REGENERATION MICROSITES AND RESOURCE LEVELS RESULTING FROM A RANGE OF SILVICULTURAL TREATMENTS IN TENNESSEE OAK-HICKORY FORESTS

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Abstract—Regeneration microsites were investigated by measuring photosynthetically active radiation (PAR), soil moisture, nutrients, and understory vegetation in (1) uncut controls and plots with partial cutting to either 50, 25, or 12.5 percent of original basal area, (2) commercial clearcuts, and (3) silvicultural clearcuts. Treatments and controls were replicated in north-facing, south-facing, and ridgetop blocks within mature oak-hickory forest. Abundance and height of herb species increased with decreases in residual basal area and shaded the regeneration layer in clearcuts. Mean percent full PAR was 3.8, 41.0, 70.0, 77.4, 81.8, and 86.7 percent in the uncut, 50 percent, 25 percent, 12.5 percent, commercial clearcut, and silvicultural clearcut plots, respectively. A regression equation ($p < .0001$, $r^2 = .91$) was developed that relates percent full PAR to basal area. No significant differences in moisture or nutrients occurred between treatments. This was likely due to high spatial variability in these resources and above-average precipitation during the study.

INTRODUCTION

Apart from direct effects, such as the removal of competing stems and the addition of stems through planting, desired results of hardwood regeneration practices are often obtained through indirect effects on basic factors and resources such as growing space, temperature, light, soil moisture, and nutrients. Although a number of proven and promising prescriptions have resulted from the substantial body of silvicultural research conducted up to the present (e.g., Brose and others 1999, Johnson and others 1986, Loftis 1990, Weigel and Johnson 2000), our understanding of the mechanisms underlying the degree of success or failure achieved with a given silvicultural alternative in a given stand is often incomplete. Further, specific levels of light, soil moisture, or nutrients that optimize establishment, growth, and survival during regeneration have yet to be identified for many hardwood species. It can be argued that variation in these basic factors can influence the results of the same regeneration treatment from region to region, and that identification of precise target levels of basic factors would expedite the adaptation of regeneration practices for different regions.

As hardwood regeneration research progresses, it is becoming increasingly recognized that the key to guiding the process of hardwood regeneration toward desired outcomes lies in understanding the physiology of oak and other hardwood species and the differential response of these species to subtle changes in basic factors (e.g., Dickson and others 2000, Gardiner and Hodges 1998, Kolb and Steiner 1990, Lockhart and others 2003). Studies of hardwood tree physiology involve variables, such as photosynthetically active radiation (PAR), that are related to but not easily converted into measures that are commonly used by field foresters to implement silvicultural treatments, such as basal area. The gap in variables that exists between the tree physiology and silviculture disciplines provides additional impetus for measurement of specific levels of light, soil moisture, nutrients, and other basic factors created by a given regeneration treatment in different stands and regions.

A replicated study was initiated in 2002 to investigate and demonstrate the effect of a range of silvicultural alternatives on the regeneration of hardwood species in the oak-hickory forest type in the Ridge and Valley Province of Tennessee. Objectives included long-term monitoring of natural regeneration in response to treatments and artificial regeneration with high-quality northern red oak seedlings planted before and after implementation of treatments. Additional objectives were to document light, soil moisture, nutrients, and the abundance and composition of competitors in the immediate vicinity of each planted northern red oak seedling. We could then identify optimum levels of these factors for artificial regeneration of this species, as well as the treatments in which these optimum conditions occurred. Results for planted oaks were not yet definitive in 2003 and thus will not be presented.

The specific objective of the portion of the overall study presented here was to establish levels of PAR, soil moisture, macronutrients, and vegetation in the immediate vicinity of planted oak nursery seedlings in six different silvicultural treatments: uncut (Control), 50 percent basal area retention (BAR), 25 percent BAR, 12.5 percent BAR, commercial clearcutting (CCC), and silvicultural clearcutting (SCC).

METHODS

This study was conducted at the University of Tennessee Forestry Experiment Station in Oak Ridge, TN (36.01° N, 84.26° W). Treatment blocks were established within a 30 ha oak-hickory forest that had experienced minimal disturbance in the 50 years prior to implementation of the study. Soils on the study site are moderately productive and belong to the Fullerton soil series.

A randomized complete block design was used for this experiment. Three blocks containing all treatments and an uncut control were delineated based on stand structure, forest composition, and landscape position. Variation between the blocks was primarily due to topographic position and aspect. All treatments and controls were randomly assigned to 1.6 ha plots, and treatments were implemented within all blocks in

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July, 2002. In order of decreasing canopy cover, treatments were: 50 percent BAR, 25 percent BAR, 12.5 percent BAR, CCC, and SCC.

Stands with 50, 25, and 12.5 percent BAR were marked with the general guideline of creating uniformly distributed stands comprised of desirable trees. Species in the plots with reasonably high and high market value were: white oak (*Quercus alba* L.), chestnut oak (*Quercus montana* Willd.), yellow-poplar (*Liriodendron tulipifera* L.), northern red oak (*Quercus rubra* L.), black oak (*Quercus velutina* Lam.), and southern red oak (*Quercus falcata* Michx.). Trees in the 36 to 46 cm d.b.h. category were favored for retention, but trees in other size classes were retained as necessary to maintain an even distribution across all of the treatment units (Olson 2003). Blocks one, two, and three were located on a north-facing slope, flat ridge top (generally), and south-facing slope, respectively. Plots within blocks were generally arranged in a linear fashion, parallel to the contour of the slope.

In the spring of 2003, 60 northern red oak nursery seedlings were planted on a 6.1 x 6.1 m spacing within all 6 plots in each of the 3 replicate blocks, which resulted in a total of 1,080 seedlings planted in the study. Seedling planting locations were concentrated near the center of each plot with a 20.1 m buffer left between the outermost seedlings and the plot edge in order to minimize edge effects. Since microsite conditions experienced by each seedling were of interest, seedling planting locations were used as the focal points for all measurements of PAR, soil moisture, nutrients, and vegetation.

PAR was measured immediately above the terminal leader of each seedling within all six treatments and all three blocks. Overall mean heights of seedlings at the time of planting and at the end of the 2003 growing season were 131 and 154 cm, respectively. PAR measurements were taken mid-May, mid-June, mid-July, and mid-August of 2003 within three 2-hour periods during the day: morning, noon, and afternoon. All measurement periods were centered around solar noon on each measurement date. For example, if solar noon occurred at 1:33 p.m. local time, noon measurements were taken from 12:33 to 2:33 p.m., morning measurements were obtained from 9:33 to 11:33 a.m., and afternoon measurements were obtained from 3:33 to 5:33 p.m.

Two Decagon Accupar Ceptometers (Decagon Devices, Pullman, WA) were used to collect all measurements of PAR. One Ceptometer was used to measure PAR within treatment plots and uncut controls. The second Ceptometer was programmed to log data in an unattended mode and placed on a tripod in either of 2 large openings that were located within 400 m of all measurement locations within the treatment plots. Synchronous measurements of PAR were obtained with the Ceptometer placed in the open and the Ceptometer carried between treatment plots for the purpose of calculating percent full PAR. This methodology eliminated the confounding effects of changes in incoming PAR resulting from time of day and minimized effects of intermittent cloud cover.

Soil moisture to a depth of 15 cm was measured in units of percent volumetric soil moisture with a portable Trase Time Domain Reflectometry (TDR) probe (Soilmoisture Corp., Goleta, CA). Measurements were taken 15 cm from the base of each planted seedling in the latter half of May, June, July, and August, 2003.

Macronutrient availability was quantified at the treatment level with Plant Root Simulator (PRS™) probes (Western Ag Innovations Inc., Saskatoon, SK). Sixteen PRS™ probes were systematically inserted into the soil 15 cm from the base of 16 northern red oak seedlings within each control and treatment plot. Eight of the PRS™ probes within each plot were negatively charged to adsorb cations, and the remaining eight were positively charged to adsorb anions. All PRS™ probes were placed in the field in mid-August and retrieved in mid-October, followed by analysis of each PRS™ probe for nitrate, ammonium, calcium, magnesium, potassium, phosphorus, iron, manganese, copper, zinc, borate, sulfur, lead, and aluminum by the manufacturer.

Potential competitors above and adjacent to 10 randomly selected northern red oak seedlings per treatment plot and control were sampled within each block during September, 2003. As a result, vegetation was measured in the immediate vicinity of a subset of 180 planted seedlings. Overstory basal area was measured with a 10-factor prism using the planted oak seedling as plot center. Percent cover of herbaceous vegetation alone and herbaceous and woody vegetation combined were estimated using a model c concave spherical densiometer (Lemmon Forest Densiometers, Bartlesville, OK) held just above the terminal leader of each planted oak seedling. All woody species were tallied using 3 height classes: 0 to 50 cm, 51 to 149 cm, and >150 cm. All woody stems 0 to 50 cm and 51 to 149 cm tall were sampled within a 1 m radius of a given planted oak seedling, and all stems >150 cm tall were sampled within a 2 m radius of a given planted oak.

Analysis of variance appropriate for a randomized complete block design was performed to explore treatment effects on PAR, soil moisture, macronutrients, and vegetation. Tukey's HSD was used for pair-wise comparisons. Simple linear regression was also used to investigate the relationship between percent full PAR and basal area. All tests were conducted with $\alpha = 0.05$.

RESULTS

Treatment implementation created a full spectrum of basal areas ranging from a mean of 29.1 m^2/ha in the uncut controls to 0.9 m^2/ha in the silvicultural clearcuts (fig. 1). Percent full PAR received by the six different treatments increased as basal area and canopy cover decreased (fig. 2). On average, the uncut controls received the least percentage of full PAR (3.8 percent), and the SCC treatments received the greatest percentage (86.7 percent). Tukey's mean separation technique revealed significant increases in percent full PAR with each increasing level of basal area and canopy cover removal, except in the case of the CCC, which did not differ significantly from the 25 percent BAR or SCC treatments (fig. 2). Mean percent full PAR for the north-facing block was lower than mean percent full PAR measured in the ridgetop and south-facing blocks.

Although values for the means in the treatments were 2 to 4 percent greater than mean percent volumetric soil moisture in the uncut controls, these differences were not significant (fig. 3). Mean percent volumetric soil moisture ranged from 13.0 percent in the uncut controls to 17.7 percent in plots with 50 percent BAR. Total precipitation in June, 2003, was lower than the seasonal average for the study region, but amounts of precipitation in May, July, and August were substantially greater than the seasonal average in 2003.

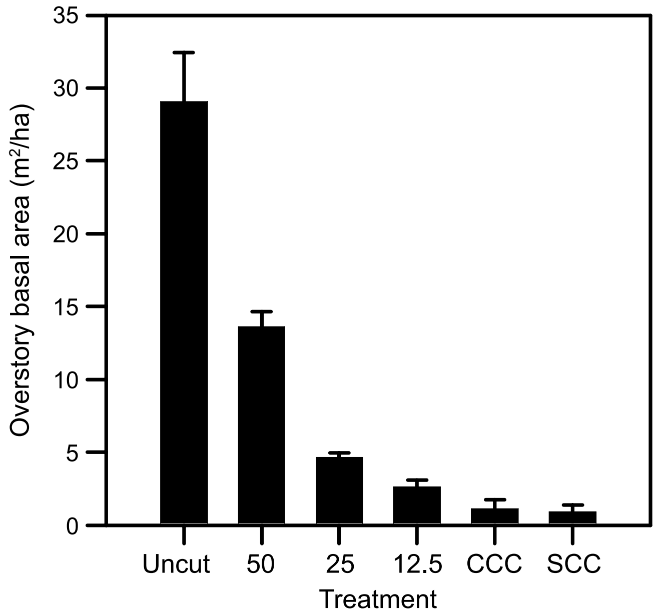

Figure 1—Mean post-treatment overstory basal area in uncut controls and treatments in 2003 in the silvicultural alternative study at the University of Tennessee Forestry Experiment Station, Oak Ridge, TN. Error bars represent 1 standard error. Uncut = uncut control, 50 = 50 percent basal area retention, 25 = 25 percent basal area retention, 12.5 = 12.5 percent basal area retention, CCC = commercial clearcut, and SCC = silvicultural clearcut.

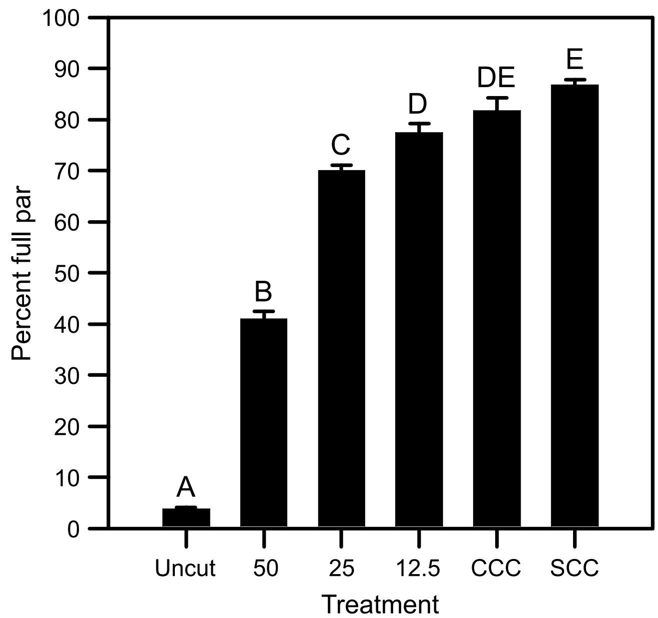

Figure 2—Mean percent full PAR in uncut controls and treatments in 2003 in the silvicultural alternative study at the University of Tennessee Forestry Experiment Station, Oak Ridge, TN. Means with the same letter are not significantly different at $\alpha = 0.05$. Error bars represent 1 standard error. Uncut = uncut control, 50 = 50 percent basal area retention, 25 = 25 percent basal area retention, 12.5 = 12.5 percent basal area retention, CCC = commercial clearcut, and SCC = silvicultural clearcut.

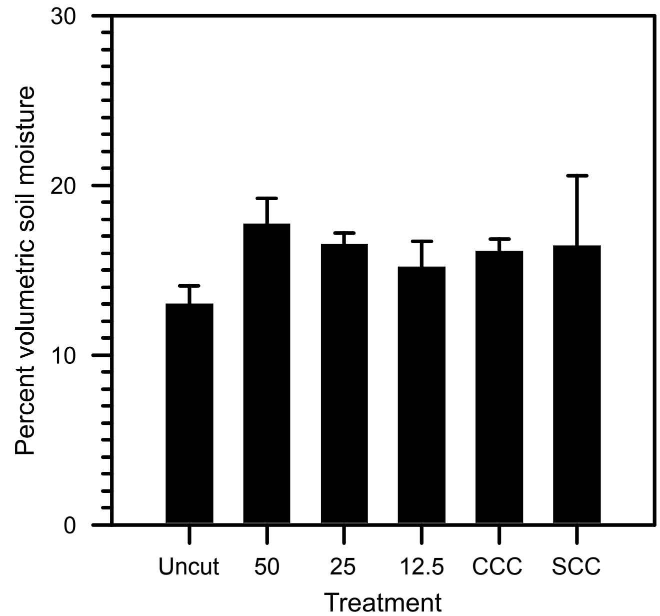

Figure 3—Mean percent volumetric soil moisture in uncut controls and treatments in 2003 in the silvicultural alternative study at the University of Tennessee Forestry Experiment Station, Oak Ridge, TN. Error bars represent 1 standard error. Uncut = uncut control, 50 = 50 percent basal area retention, 25 = 25 percent basal area retention, 12.5 = 12.5 percent basal area retention, CCC = commercial clearcut, and SCC = silvicultural clearcut.

No significant differences in macronutrients were detected between treatments. There was a slight trend toward greater amounts of nitrate in the treatment plots than in the uncut controls, but variability between blocks in nitrate levels was very high (fig. 4).

Results for mean percent herbaceous and woody cover measured above each planted oak seedling with a densiometer in September, 2003, revealed that the proportion of percent cover overtopping oak seedlings comprised of herbaceous species generally increased with decreasing levels of basal area (table 1). A mean value of 0 percent herbaceous cover overtopped planted oak seedlings in the uncut controls, and the greatest mean percent cover of herb species occurred in the CCC treatment. Of the herbaceous vegetation overtopping the northern red oak seedlings in this study, 54 percent was fireweed (*Erechtites hieracifolia* L.), 38 percent was horseweed (*Erigeron canadensis* L.), and the other 8 percent was either pokeweed (*Phytolacca americana* L.) or wild lettuce (*Lactuca* spp. L.). The density of woody competitors 0 to 50 cm tall in the vicinity of planted oak seedlings was significantly greater in the 50 percent BAR treatment than in the uncut controls (table 2). However, no significant differences were detected between the treatments and controls in the density of woody competitors in the 51 to 149 cm and >150 cm size classes.

The amount of basal area retained within treatments was highly correlated with percent full PAR measured in the understory of treatments. Results of regression analysis indicated that nearly 91 percent of the variation in the percent full PAR received within a given treatment can be explained by the basal area of that treatment (fig. 5). Actual PAR values change from minute to minute and across the growing season, but mean PAR values calculated across all 4 measurement months

Table 1—Mean percent cover of woody vegetation, herbaceous vegetation, and open sky above planted oak seedlings by treatment in 2003 in the silvicultural alternative study at the University of Tennessee Forestry Experiment Station, Oak Ridge, TN

Treatment[a]	Woody vegetation	Herbaceous vegetation	Open sky
	- - - - - - - - *percent cover* - - - - - - - -		
Control	88	0	12
50 % BAR	35	1	64
25 % BAR	17	7	76
12.5 % BAR	27	5	68
CCC	10	12	78
SCC	6	5	89

[a] BAR = basal area retention; CCC = commercial clearcut; SCC = silvicultural clearcut.

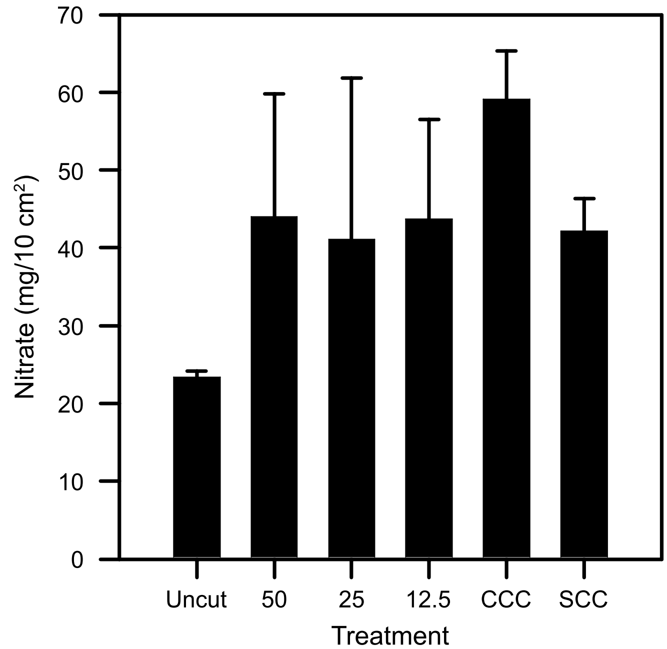

Figure 4—Mean amounts of nitrate in uncut controls and treatments in 2003 in the silvicultural alternative study at the University of Tennessee Forestry Experiment Station, Oak Ridge, TN. Error bars represent 1 standard error. Uncut = uncut control, 50 = 50 percent basal area retention, 25 = 25 percent basal area retention, 12.5 = 12.5 percent basal area retention, CCC = commercial clearcut, and SCC = silvicultural clearcut.

Table 2—Mean density of woody stems in the immediate vicinity of planted oak seedlings by treatment and height class in 2003 in the silvicultural alternative study at the University of Tennessee Forestry Experiment Station, Oak Ridge, TN

	Height class		
Treatment[a]	0-50 cm	51-149 cm	> 150 cm
	- - - - - - - - - - - - - - - - - - *stems/ha* - - - - - - - - - - - - - - - - - -		
Control	56,582 (6,856)[b]B[c]	4,459 (1,505)A	18,843 (4,465)A
50% BAR	130,149 (2,4571)A	5,308 (2,131)A	9,289 (3,388)A
25% BAR	114,225 (16,657)AB	7,113 (2,791)A	10,616 (2,955)A
12.5% BAR	114,756 (8,495)AB	5,839 (1,860)A	6,369 (1,657)A
CCC	120,173 (12,827)AB	4,618 (1,805)A	6,900 (3,909)A
SCC	115,180 (3,996)AB	5,626 (1,914)A	6,369 (1,657)A

[a] BAR = basal area retention; CCC = commercial clearcut; SCC = silvicultural clearcut.
[b] One standard error is presented in parentheses.
[c] Within height classes, means with the same letter are not significantly different at $\alpha = 0.05$.

were 46, 429, 798, 907, 941, and 1,085 µmoles m^{-2} s^{-1} in the uncut controls, 50 percent BAR, 25 percent BAR, 12.5 percent BAR, CCC, and SCC treatments, respectively.

DISCUSSION AND CONCLUSIONS

The result of significant increases in percent full PAR with increased levels of basal area removal was intuitive as a reduction in canopy cover and leaf area that would intercept incoming PAR should accompany removal of basal area. However, the most substantial differences in percent full PAR existed primarily between the controls and overstory treatments with greater canopy cover (that is, 50 percent BAR, and 25 percent BAR). Increases in mean percent full PAR were relatively minor, and some variances were greater in treatments with < 25 percent BAR. Further, mean percent full PAR in CCCs was not significantly different from that in 12.5 percent BAR, or that in SCCs. The fact that mean percent full PAR did not reach 100 percent in either the CCCs or SCCs is likely a

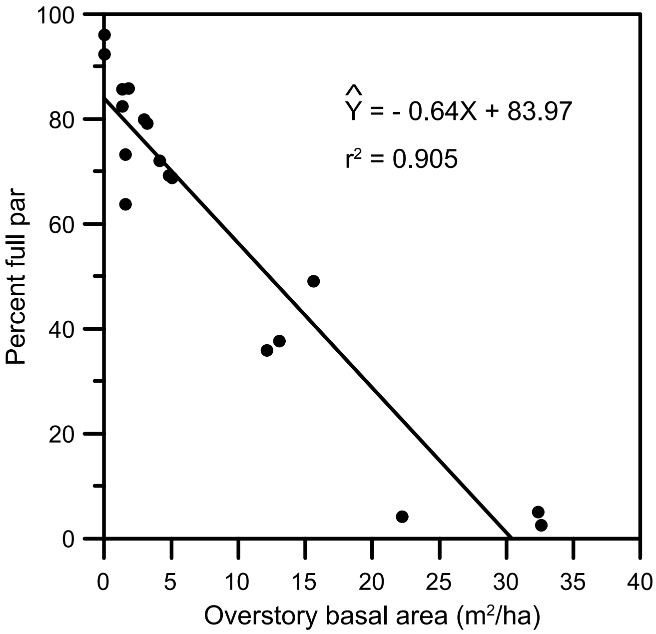

Figure 5—Scatter plot of percent full PAR versus overstory basal area with regression line and equation based on measurements obtained in uncut controls and treatments in 2003 in the silvicultural alternative study at the University of Tennessee Forestry Experiment Station, Oak Ridge, TN.

function of the height above the ground at which PAR measurements were taken and the influence of stump sprouts, small residual stems, and tall herbaceous vegetation that occurred in the clearcuts. PAR was not measured at various heights to obtain vertical profiles in PAR in this study, but it is very likely that seedlings smaller than the planted oaks receive < 86.7 percent full PAR. Horizontal patchiness in the regeneration layer of clearcuts is fairly common 1 to 2 years after cutting, and the greater variance in percent full PAR observed in the 12.5 percent BAR and CCCs was likely due to variability in the distribution of sprout clumps, residual stems, and effects of down wood and seedbed conditions on the germination and growth of herbaceous and woody vegetation.

The lack of significant differences in percent volumetric soil moisture could have resulted from above-average precipitation during the 2003 growing season and perhaps from variability in soil moisture between blocks. Although differences were not statistically significant, the lower mean value for soil moisture in the uncut controls than in the treatments is consistent with previous research in which cutting led to short-term increases in soil moisture. Using the same instrument and measurement protocol on drier, coarse-textured soils in northern Lower Michigan, Buckley and others (1998) demonstrated significantly greater volumetric soil moisture in partially cut and clearcut northern red oak and red pine stands over the first two growing seasons following treatment implementation.

It is likely that high variability in macronutrients within and between blocks was responsible for the lack of significant differences in measured amounts of macronutrients between treatments. The inherent patchiness in down wood, litter, forest floor disturbance, and other factors influencing nutrient dynamics probably contributed to the high variability in nitrate and other macronutrients within the treatments as opposed to the controls. Although no differences were significant and variances were high, the trend toward greater amounts of nitrate in the treatments than in the controls is consistent with the greater decomposition and nitrogen mineralization that might be expected in recently harvested stands (Vitousek and Matson 1984). A more intensive sampling effort may have revealed statistically significant differences between treatments and controls for some macronutrients, and it is clear that in conjunction with variability in light, patchiness in nutrients may contribute to within-treatment variation in the performance of tree seedlings and saplings.

Results for herbaceous and woody competitors in the immediate vicinity of planted oak seedlings suggest that release of regenerating seedlings from competition with overstory trees for resources is at least partially attenuated by increased competition with herbs and woody stems in the regeneration layer. In this study, fireweed and horseweed were very abundant in treatments with little or no canopy cover, and the development of these species over the growing season was reflected in decreases in percent full PAR measured immediately above planted oaks within these treatments from May to August. In fact, many planted oaks received 100 percent full PAR in May and June in treatments with little or no residual basal area but were overtopped by fireweed and horseweed by the end of the growing season. Whether these species or completely different suites of herbaceous species develop in treatments with low residual basal area depends on species composition of the seed bank and local seed sources. It can be argued that differences in the composition of herb species could result in different outcomes of a regeneration treatment from region to region. The development of the herbaceous layer in response to overstory treatments and competitive effects of different herbaceous species on tree regeneration warrant further investigation.

The significantly greater abundance of woody stems in the 0-50 cm height class in the 50 percent BAR treatment than in the controls and lack of significant differences between the remaining treatments and controls for this size class suggest that increased levels of logging disturbance and perhaps fewer seed sources in treatments with low residual basal area may have offset the positive effects of increased levels of percent full PAR. The lack of significant differences in the density of stems 51 to 149 cm tall and ≥ 150 cm tall may have also been due to logging disturbance and an insufficient amount of time for regenerating stems to enter these larger size classes following treatment implementation. Based on follow-up visits to the study sites in 2004 and 2005, this situation is changing rapidly as stump sprouts continue to develop.

The strong relationship between percent full PAR and overstory basal area indicated by the regression results suggests that managers could use this relationship as a guide in selecting an appropriate amount of basal area retention in order to achieve a specified level of percent full PAR in the understory of oak-hickory forests similar to those studied. Percent full PAR and basal area relationships for additional forest types would be useful, although the relationship may be weaker in stands with more complex canopy structure, such as old-growth northern hardwoods. Strong relationships between mean percent full PAR and basal area were demonstrated by Buckley and others (1999) in northern red oak and red pine stands. Slopes of the regression equations varied with forest type. Due to differences between species in leaf placement and crown architecture (Horn 1971), it is likely that levels of percent full PAR achieved in the understory of stands reduced to a given level of basal area can vary with changes in canopy species composition. Thus, it is possible for the same prescription to result in different levels of PAR across stands differing in composition. The magnitude of these differences warrants further investigation, and additional work in this area is planned.

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