 4.4 | 8.2 | 23.7 | 3.2 | 39.4 | 545 | 689 | 42 | 262 | 1538 |

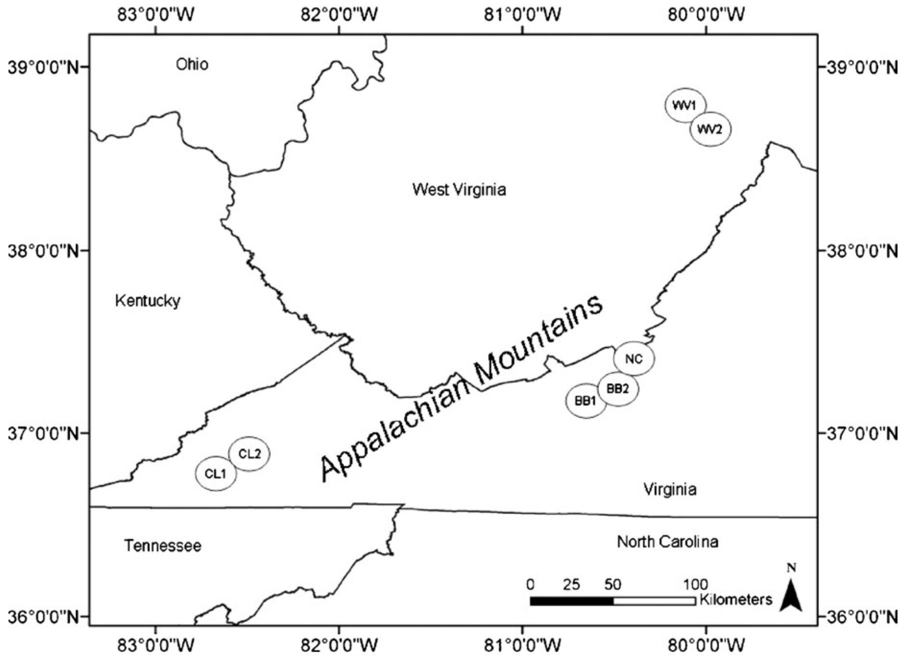

**Fig. 1.** Study site locations.

with tolerant midstory species occupying the lower canopy strata (Table 1). Two sites were located on Cumberland Plateau in the Clinch Ranger District of the Jefferson National Forest in southwest Virginia (CL1 and CL2) (Fig. 1). The average stand ages were between 76 and 100 years. They contained about 35 $m^2$/ha of basal area in around 1244 and 1017 stems/ha over 5 m in height. The average slope ranged between 16 and 30%, aspects were southeast, and precipitation averaged 125 cm distributed throughout the year. July temperatures averaged 21 °C and December temperatures averaged 3 °C. The soil series is mapped as Muskingum. It is a fine-loamy, mixed, semiactive, mesic typic Dystrudept, moderately deep, well drained, and moderately preamble channery silt loam (NRCS, 2008). Upland oak site index, based on site index curves developed from data combined for northern red oak, southern red oak, white oak, scarlet oak, and chestnut oak ranged from $SI_{50}$ 18 to 20 m (Olsen, 1959).

Two sites were located on the Allegheny Plateau in West Virginia on land owned by the MeadWestvaco Corporation (WV1 and WV2) (Fig. 1). These stands ages averaged 63 and 73 years. They contained around 35 $m^2$/ha of basal area in 1294 and 1538 stems/ha over 5 m in height. The average slope ranged between 9 and 38%, aspects were west and southeast, and precipitation averaged 113 cm distributed throughout the year. July temperatures averaged 21 °C and December temperatures averaged −2 °C. The soil series were mapped as a complex of Gilpin–Dekalb series, an ultisol and entisol of similar origin; Gilpin a fine-loamy, mixed, active, mesic Typic Hapludult and Dekalb a loamy-skeletal, siliceous, active, mesic Typic Dystrudept. Both series are moderately deep, acidic, and well to excessively well drained (NRCS, 2008). Upland oak site index ranged between $SI_{50}$ 23 and 24 m (Olsen, 1959).

Three sites were located in the Ridge and Valley (RV) in the Eastern Divide Ranger District of the Jefferson National Forest in southwest Virginia (BB1, BB2, and NC) (Fig. 1). These stands ages averaged 62, 99, and 100 years. They contained around 26 $m^2$/ha of basal area in 966, 1283, and 1094 stems/ha over 5 m in height. The average slope ranged between 12 and 21%, aspects were southeast, and precipitation averaged 105 cm throughout the year. July temperatures averaged 21 °C and December temperatures averaged 2 °C. The soil series were mapped as a complex of Berk–Weikert. The Berks series is a loamy-skeletal, mixed, active, mesic Typic Dystrudept, while Weikert is a Lithic Dystrudept. Both of these soils are well drained but the Lithic, Weikert is shallow where as the Typic, Berks is moderately deep (NRCS, 2008). Upland oak site index ranged between $SI_{50}$ 18 and 23 m (Olsen, 1959).

## 2.2. Treatments

The three treatments included a shelterwood (SW), leave-tree (LT), and clearcut (CC). The SW retained 12–14 $m^2$/ha of residual basal area during the initial harvest in healthy canopy trees of desired species (Table 2). This created a partial light environment on the forest floor designed to encourage the recruitment of advance regeneration of intermediately shade tolerant species such as oak. Initial plans called for an overstory removal between ages 5 and 10 depending on the growth of advance regeneration. The (LT) retained approximately 25–45 trees/ha totaling around 5 $m^2$/ha of residual basal in the initial harvest these were desirable healthy overstory stems (Table 2). These trees will remain throughout the next rotation creating a two-aged stand. The CC

**Table 2**
Residual basal area ($m^2$/ha) 1 year after harvest for all of the tree plots from which data were collected.

| Site | Treatment | | | | | |
|---|---|---|---|---|---|---|
| | CC | | LT | | SW | |
| | Mean BA ($m^2$/ha) | [*n*] | Mean BA ($m^2$/ha) | [*n*] | Mean BA ($m^2$/ha) | [*n*] |
| BB1 | 1.3 | [2] | 2.9 | [3] | 15.9 | [3] |
| BB2 | 0.0 | [3] | 3.8 | [3] | 14.3 | [2] |
| NC | 0.7 | [2] | 3.1 | [3] | 8.0 | [3] |
| CL1 | 2.6 | [3] | 7.2 | [3] | 14.8 | [3] |
| CL2 | 0.9 | [3] | | | 20.1 | [2] |
| WV1 | 0.0 | [3] | 3 1 | [3] | 8.6 | [1] |
| WV2 | 0.0 | [3] | 7.1 | [3] | 17.0 | [2] |
| All | 0.8 | [19] | 4.5 | [18] | 14.2 | [16] |

Missing values indicate either no treatment was applied at that site, or the treatment basal area was not consistent with the target.

harvested all stems greater than 5 cm dbh (Table 2). This created full light conditions to the regeneration. Other treatments were also located at these sites but stump sprouting was not investigated. These treatments were included in a larger study of the impacts of harvesting on ecosystem diversity and function. All treatment harvests were done operationally by the landowners using the best management practices required for each site. Each treatment was implemented on a 2-ha area at each site. Treatments were implemented between August 1997 and March 1998 at CL1 and CL2, between May 1997 and September 1998 at WV1 and WV2, and between November 1995 and June 1996 at BB1, BB2, and NC.

### 2.3. Study design and sampling

The study was established as a randomized complete block design. Each of the seven sites served as a block with each 2-ha treatment plot serving as an experimental unit. Within each experimental unit there were three, 24 m × 24 m tree plots which served as sub-samples. Prior to harvest the tree plots were randomly located within the 2-ha treatment plot, except that tree plots were located a minimum of 22 m from the border to minimize edge effect.

Prior to harvest each tree in the tree plot greater than 5 m in height was measured. Each tree was tagged and catalogued with an *x*, *y* coordinate system for subsequent sampling; dbh and species were recorded. During the summers of 2006–2007, 9–11 years after harvest, the sub-plots at each site were measured again. Data were collected on all residual trees within the tree plots including date, tag number, species, dbh, and crown class. A full inventory of the stumps was also completed at this time within each tree plot. Previously tagged trees that were cut during harvest were located and the following data were collected on the stumps which sprouted: tree number, species, sprout diameter at ground/stump level, dbh, height, and crown class of all sprouts.

Residual basal area in several of the tree plots at various locations fell outside of the established treatment criteria. All three of the plots in the LT at CL2 were located in a streamside management zone; consequently residual basal area was much greater than planned (Table 2). Residual basal area at two SW plots at WV1 was well below the targets (Table 2). In the CC at BB1 and NC, several large trees were retained as wildlife trees in the plots. Individual plots that fell outside the target basal area range for the treatments were not used in the analysis comparing the three treatments because they did not accurately reflect the designated treatment. These data were used, however, in the regression analysis as they fit into the spectrum of different residual basal areas.

Twenty-eight species with stump sprouts were identified in the plots. Because of the large number of species, they were combined into six groups according to abundance in the plots, similarities in silvical characteristics, and economic importance. Chestnut oak ($n = 411$) and red maple (*Acer rubrum* L.) ($n = 881$) were abundant enough to form individual species groups. Red oak species of the *Erythrobalanus* group, including northern red oak, black oak, and scarlet oak were pooled into a single red oak group ($n = 528$). White oak and hickory, including pignut hickory (*Carya glabra* (Mill.) Sweet), mockernut hickory (*Carya alba* (L.) Nutt.), and bitternut hickory (*Carya cordiformis* (Wangenh.) K), were grouped ($n = 242$). The mixed mesic species group included yellow-poplar (*Liriodendron tulipifera* L.), black cherry (*Prunus serotina* Ehrh.), cucumbertree (*Magnolia acuminata* (L.) L), fraser magnolia (*Magnolia fraseri* Walter), sugar maple (*Acer saccharum* Marsh.), basswood (*Tilia americana* L.), white ash (*Fraxinus americana* L.), and green ash (*Fraxinus pennsylvanica* Marsh.) ($n = 733$). A final group included those species which are midstory species, not normally occupying an upper canopy position, and those species which are short lived and drop out of stands relatively early in the stem exclusion phase ($n = 1539$). These species include striped maple (*Acer pensylvanicum* L.), downy serviceberry (*Amelanchier arborea* (Michx. f.)), sweet birch (*Betula lenta* L.), American chestnut, flowering dogwood (*Cornus florida* L.), American beech (*Fagus grandifolia* Ehrh.), hophornbeam (*Ostrya virginiana* (Mill.) K. Koch), sourwood (*Oxydendrum arboreum* (L.) DC.), pin cherry (*Prunus pensylvanica* L. f.), black locust (*Robinia pseudoacacia* L.), and sassafras (*Sassafras albidum* (Nutt.) Nees).

## 3. Statistical analysis

The percent of stumps that sprouted was calculated for each plot. After an arcsine transformation these data did not result in a normal distribution required for analysis of variance (ANOVA) (Ott and Longnecker, 2001). Therefore these data were analyzed using a non-parametric one-way ANOVA. The differences among treatments were compared using Wilcoxon scores and the Kruskal–Wallis test (Ott and Longnecker, 2001, SAS, 2006). The response variable was the percent of those cut stumps which sprouted by physiographic province and among treatment for each species group. An $\alpha$ level of 0.05 was used to test significance for all analyses.

To better estimate the potential contribution of stump sprouts to future stand composition, a separate analysis was conducted on stumps that produced competitive stump sprouts (CSSs). Competitive sprouts were defined as those that were in a dominant or codominant crown class position in the canopy of the developing regeneration. This analysis was based on the percent of stumps that produced a dominant or codominant sprout.

The number of sprouts per stump was compared within species groups, between physiographic provinces, and among the treatments using a mixed model ANOVA procedure with the restricted/residual maximum likelihood (REML) variance estimation method (Littell et al., 2006; SAS, 2006). This model allowed for species group, treatment, and province effects to be considered fixed effects. Site effects represented block effects and were considered random, creating the mixed model (Littell et al., 2006). The slice option was used to obtain a simple effects test among means for species group, treatment, and province effects. Least squares means comparisons were used to test for differences at an $\alpha$ level of 0.05.

Regression analysis was run by species group using residual basal area as the regressor (Excel, 2003). The response variables were the percent of stumps that sprouted and the number of sprouts per stump. Logistic regression was used to test the influence of dbh on the percent of stumps that sprouted as well. However, the results of the logistic regression investigating the influence of dbh on sprouting were not significant. This was probably because there was little variation in dbh as these stands were similar in age and had similar diameter distributions.

## 4. Results

### 4.1. Overall proportion of stumps that sprouted

Among all species groups treatment and physiographic province significantly affected the proportion of stumps that sprouted 9–11 years after harvest (Table 3). In the red oak, chestnut oak, and white oak/hickory groups, sprouting was greater in the RV than in the Appalachian Plateau (AP) (Table 3). The differences between physiographic provinces were largest in the white oak/hickory group where 6% or fewer of the stumps sprouted on the AP while 19–36% of the stumps sprouted in the RV. In both provinces, the proportion of stumps that sprouted was less in the

**Table 3**
Percent of all cut stumps which had surviving sprouts 9–11 years after harvest.

| Spp. | Treatment | Province | | | |
|---|---|---|---|---|---|
| | | Plateau | | Ridge and Valley | |
| | | Percent ± S.E. | [*n*] | Percent ± S.E. | [*n*] |
| Red oak group | CC | 41.6 ± 1.40 | [72] A | 60.0 ± 1.14 | [90] A* |
| | LT | 22.7 ± 1.27 | [66] B | 29.8 ± 1.76 | [77] B |
| | SW | 23.5 ± 1.05 | [86] B | 32.8 ± 1.25 | [134] B* |
| Chestnut oak | CC | 50.0 ± 3.65 | [44] A | 78.5 ± 1.32 | [107] A* |
| | LT | 24.1 ± 2.82 | [29] B | 73.5 ± 2.37 | [87] B* |
| | SW | 17.8 ± 2.01 | [28] C | 39.6 ± 1.04 | [116] C* |
| Red maple | CC | 65.1 ± 0.62 | [264] A* | 49.3 ± 1.08 | [73] B |
| | LT | 51.8 ± 0.99 | [162] B | 69.6 ± 1.42 | [66] A* |
| | SW | 52.2 ± 0.27 | [268] B* | 31.2 ± 2.50 | [48] C |
| White oak/hickory | CC | 0.0 | [24] | 36.2 ± 3.43 | [45] A |
| | LT | 0.0 | [16] | 25.5 ± 2.00 | [85] B |
| | SW | 6 ± 1.51 | [18] A | 19.4 ± .74 | [54] C |
| Mixed mesic | CC | 48.7 ± 0.42 | [190] B* | 20.2 ± 6.33 | [15] B |
| | LT | 28.4 ± 0.84 | [222] C | 31.0 ± 3.68 | [29] A |
| | SW | 61.2 ± 0.33 | [250] A* | 11.3 ± 2.34 | [27] C |
| Midstory | CC | 32.1 ± 0.67 | [264] A | 39.9 ± 1.10 | [223] A |
| | LT | 28.1 ± 0.10 | [433] B | 23.1 ± 0.85 | [160] B |
| | SW | 31.3 ± 0.12 | [233] A* | 15.0 ± 0.63 | [226] C |

Letters signify differences among treatment means within species groups.
* Signify differences between physiographic provinces ($\alpha = 0.05$).

LT and SW compared to the CC. For example on the AP, in the red oak group 42% of the stumps in the CC sprouted while only 23% of the stumps in the LT or SW sprouted (Table 3). Likewise, in the RV, 60% of the red oak stumps sprouted in the CC but only 30 and 33% of the stumps in the LT and SW sprouted. Sprouting in the chestnut oak group was greater than in the other oak groups. However, it too dropped in the partial harvesting treatments. In the RV, sprouting dropped from the CC (78%) and LT (73%), to the SW in which only 33% of stumps sprouted; but on the AP sprouting dropped from 50% in the CC to 35 and 18% in the LT and SW, respectively. In contrast to the oak groups, stump sprouting in the red maple and mixed mesic groups did not consistently decrease in the partial harvesting systems (Table 3).

### *4.2. Proportion of stumps that produced competitive sprouts*

At 9–11 years following harvest, the regenerating stands in this study are now entering the stem exclusion stage. Consequently, individual stems are starting to differentiate into crown classes. It is possible to identify dominant and codominant stems that have a higher probability of the competing successfully. Therefore, we conducted a separate analysis of the stumps that produced competitive sprouts that are in the dominant and codominant crown classes (Table 4).

The proportion of stumps that produced competitive sprouts differed between the two physiographic provinces. In general, the oaks sprouted better in the RV than in the AP. For example, in the red oak species group, a larger proportion of stumps produced competitive sprouts in the RV than on the AP (Fig. 2). In the RV, 57% of the stumps of the red oak group in the CC produced competitive stump sprouts while in the CC on the AP only 30% of stumps in this group produced competitive sprouts. More red oak group stumps produced competitive sprouts in the RV than in the AP in the LT and SW as well. A similar pattern was observed for chestnut oak and the white oak/hickory group (Fig. 2) with higher sprouting in the RV than in the AP in all the treatments. The white oak/hickory group had no stumps with competitive sprouts on the AP and less than 30% in the RV (Fig. 2). In contrast, in the red maple and mixed mesic species groups, there was no consistent pattern in the proportion of stumps that produced competitive sprouts between the RV and the AP (Fig. 2). In these species groups the number of stumps that produced competitive sprouts varied more by treatment.

The proportion of stumps that produced competitive sprouts was also affected by the harvesting treatments (Fig. 2). Averaged across all species groups, the proportion of stumps with competitive sprouts on the AP ranged from 30% in the CC, to 16% in the LT and 14% in the SW. The impact of these treatments was more pronounced in the RV where the proportion of competitive sprouts declined from 57% in the CC to 20% in the LT and 27% in the SW. Among the oaks, fewer stumps produced competitive sprouts in the LT and SW compared to the CC. In the red oak group, the proportion of stumps with competitive sprouts on the AP ranged from 30% in the CC, to 16% in the LT and 14% in the SW. The impact of these treatments on the red oak group was even more pronounced in the RV where the proportion of competitive sprouts declined from 57% in the CC to 20% in the LT and 27% in the SW. In a similar manner, the proportion of white oak–hickory stumps with competitive sprouts was fewer in the LT (19%) and the SW (12%) compared to the CC (28%) in the RV. The midstory group followed the same general trend as the oaks in the RV with a lower proportion of stumps producing competitive sprouts in the LT and SW treatments (Fig. 2). In contrast to the oaks, no consistent trend was observed for the midstory group in the AP, and the red maple and the mixed mesic groups on the AP and RV (Fig. 2). Red maple had the highest overall percent of stumps with competitive sprouts and there was no consistent pattern associated with treatment. All treatments except the SW in the RV had competitive stump sprout means above 40% with two treatments above 60%. There was also no consistent pattern among treatments in the mixed mesic group. The highest proportion of stumps that produced competitive sprouts in the midstory group was in the RV CC, although in the AP, the CC produced the least proportion of competitive sprouts.

### *4.3. Effects of residual basal area on stump sprouting*

Regression analysis showed residual basal area to be negatively correlated with the percentage of stumps that sprouted in the red

**Table 4**
Mean number of total sprouts, and codominant and dominant sprouts per clump, for those stumps which sprouted, by species group compared among treatments and between physiographic province 9–11 years after harvest.

| Spp. group | Treatment | Total number of stumps | | Average number of sprouts per stump | | Average number of dominant and codominant sprouts per stump | |
|---|---|---|---|---|---|---|---|
| | | Plateau | Ridge and Valley | Plateau | Ridge and Valley | Plateau | Ridge and Valley |
| | | *n* | *n* | Mean ± S.E. | Mean ± S.E. | Mean ± S.E. | Mean ± SE |
| Red oak group | CC | 72 | 90 | 5.5 ± 0.55 AB* | 3.6 ± 0.22 | 3.6 ± 0.38 A* | 2.3 ± 0.19 A |
| | LT | 66 | 77 | 5.9 ± 0.99 A* | 3.3 ± 0.39 | 4.0 ± 1.09 A* | 2.4 ± 0.37 AB |
| | SW | 89 | 134 | 4.2 ± 0.69 B | 3.0 ± 0.26 | 2.4 ± 0.41 B | 1.6 ± 0.15 B |
| Chestnut oak | CC | 44 | 107 | 3.8 ± 0.49 | 4.8 ± 0.26* | 2.6 ± 0.35 | 2.6 ± 0 17 |
| | LT | 29 | 87 | 3.9 ± 0.77 | 4.4 ± 0.29 | 2.8 ± 0.85 | 2.4 ± 0.16 |
| | SW | 28 | 116 | 4.0 ± 2.07 | 4.3 ± 0.35 | 1.7 ± 0.33 | 2.3 ± 0.25 |
| Red maple | CC | 264 | 73 | 6.2 ± 0.36 A | 6.6 ± 0.60 | 3.8 ± 0.27 A | 3.7 ± 0.41 A |
| | LT | 162 | 66 | 5.9 ± 0.40 AB | 6.8 ± 0.53 | 3.8 ± 0.37 A | 3.4 ± 0.34 A |
| | SW | 268 | 48 | 4.9 ± 0.32 B | 6.2 ± 0.67 | 2.6 ± 0.18 B | 2.7 ± 0.26 B |
| White oak/hickory | CC | 24 | 45 | – | 3.2 ± 0.37 | – | 2.4 ± 0.27 |
| | LT | 16 | 85 | – | 2.8 ± 0.44 | – | 2.0 ± 0.32 |
| | SW | 18 | 54 | 3.0 | 3.1 ± 0.41 | – | 1.8 ± 0.31 |
| Mixed mesic | CC | 190 | 15 | 4.3 ± 0.33 | 4.7 ± 0.28 | 2.8 ± 0.58 | 3.4 ± 0.124 A |
| | LT | 222 | 29 | 3.9 ± 0.27 | 3.7 ± 0.42 | 2.9 ± 0.29 | 2.7 ± 0.29 AB |
| | SW | 250 | 27 | 4.1 ± 0.35 | 3.1 ± 0.34 | 2.6 ± 0.50* | 1.6 ± 0.15 B |
| Midstory | CC | 264 | 223 | 4.5 ± 0.35 | 4.3 ± 0.88 A | 2.8 ± 0.22 | 4.5 ± 0.50 A* |
| | LT | 433 | 160 | 3.6 ± 0.34 | 4.3 ± 1.08 AB | 2.3 ± 0.25 | 3.0 ± 0.53 AB |
| | SW | 233 | 226 | 4.1 ± 0.23 | 3.0 ± 1.00 B | 2.5 ± 0.15 | 1.5 ± 0.50 B |

Letters signify differences among treatment means within a species group ($\alpha < 0.05$).

* Signify differences between physiographic province means within species group ($\alpha = 0.05$).

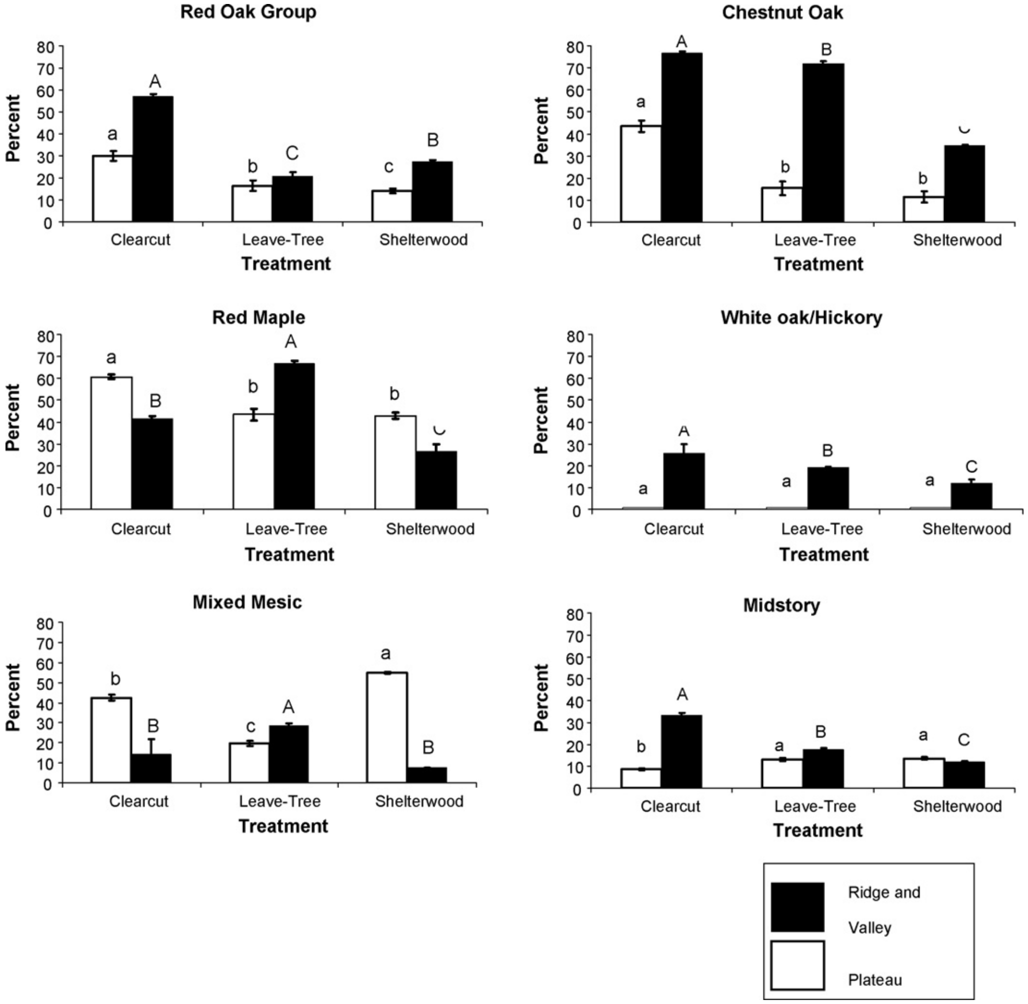

**Fig. 2.** Percent of stumps which produced dominant and codominant sprouts 9–11 years after harvest by species group among treatments. Capital letters signify a difference ($\alpha = 0.05$) among treatment means in the Ridge and Valley. Lower case letters signify a difference ($\alpha = 0.05$) among treatment means on the Appalachian plateau.

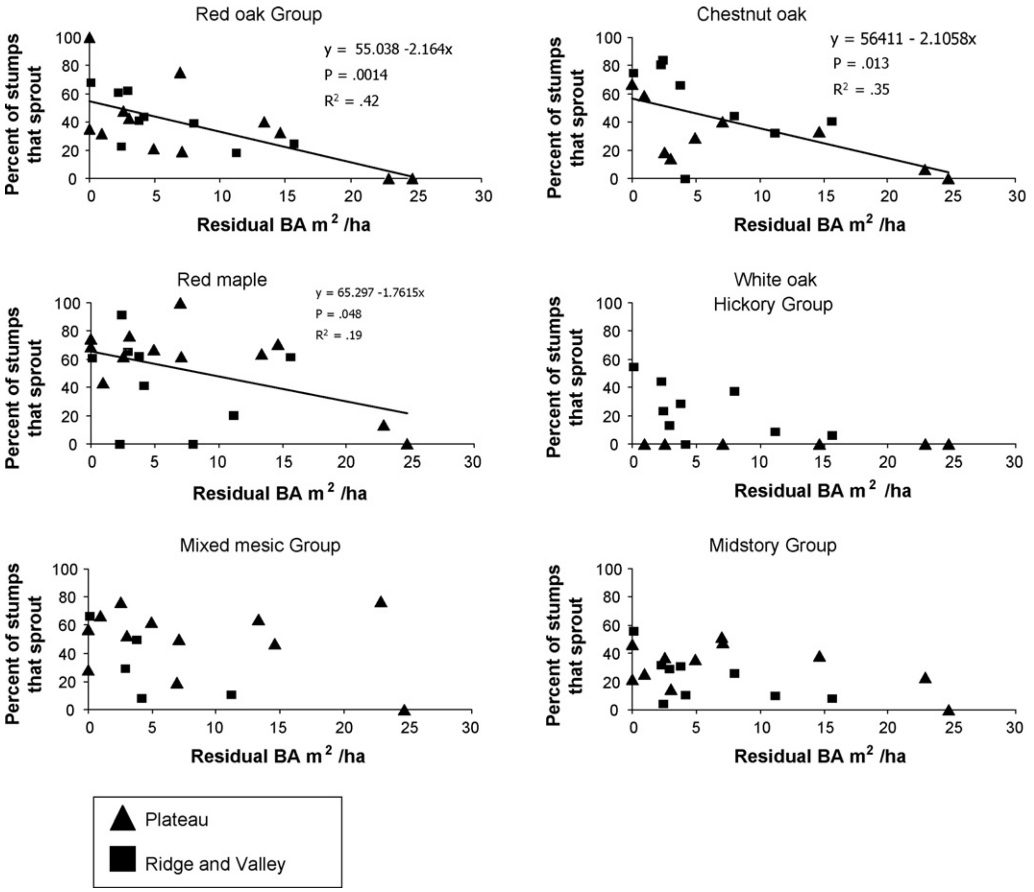

**Fig. 3.** Regression of percent of stumps that sprouted 9–11 years after harvest by residual basal area (m$^2$/ha) for species groups. Trend lines, equations, and $R^2$ values are displayed for significant ($\alpha = 0.05$) relationships. Each point represents the data for a 24 m × 24 m tree plot.

oak, chestnut oak, and red maple groups (Fig. 4). The regression analysis indicates that approximately 55% of the stumps of red oak and chestnut oak would sprout in a clearcut where there was no residual basal area. A significant drop in the percent of stumps which sprouted occurred when there were residual trees left following harvest, such as in the LT and SW treatments. Sprouting of the red oak and chestnut oaks decreased around 2% for each 1 m$^2$/ha increase in residual basal area (Fig. 4). Red maple followed a similar trend, with a reduction of just less than 2% for each 1 m$^2$/ha increase in residual basal area. There was no relationship between the residual basal area and the proportion of stumps that sprouted in the white oak, mixed mesic, and midstory species groups (Fig. 3).

For most of the species examined in this study, there was no relationship between the number of sprouts per stump and the residual basal area left in the stand (Fig. 4). An exception occurred in chestnut oak where the number of sprouts per stump decreased as residual basal area increased.

## 5. Discussion

The proportion of stump that sprouted in the clearcuts in our study was similar to what has been reported in other studies. Sprouting in chestnut oak was the most prolific among the oaks, which has also been observed in several other studies (Cook et al., 1998; Weigel and Johnson, 1998; Campbell, 1965). In the red oak group, the intercept of the regression analysis indicates that about 55% of the stumps would sprout in a clearcut which is similar to the first year stump sprout survival observed by Weigel and Johnson (1998). Since the plots in our study were 9–11 years old, this suggests that most of the stumps that initially sprout survive until the beginning of the stem exclusion stage. The number of spouts per stump observed in our study was also similar to that reported by Johnson (1975).

In both physiographic provinces there were more competitive sprouts per stump in the CC than in the LT or the SW. The decline in sprouting was greatest in chestnut oak which has important implications for regeneration of this species, which normally has high rates of sprouting (Cook et al., 1998; Weigel and Johnson, 1998). All oak sprouting declined around 2% for each 1 m$^2$/ha increase in residual basal area. This suggests that increased residual basal area reduces both sprouting frequency and vigor. A reduction in stump sprouting of this magnitude could have serious impacts on chestnut oak's ability to perpetuate itself in these stands. The low rates of sprouting on the AP in general and especially in the LT and SW indicate that stump sprouting may not be a reliable source of regeneration for chestnut oak in these systems on similar sites in this region.

The white oak/hickory group sprouted very poorly in all of the treatments. In the RV, only around 30% of the stumps sprouted in the clearcut which is similar to what Weigel and Johnson (1998) found for white oak under similar conditions. This suggests that sprouting is not a reliable source of regeneration for these species under similar stand and management conditions.

Unlike the oaks, sprouting of red maple, the mixed mesic species group, and the midstory species groups did not consistently decrease in the partial harvesting systems. In all three of these species groups, higher proportions of stumps produced competitive sprouts in the partial harvests than in the clearcut. In contrast, there was a large reduction in oak sprouting in these

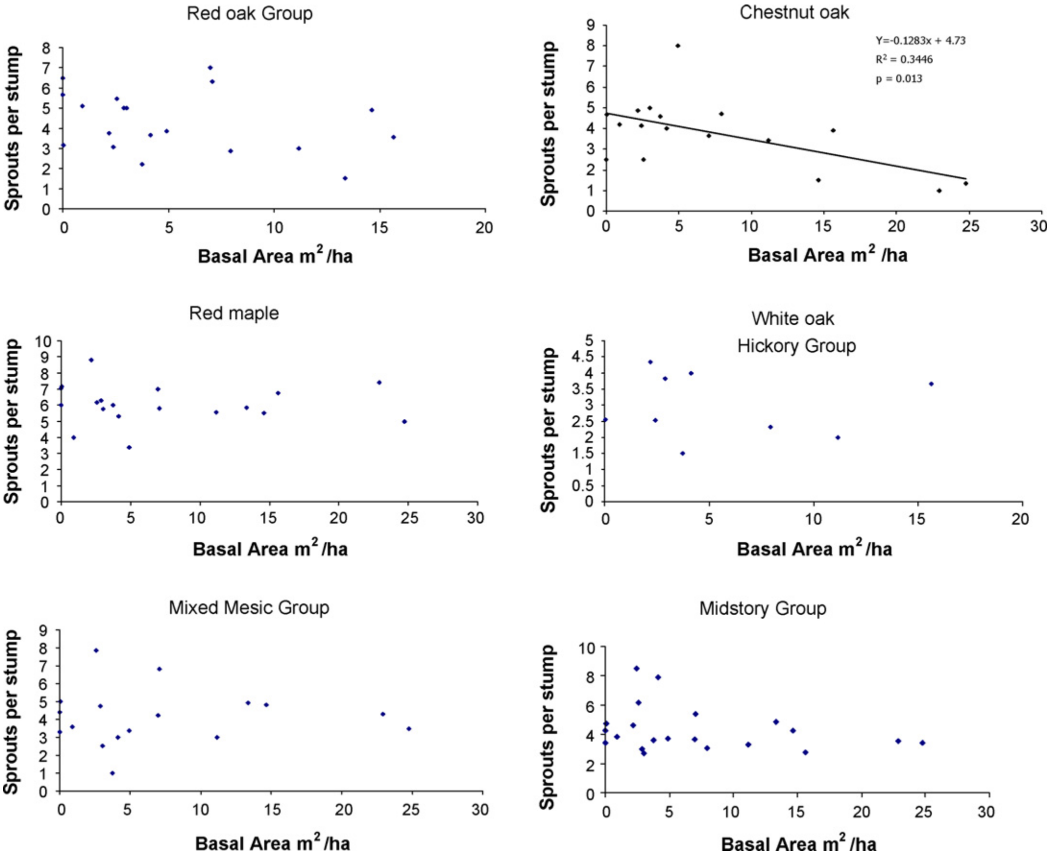

**Fig. 4.** Regression analysis of the number of all sprouts per stump by the residual basal area ($m^2$/ha) for each species group 9–11 years after harvest. Trend lines, equations, and $R^2$ values are displayed for significant ($\alpha = 0.05$) relationships.

treatments. Because sprouting of species such as red maple remains higher than the oaks when a leave-tree or shelterwood regeneration system is implemented, it is likely that this species and others in the mixed mesic and understory species groups will increase in abundance in future stands managed under these partial harvest systems. Also the oak component of these stands will likely decline as well.

The decrease in sprouting of the oaks in the partial harvests may be attributed to lower light levels. However, Lorber (2002) concluded that the clearcut had higher light levels than the leave-tree and shelterwood, but the leave-tree and shelterwood had similar light levels. The light level differences could explain the stump sprouting differences between the CC and the alternative treatments, but not the difference seen between the alternatives. A cause of the reduction in spouting for the oak species in stands where partial harvesting leaves residual trees in the stand could lie in oak's ability to root graft (Lyford, 1980). Other trees have been shown to affect cut stumps through root grafting (Loehle and Jones, 1990). Root grafts may reduce sprouting and vigor of cut stumps because of competition for water and nutrients, and chemical communication through these grafts (Bormann, 1966; Kozlowski and Cooley, 1961; Loehle and Jones, 1990). Uncut trees can take the nutrients and carbohydrates stored in the root systems of trees which have been harvested via root grafts creating a parasitic relationship through the grafts (Bormann, 1966; Loehle and Jones, 1990).

Residual trees connected to cut stumps through root grafts can influence stump sprouting. Stump sprouts are produced from dormant buds near the base of a cut stump (Johnson et al., 2002). Dormant buds are buds that developed in leaf axils and therefore are still connected to the tree's pith (Kozlowski and Pallardy, 1997). These buds are kept dormant through a hormonal feedback mechanism from dominant apical meristems. That results in low concentrations of auxin (IAA), a growth promoter, and high levels of abscisic acid (ABA), a growth inhibitor. When the dominant meristem is removed these hormonal feedbacks are removed and the dormant buds at the base of the tree become active, divide and expand to form stump sprouts. Apical meristems of residual trees which are connected to the cut stumps through root grafts could maintain hormonal control and decrease the sprouts vigor. They may even inhibit the formation of stump sprouts in stands that have undergone partial harvesting treatments as this study demonstrated.

All of these impacts on stump sprouting must be considered when implementing alternative silvicultural treatments. The treatments all serve specific sets of goals; but by relying on regeneration sources from more traditional silvicultural methods which do not leave residuals in the stand, managers may in fact not have an accurate representation of the regeneration potential for target species. It has been shown that the most competitive form of regeneration for oaks on fair quality sites in the southern Appalachians is stump sprouting. If the density and vigor of sprouts are reduced by partial harvesting systems, species shifts can be expected under these systems. This study presented strong evidence all oak species with the exception of white oak, regardless of initial sprouting rates, exhibit around a 2% reduction in sprouting as residual basal area is increased by 1 $m^2$/ha. White oak did tend to follow this however the relationship was not significant. These same effects are not seen in oak's main competitors on these sites. Maple's sprouting peaked in a partial harvest treatment where red oak group's sprouting saw the largest reduction. The mixed mesic species also showed no effect from residual basal area and peaked in shelterwood which had the lowest sprouting percentages of all oak species. This a serious concern on sites where oak is being replaced by other more mesic species such as yellow-poplar, which do not show similar effects or nearly as strong of an effect from these partial harvesting systems. This suggests alternative silvicultural systems, such as a LT and SW, are not fostering favorable conditions to regenerate oak because stump sprouts, the traditional source of regeneration in this region, are negatively affected by the residual trees.

The results of this study suggest that on fair to good quality sites in the southern Appalachians, silvicultural systems which retain residual trees can significantly reduce the number of harvested oak stumps which sprout. This must be taken into consideration when deciding which silvicultural systems are to be used in this region. Alternative systems which retain residuals will likely cause a shift in species composition of the future stand, especially if they negatively affect the most competitive form of regeneration for that species. This will be more important for oak dominated stands where stump sprouts are among the most important form of oak regeneration (Johnson et al., 2002). It will be more important in stands such as the ones in our study that lacked significant quantities of advanced regeneration prior to harvest (Lorber, 2002).

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