Logging Intensity Impact on Small Oak Seedling Survival and Growth on the Cumberland Plateau in Northeastern Alabama

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ABSTRACT

Ground disturbance caused by forest harvest operations can negatively impact oak regeneration. On the Cumberland Plateau, for successful regeneration, managers often must rely on very small (less than a ft in height) oak advance reproduction that is susceptible to disturbance by harvesting equipment. Furthermore, sites on the Plateau top are often harvested when conditions are too wet to permit operations elsewhere, increasing the risk to small seedlings that may be more easily pulled from the moist soil. This study was designed to assess the effect of unrestricted and restricted harvesting equipment traffic on small oak advance reproduction under a clearcutting prescription. A feller-buncher and grapple skidding were used to harvest sites under "free access," resulting in unrestricted traffic on the sites, or under "trail access," with restricted site traffic. Six hundred eighty-seven oak seedlings were permanently tagged (preharvest); species, height, and basal diameter were recorded and have been remeasured 1, 2, and 8 years postharvest. Fifty-two percent of the tagged seedlings survived after 8 years. The survival rate for seedlings exposed to restricted traffic did not differ from that for seedlings exposed to unrestricted traffic. No evidence of seedlings being pulled out of the ground was observed. After three growing seasons, there was no significant difference in visual site disturbance between the two treatments. After eight growing seasons, the status of the reproduction suggests that little damage was incurred under unrestricted equipment traffic.

Keywords: clearcutting, competition, Cumberland Plateau, disturbance, regeneration, reproduction

Forest harvest operations usually result in ground disturbances that may negatively impact regeneration. Concern over the detrimental impact that unrestricted harvest machinery has on soil physical properties and site productivity has been most extensively reported in southern pine stands (Reisinger et al. 1988). As upland hardwood forests on the rolling plateau surface of the mid-Cumberland (the portion of the Cumberland Plateau in 18 Tennessee counties and 3 northeast Alabama counties) have been degraded by generations of selective logging and other disturbances (Hart and Grissino-Mayer 2008), clearcutting is often the only viable management option (McGee 1986). Clearcutting on the slightly undulating to flat surface of the Plateau is most economical when implemented by mechanical harvesting; common equipment used includes feller-bunchers and rubber-tired grapple skidders. A common harvesting practice is to move operations to the Plateau top during winter logging when conditions are wetter, as the sandy soil and flat surface provide more suitable harvesting conditions than the side slopes of the area.

Soil disturbance may be exacerbated under wet soil conditions (Moehring and Rawls 1970, Aust et al. 1995, Greacen and Sands 1980). Site degradation issues were initially broached on these Plateau top sites during review for certification under the Sustainable Forestry Initiative (SFI; American Forest and Paper Association 1994). Topographic position and site conditions dictate expression of species dominance in these systems, often resulting in patchy distributions. With unrestricted equipment traffic on sites with few natural impediments, desirable reproduction may be adversely impacted as small clumps or patches are disturbed.

Regeneration of hardwood stands in similar upland systems has been documented in key studies by Loftis (1983, 1985, 1990), McGee (1967, 1975), McGee and Hooper (1970), Sander (1971, 1972), Sander and Clark (1971), and Sander et al. (1976). Studies have shown that advance reproduction of oak is necessary in obtaining oak as a component of the future overstory, and that successful growth of oak reproduction following a harvest is a function of the size of advance reproduction and the preexisting vegetation structure (Beck and Hooper 1986, Johnson et al. 2009, Loftis 1983, McGee 1975). Stump sprouts and advance reproduction must both be considered when evaluating the reproduction potential. On Cumberland Plateau sites, reproduction in larger size classes is nonexistent and constraints in time and resources prohibit developing small advance reproduction into larger size classes. As a result, managers rely on small reproduction (less than 1 ft in height) leading to uncertain regeneration. Understanding the physical effect of harvesting practices on these small seedlings may be useful for predicting future stand composition.

Current forest conditions on the Cumberland Plateau vary greatly (Hart and Grissino-Mayer 2008, Hinkle et al. 1993). Most poor quality stands are an artifact of past disturbances (both natural and artificial) or result from inherently low site productivity due to

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topography and geology. The most viable and often cost-effective option to improve poor quality stands on the better sites is through clearcutting.

Assessments of ground disturbances that result from silvicultural operations under site conditions similar to the Cumberland Plateau region have focused on physical site characteristics. Relevant studies for the mid-Cumberland do not exist. Studies from other areas that examined soil and litter displacement have described the surface soil conditions associated with forest operations conducted with the appropriate equipment (Aust et al. 1998, Dryness 1965, Greacen and Sands 1980, Green and Stuart 1985, Incerti et al. 1987, Miller and Sirois 1986, Reisinger et al. 1988). Few studies in the Cumberland Plateau region have focused on the impacts of harvesting traffic on small oak reproduction (Shostak et al. 2002).

This study was designed to assess the effect of restricted and unrestricted traffic by harvesting equipment on small oak advance reproduction following clearcutting. Because of the nature of sites on the Plateau top, clearcutting operations with a feller-buncher and grapple skidding usually allow the feller-buncher free access to all trees on the site and result in unrestricted traffic throughout the site. An alternative to this free-access technique is to designate trails of access and allow the feller-buncher to harvest only trees that can be reached from these trails. Trees are then bunched and placed on the trail for skidding. Current management objectives include maintaining the oak component while providing a complex and diverse species mix that will complement wildlife habitat requirements and objectives. The objectives of this study were to examine the soil surface disturbance under two harvest-traffic intensities, to document the response of small (< 1 ft tall) oak advanced reproduction, and to assess the overall composition and size of the reproduction cohort.

Methods

Study Area

The study site is located in Jackson County, Alabama and concentrates on a 20-acre area on the strongly dissected southern portion of the mid-Cumberland Plateau. The soils are mapped as Hartsells fine sandy loam rolling phase (fine-loamy, siliceous, subactive, thermic Typic Hapludults), which occur on undulating surfaces with slopes not exceeding 10% (Soil Survey Series 1954, Soil Survey Staff 2010). The soil is well-drained and low in fertility with a site index of 60 (base age 50) for the upland oaks (white oak, *Quercus alba* L.; scarlet oak, *Q. coccinea* Muench.; chestnut oak, *Q. montana* L.; and black oak, *Q. velutina* Lamarck) and 85 (base age 50) for yellow-poplar (*Liriodendron tulipifera* L.; Smalley 1982). Yellow-poplar typically occurs on concave surfaces on the Plateau (Smalley Land type 1, broad, undulating sandstone uplands (Smalley 1982)). Oak reproduction is usually prolific on these sites, although seedling height is often less than 2 ft. Clearcutting is commonly used for regenerating these sites because competition is sparse and oak advance reproduction numbers are greater than those found on more mesic (Plateau escarpment) sites.

Study Design

Two disturbance treatments were tested. Treatments were applied to 10 2-acre blocks, each 132 ft wide by 660 ft long and oriented east–west across the landscape, with 1 66-ft-wide strip assigned to each treatment. There was no buffer between treatments. Treatments were assigned systematically, alternating free access by the equipment (unrestricted traffic) with trail-only access (restricted traffic). The operator harvested the blocks systematically, starting at the northern end and working south. In the unrestricted traffic treatment, the operator of the feller-buncher (Hydro-Ax 611 Ex feller-buncher) was allowed to choose the shortest route when approaching the trees. When possible, the trees were skidded (John Deere 540 B skidder) after grouping by the feller-buncher. However, many were skidded from the fell point. In the restricted traffic treatment, the operator of the feller-buncher was allowed to select, cut, and bunch trees only from an access trail. This trail was then used for skidding. Whole trees were skidded to a central landing deck, topped, and limbed, and tops and limbs returned via the same skid trails. The entire 20-acre area was clearcut harvested by the same operator in the fall 2001/winter 2002, during the months of November through March. Of the 77.5 tons per acre of product removed, 72 tons per acre were hardwood pulpwood, 4 tons per acre were red oak sawtimber, and the remaining products were mixed sawtimber.

Data Collection and Analysis

Five measurement subplots per treatment block were systematically established at 110-ft intervals in the center of each block prior to treatment application. Main skid trails were not centrally located and, therefore, not included in these plots but ancillary skid areas were prevalent throughout each unit and each sample plot. Reproduction was sampled on 0.01-acre circular plots. Seedlings were tallied by species in 1-ft height classes, up to 4.0 ft tall, and then by dbh (dbh, ca. 4.5 ft above the surface.) Using the same subplot center, a 0.025-acre plot was used to record species and dbh for all trees with dbh greater than 1.6 in. for pretreatment only.

We selected 5–10 oak seedlings that were representative of the subplot and permanently tagged each with a brass tag. Data collected about these tagged oaks included species, distance and azimuth from plot center, height, and basal diameter. All reproduction data was collected in 2001, 2002, 2004, and 2009.

We assessed and recorded soil and litter displacement (disturbance) on the regeneration subplots immediately after harvesting in March 2002, and in the fall of 2003 and fall of 2004. We recorded the soil disturbance class (defined in Kluender and Stokes (1994)) and assigned a numerical disturbance score as untrafficked=0; trafficked with litter in place=1; trafficked with litter removed=2; trafficked with mineral soil exposed=3; or trafficked with mineral soil displaced to top of litter=4. At least one-third of the subplot had to be impacted for characterization. Additionally, we recorded the number and depth of soil depressions.

Precipitation and soil moisture data were obtained from the USDA Natural Resources Conservation Service (NRCS) NWCC Soil Climate Analysis Network (SCAN) site, located near Hytop, Alabama, in Jackson County, approximately 4 miles southwest of the study site. The Hytop site (number 2054) was established in 2002. Soil pedon characterization on site was Hartsells series; the same series identified at the study site.[1] Rainfall was collected using a tipping bucket (model TE525, Campbell Scientific, Logan, Utah) and volumetric soil moisture was recorded using probes (hydraprobe, Stevens-Vitel, Portland, Oregon) at 5 depths, 2, 4, 8, 20, and 40 in. (Schaefer et al. 2007).

We calculated means for data collected from five subplots of the same plot and used them for remaining data analysis. Analysis of variance (ANOVA) according to a complete block design was used

Table 1. Pretreatment overstory tree basal area (ft^2/ac) and stems per acre (SPA) by species for all trees 1.5 in. dbh and greater. There were no significant differences between unrestricted and restricted traffic treatments for basal area ($F_{1,19}$ $P = 0.8251$) and stems per acre ($F_{1,19}$ $P = 0.4657$).

	Unrestricted traffic		Restricted traffic	
Overstory species	Basal area (ft^2/ac)	SPA	Basal area (ft^2/ac)	SPA
Acer rubrum	11.9	132	3.3	32
Carya spp.	4.3	20	5.7	24
Liriodendron tulipifera	1.3	4	3.9	12
Nyssa sylvatica	2.1	56	1.3	48
Oxydendrum arboreum	10.2	116	8.7	112
Quercus alba	4.5	32	8.7	72
Quercus coccinea	44.5	32	40.0	28
Quercus montana	34.7	108	42.8	176
Quercus velutina	14.2	12	14.5	16
Sassafras albidum	0.9	8	1.7	28
Total	128.5	520	130.6	548

to quantify the significance of treatment differences; Tukey's honestly significant difference (HSD) tests were used to separate means of oak seedling survival and growth comparisons. For the seedling tally data and soil disturbance indices, repeated measures ANOVA using SAS Institute Incorporated, General Linear Models (SAS PROC GLM) procedure, with year as the repeated measure under two main treatments, unrestricted- and restricted-harvest equipment traffic, were used, and the Manova test criteria were examined for the interaction between year and seedling tallies and between year and disturbance indices. The Wilks' lambda F ratio and associated *P*-values were used to examine differences in seedling tally levels, and univariate tests for within year effects were separated using Tukey's Studentized range test. Duncan's new multiple range test was used to separate the disturbance indices means. All tests were performed using SAS version 8.01 and the alpha level used for significant differences was 0.05 (SAS Institute 2000).

Results

Preharvest Overstory and Reproduction Composition

Harvest blocks averaged 130.0 ft^2 of basal area per acre (BA/ac) and had 534 stems (all species) per acre (SPA) 1.5 in. dbh and greater (Table 1). Basal areas and SPAs were similar for blocks ($F_{1,19}$ $P = 0.8251$, $F_{1,19}$ $P = 0.4657$, respectively.) The dominant species in the stands were the oaks (black oak, chestnut oak, scarlet oak, and white oak; Table 1). Oaks represented 79% of the total BA/ac. Other common mid- and overstory species included sourwood (*Oxydendrum arboreum* DC.), red maple (*Acer rubrum* L.), and hickories (*Carya glabra* Sweet, *C. ovalis* Sarg., *C. ovata* K. Koch., and *C. tomentosa* Nutt.), representing 7, 6, and 4% of the total BA/ac, respectively.

Soil Disturbance, Precipitation, and Soil Moisture

Average calendar-year precipitation over 2002–2009 was 54.7 in. Precipitation for this region is fairly evenly distributed over the year. During winter months from 2002–2009 (November, December, January, February, and March), the average precipitation was 24.9 in., 45% of the total. During the harvesting operations in November–December 2002 through January–March 2003, the total precipitation was 27.2 in., slightly above the 7-year average of winter periods considered, which ranged from a low of 16.3 in. in winter 2006–2007, to a high of 33.1 in. in winter 2004–2005.

Soil moisture for the Hartsells soil series during the study period was examined by soil depth, and was 22.5, 19.4, 23.7, 23.6, and 14.6% for the 2, 4, 8, 20, and 40 in depths, respectively. Closer examination of the 2–8-in.-depth measurements, the rooting zone for the small oak seedlings, showed that soil moisture was below the yearly average during the months of June, July, August, September, and November and was above average for the remaining months (Figure 1).

Both treatment and year had a significant effect on the soil disturbance class; however, no treatment by year interaction was detected. In March 2002, immediately after harvest, there was more observable logging disturbance (primarily greater bare soil exposure) in the unrestricted traffic blocks than in the restricted traffic blocks. This resulted in a significantly larger average disturbance score for the unrestricted traffic blocks of 2.8 (std 0.3) compared to 2.1 (std 0.6) for the restricted traffic blocks ($F_{1,19}$ $P = 0.0212$). However, in 2003 and 2004, the treatment-to-treatment difference in disturbance was no longer significant. The amount of measured disturbance decreased with time within each treatment, and by 2004 the average soil disturbance class values were 0.1 for the unrestricted traffic and < 0.1 for the restricted traffic blocks, indicating a rapid recovery in site disturbance in just 3 years after clearcut harvesting.

In 2002, 41% of the restricted traffic subplots were characterized as trafficked with litter in place or litter disturbed, but without any mineral soil exposed, and 52% of the subplots had traffic with mineral soil exposed. Sixty percent had at least one 6-in.-deep depression. Eighteen percent of the unrestricted traffic subplots had litter in place or slightly disturbed litter and 82% had exposed mineral soil. Fifty-four percent had at least one 6-in.-deep depression. In 2003, 4% of the restricted traffic subplots had traffic with litter in place or with litter disturbed, and 6% had mineral soil exposed. In 2003, 12% of the unrestricted traffic subplots had litter disturbance, and 26% had mineral soil exposed. Twenty-two percent of both restricted and unrestricted traffic subplots had depressions in 2003. By 2004, 2% of restricted traffic subplots and 10% of unrestricted traffic subplots had traffic with litter in place, and the remaining plots were all characterized as untrafficked. There were no depressions recorded in 2004.

Preharvest and Postharvest Reproduction Composition

A total of 28 different species was tallied in the regeneration plots (hickory reproduction was not separated by species) prior to treatment. There were no differences in reproduction totals among treatment blocks ($F_{1,19}$ $P = 0.0824$). Regeneration plots averaged 1,627 SPA for all stems up to 4 ft in height. Twenty-nine percent of this reproduction was less than 1 ft in height and 81% was less than 2 ft tall. Oaks comprised 27% of the reproduction less than 2 ft tall (362 SPA oak). The majority of the remaining small size-class stems (1–4 ft tall) were *Sassafras albidum* (Nutt.) Nees. (16%) and *Vaccinium* spp. (28%).

Forty-one different species were tallied in the regeneration plots 8 years postharvest. Total seedling counts in all reproduction classes did not differ among treatments ($F_{3,16}$ $P = 0.5177$), and there was no treatment by year interaction ($F_{3,54}$ $P = 0.8326$). Total seedling counts were greater 8 years following the harvest than preharvest levels ($F_{1,19}$ $P < 0.0001$; Table 2). There were also some differences by size classes. For all species, seedling numbers were significantly greater 8 years following harvest for those seedlings that were between 3 and 4 ft tall, and for those seedlings greater than 4 ft tall and less than 1.5 in. dbh (Table 2). Seedlings from 1–2 ft in height

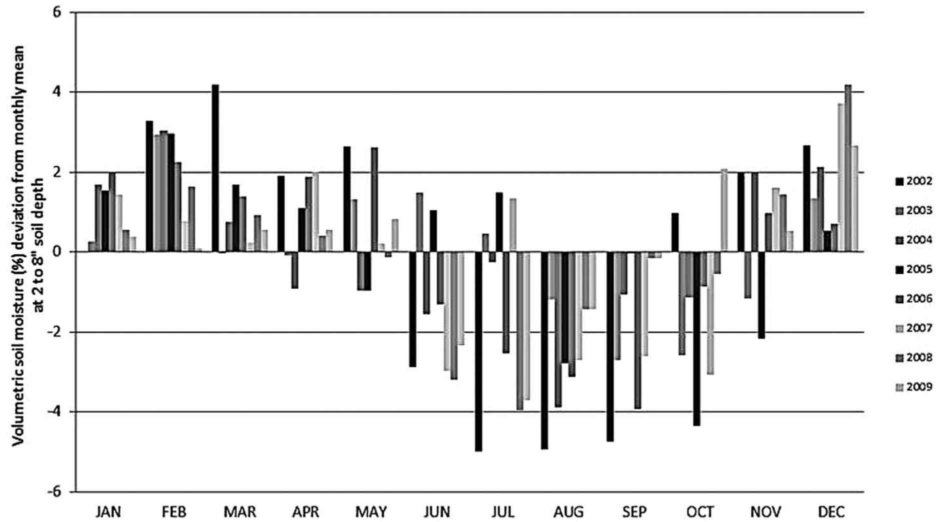

Figure 1. Volumetric soil moisture (%) deviation from monthly mean at 2–8 in. soil depth during 2002–2009 for a Hartsells soil series, Jackson County, Alabama.

Table 2. All species reproduction plot tallies comparisons among years, in SPA, from 2001 (pretreatment) through three and eight growing seasons. No differences by size class and year were found between traffic treatments. Rows with different letters indicate differences among years for all stems by size class.

	Restricted traffic			Unrestricted traffic			ALL (restricted and unrestricted traffic)			
	2001	2004	2009	2001	2004	2009	2001	2004	2009	P-value
Size class	SPA	SPA	SPA	SPA	SPA	SPA	SPA	SPA	SPA	
Up to 1.0 ft	402	508	806	526	494	838	928bc	1002c	1644b	<0.001
>1.0–2.0 ft	880	826	604	832	666	594	1712a	1492ab	1198b	0.0290
>2.0–3.0 ft	166	422	326	248	362	382	414bc	784a	708ab	<0.0001
>3.0–4.0 ft	108	196	210	92	128	202	200bc	324ab	412a	<0.0001
>4.0 ft to 1.5 in. dbh	112	196	942	120	224	866	232bc	420b	1808a	<0.0001
>1.5–6.0 in. dbh	62	18	50	76	10	50	138a	28b	100a	<0.0001
>6.0 in. dbh	66	6	6	54	2	4	120a	8b	10b	<0.0001
Total	1796	2172	2944	1948	1886	2936	3744a	4058b	5880b	<0.0001

significantly declined, as did all trees tallied that were 6.0 in. dbh and greater (Table 2).

There were no treatment differences for total oak reproduction tallies, nor any differences among restricted versus unrestricted traffic treatments when examined by size classes. In both the restricted and unrestricted traffic treatments, the number of the small (< 1 ft tall) oak seedlings did not change over time, while the oaks 1–2 ft tall significantly decreased (Table 3). However, after eight growing seasons, there were significantly more oak seedlings in the greater than 4 ft tall and less than 1.5-in.-dbh size class compared to numbers tallied in previous years.

In addition to the oaks, eight tree species and one shrub dominated the reproduction cohort. None showed any response difference between the traffic treatments. For the smallest size class, *Vaccinium* spp. had the highest density increase following harvest, followed by red maple and sourwood (Figure 2A). Sourwood, *Vaccinium* spp., and yellow-poplar all increased for stems greater than 1 ft and less than 2 ft tall (Figure 2B). Except for the oaks and black cherry (*Prunus serotina* Ehrh.), all seedling densities increased for seedlings between 2 and 3 ft tall (Figure 2C). Hickory seedlings in this size class increased from 54 to 152 SPA in the restricted traffic treatment and from 106 to 194 SPA in the unrestricted traffic treatment, representing 51 and 47% of total seedlings, respectively. Four species increased by 20 SPA or greater in the 3–4-ft height class, including the oaks (increased from 5 to 26 SPA), red maple (increased from 4 to 26 SPA), sourwood (increased from 2 to 16 SPA), and yellow-poplar (increased from 0 to 23 SPA; Figure 2D). Thirty percent of all stems tallied 8 years postharvest were in the 4 ft tall to 1.5-in.-dbh size class compared to only 6% preharvest, and all species increased their densities in this class (Figure 2E). Red maple increased from 13 to 146 SPA, the oaks increased from 7 to 106 SPA, and yellow-poplar increased from 0 to 193 SPA. Posttreatment, these three species comprised 16, 12, and 21% of the total stems in this size class.

Preharvest and Postharvest Oak Seedling Response

Oak reproduction was comprised of four species: black oak, chestnut oak, scarlet oak, and white oak. Prior to the harvesting operation, we tagged 687 oak seedlings, of which 40% were scarlet oak, 26.7% were black oak, 24.2% chestnut oak, and 9.0% were white oak.

Initially, all tagged advanced reproduction was less than 1 ft in height (average 0.7 ft) and had basal diameters between 0.01 and 0.1 in. Survival of the permanently tagged oak seedlings did not differ significantly by treatment 8 years after clearcutting ($F_{1,19}$ P = 0.8903), with 46.4% surviving in the unrestricted traffic and 47.1% surviving in the restricted traffic treatments (Table 4). Within each oak species, there were no significant differences in survival between traffic treatments (Table 4). For example, for black oak, there was no difference between restricted and unrestricted traffic ($F_{1,19}$ P =

Table 3. Oak reproduction plot tallies comparisons among years, in SPA, from 2001 (pretreatment) through one, three, and eight growing seasons. No differences by size class and year were found between traffic treatments. Rows with different letters indicate differences among years for all stems by size class.

	Restricted traffic				Unrestricted traffic				ALL (restricted and unrestricted traffic)				
Size class	2001 SPA	2002 SPA	2004 SPA	2009 SPA	2001 SPA	2002 SPA	2004 SPA	2009 SPA	2001 SPA	2002 SPA	2004 SPA	2009 SPA	P-value
<1.0 ft	140	174	98	92	152	124	94	98	146	149	96	95	0.1080
>1.0–2.0 ft	212	56	88	36	220	38	54	42	216a	47b	71b	39b	0.0001
>2.0–3.0 ft	58	18	8	20	22	0	4	8	40a	9c	6b	14a	0.0245
>3.0–4.0 ft	6	6	16	30	4	6	4	22	5b	6b	10a	26ab	0.0001
>4.0 ft to 1.5 in. dbh	8	10	22	124	6	6	20	88	7b	8b	21b	106a	0.0001
>1.5–6.0 in. dbh	12	4	2	18	12	2	2	14	12b	3c	2c	16a	0.0001
>6.0 in. dbh	28	2	4	2	26	2	2	2	27a	2b	3b	2b	0.0001
Total	464	270	238	322	442	178	180	274	453a	224b	209b	298b	0.0001

0.5022). It should be noted that the large variation in survival contributed to insignificant results, as did a small sample size for individual species such as white oak. During each inventory of the tagged seedlings after clearcutting, dead seedlings were inspected to determine cause of death. All but 10 of the seedlings were accounted for, i.e., stems, roots, or both were present. Each seedling was inspected for evidence that death was due to physical damage caused by the logging operations. There was no evidence that seedlings had been ripped from the ground by logging activities, or that logging equipment contributed to the death of the seedlings (no physical evidence found on the dead seedling, such as crushing or bending). There was no physical evidence of damage to the seedlings that were still alive. During the first growing season posttreatment, 20 tagged oak seedlings had new sprouts, 8 in the restricted traffic treatment and 12 in the unrestricted. We did not discern if the original stem was damaged by the operation or some other perpetration. By 2004, all new sprouts were equal in height or taller than the original stem.

Eight growing seasons after logging, the height and basal diameter of the tagged oak seedlings did not differ significantly between the two traffic treatments (Table 4). Oak seedlings averaged 4.3 ft tall and 0.7 in. basal diameter in the restricted traffic treatments and 4.1 ft tall and 0.8 in. basal diameter in the unrestricted-traffic treatments. Seedling height growth for surviving seedlings ranged from 2.6 ft for black oak to 4.6 ft for white oak, and diameter growth ranged from 0.5 in. for black and chestnut oak to 0.8 in. for white oak. Before harvest the tallest oak seedling was a scarlet oak (3.7 ft tall); but 8 years after harvest, the tallest tagged oak seedling was a 20.0 ft tall chestnut oak with a 2.1-in. basal diameter.

Discussion

Efficient harvesting by clearcutting degraded, low quality upland hardwood forests on the Cumberland Plateau surface requires the use of mechanical systems. Impacts on the surface of the forest floor are influenced by various factors, including the type of equipment, extent of logging traffic on site, and inherent soil characteristics (Reisinger et al. 1988). On this study site, the feller-buncher cut and collected trees and the grapple skidder advanced the trees to the landing. No harvesting system productivity data were collected, but the operator was able to follow the designated traffic trails, with more controlled traffic on the restricted traffic designated blocks. During this study, soil moisture for Hartsells soils on the Cumberland Plateau was above average for the winter months as measured at a nearby site. Although the Plateau tops are often harvested when conditions are too wet for machinery on the side slopes, only minimal degradation to the site was found for clearcut harvesting that involved either controlled equipment access (restricted treatment) or free equipment access (unrestricted treatment). The harvesting methods used in this study did not initially result in severe soil disturbance nor did the equipment pull advance reproduction seedlings from the ground; and logging impacts observable on the soil surface did not persist. Surface disturbances, including litter and some upper soil horizon displacement and rutting, dissipated within just three growing seasons. The minimal disturbance to the site regardless of logging treatment may be due to the ability of this soil series to rapidly drain water as reported by Tsegaye et al. (2005). Similarly, McDonald et al. (1995) found few changes in soil physical properties in a thermic Typic Hapludults soil in south-central Alabama that was moderately and heavily trafficked by a loader skidder.

The time required for a disturbed soil to recover depends on soil type and disturbance degree. Natural processes help restore disturbed soils to their preharvest conditions, including precipitation, freezing and thawing cycles and leaf fall. This study only examined observable physical disturbance effects; no bulk density or soil compaction measurements were taken. Wang et al. (2005) found that clearcutting on an upland hardwood site in West Virginia with mechanized equipment produced no significant changes in soil bulk density between post (immediately after 10 loaded machine passes) and preharvest measurements. The predominant soil series in this study was a fine sandy loam. Sandy soil texture compacts little. Research in other systems found insignificant levels of compaction on 11 Coastal Plain soil types 1 year postharvest (Hatchell et al. 1970), little surface disturbance and no tire ruts in a loamy sand soil (King and Haines 1979) and rapid recovery of silt loam soils to compaction following harvesting in an upland oak-hickory forest in Indiana (Reisinger et al. 1992). The narrow width (66 ft) of the harvest blocks allowed for minimal vehicle passes for both the restricted and unrestricted traffic blocks; although the operator traversed over a greater proportion of the area in the unrestricted traffic blocks, the equipment often traveled repeatedly in the same tracks. Bulk density has been reported to increase or to remain constant with increasing number of passes (Green and Stuart 1985).

In the southern United States, most studies examining mechanized harvesting systems and their effects on residual trees, including reproduction, have focused on pine seedling growth (see Reisinger et al. 1988 for study reviews). Little study has focused on the potential for advanced reproduction damage due to the physical effect of the equipment pulling seedlings from the soil. For regeneration of oaks, competitive seedlings must be present prior to disturbance and they must be resilient enough to survive the disturbance (Johnson et al.

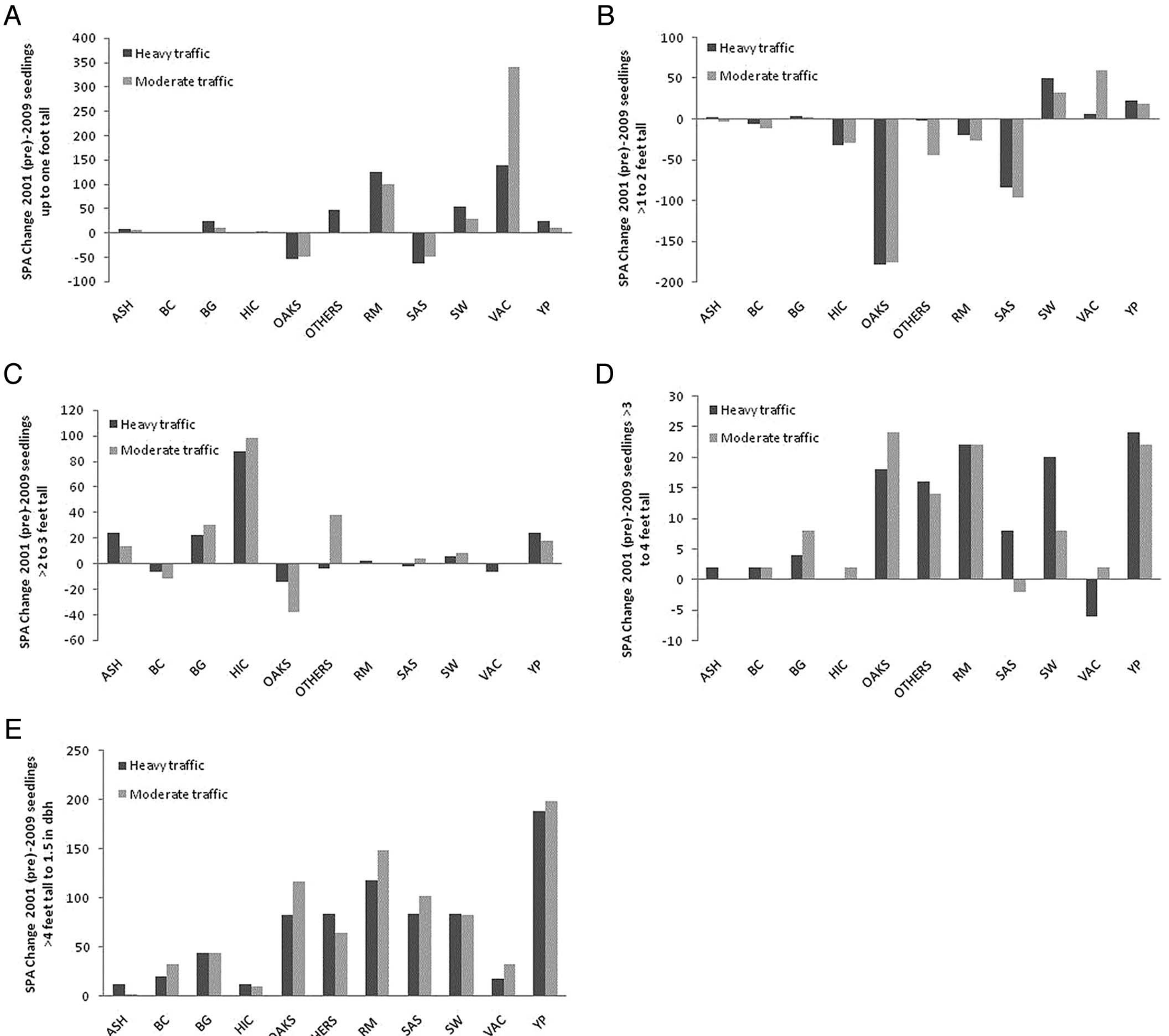

Figure 2A–2E. Change in SPA by species under restricted and unrestricted equipment traffic during clearcutting upland hardwood forests on the Cumberland Plateau, by regeneration class size, A. up to 1 ft tall; B. greater than 1–2.0 ft tall; C. greater than 2.0–3.0 ft tall; D. greater than 3.0–4.0 ft tall; E. greater than 4.0 ft tall to 1.5 in. dbh. Species abbreviations are: Ash (*Fraxinus* spp.); BC (*Prunus serotina*); BG (*Nyssa sylvatica*); HIC (*Carya glabra, C. ovalis, C. ovata, C. tomentosa*); Oaks (*Quercus alba, Q. coccinea, Q. montana, Q. velutina*); Others (*Ilex* spp., *Rhamnus caroliniana, Rhus* spp., *Ulmus* spp., *Viburnum prunifolium, V. acerifolium*); RM (*Acer rubrum*); SAS (*Sassafras albidum*); SW (*Oxydendrum arboretum*); VAC (*Vaccinium* spp.); YP (*Liriodendron tulipifera*).

2009, Loftis 1990, Sander 1972). Maintaining an adequate number of these seedlings is essential to sustaining the oak stocking in these stands.

Regenerating low quality upland hardwood stands on the Cumberland Plateau by clearcutting has been shown to result in a favorable distribution and growth of the most desirable species (McGee 1986). These xeric sites are more conducive to oak reproduction success mainly due to reduced competition (Kolb et al. 1990, Miller et al. 2004). Mechanical harvesting traffic had no discernible effect on the growth or survival of a sample of advanced oak reproduction in this study, on these coarse-textured, sandy-loam soils. Others have found that severe soil compaction reduced oak seedling germination, establishment, and growth and attributed these problems to stunted root systems (Jordon et al. 2003, Tworkoski et al. 1983). We did not quantify soil compaction or bulk density. However, if there were deleterious changes in soil compaction and higher bulk densities, these did not constrain tree establishment and growth on these more xeric upland sites, as evidenced by the seedling response following eight growing seasons. Results may vary, however, with soils that are finer textured and poorly drained depending on topography and other factors affecting soil moisture during the logging season.

Oaks dominated the overstory before harvest, accounting for about 80% of stand basal area (trees $>$ 1.6 in. dbh), whereas red maple constituted 6% of the stand's basal area, and yellow-poplar less than 1%. Black et al. (2002) found red maple comprised 5% of

Table 4. Mean and standard error (in parenthesis) of the survival (%), change in height (in.) and change in basal diameter (in.) of oak seedlings, by species, between restricted and unrestricted harvesting traffic treatments from 2001 (pretreatment) to eight growing seasons posttreatment (2009) for clearcut Cumberland Plateau upland hardwood forests.

	Traffic intensity	Survival (%)	P-value	Height growth (in.)	P-value	Diameter growth (in.)	P-value
Black oak	Restricted	58.1 (20.2)	0.5022	3.2 (2.9)	0.6170	0.6 (0.5)	0.6201
	Unrestricted	52.4 (17.3)		2.6 (2.3)		0.5 (0.5)	
Chestnut oak	Restricted	46.3 (21.9)	0.9066	4.3 (3.9)	0.6740	0.5 (0.4)	0.2586
	Unrestricted	45.3 (11.5)		4.1 (4.7)		0.6 (0.6)	
Scarlet oak	Restricted	55.6 (8.0)	0.0588	3.2 (3.2)	0.8715	0.6 (0.6)	0.5232
	Unrestricted	43.6 (17.1)		3.2 (3.4)		0.6 (0.6)	
White oak	Restricted	28.5 (26.7)	0.3293	4.5 (4.5)	0.9165	0.8 (0.8)	0.8282
	Unrestricted	44.7 (41.6)		4.6 (4.9)		0.8 (0.8)	
All oaks	Restricted	47.1 (12.3)	0.8903	3.5 (3.5)	0.8020	0.6 (0.6)	0.6862
	Unrestricted	46.4 (12.1)		3.4 (3.7)		0.6 (0.6)	

presettlement forests in east-central Alabama, while McGee (1986) tallied less than 1% of overstory as red maple in a mature Cumberland upland stand in Tennessee. After clearcutting, competition with oak reproduction was dominated by red maple and yellow-poplar. Speculation exists that red maple invasion on oak-dominated sites may be facilitated by fire cessation (Abrams 2005). Red maple and yellow-poplar are noteworthy competitors and loss of oak forests to them is widely reported (Beck and Hopper 1986, Hix and Lorimer 1991, Loftis 1983, Morrissey et al. 2010, Schweitzer and Dey 2011).

The importance of having adequate numbers of large oak advance reproduction before regeneration harvesting is a well-established maxim in oak silviculture (Johnson et al. 2009). The conduct of logging operations did not materially affect the density or size structure of the existing oak advance reproduction, which was dominated by small (< 1 ft tall) seedlings before cutting. Eight years after harvesting, the density of oak advance reproduction < 3 ft tall declined through mortality and outgrowth into larger size classes. Consequently, oak density in the > 3 ft tall to < 1.5-in.-dbh size classes increased, while oaks > 6 in. dbh declined substantially. In examining harvest impacts on oak regeneration on the Cumberland Plateau escarpment in Kentucky, Stringer (2006) also concluded that oak advance regeneration > 3 ft tall maintained itself through harvesting. Though modest size gains were made by the small oak advance reproduction, the density of oaks throughout all the size classes is challenged by other species after 8 years. For example, red maple seedlings increased from 13 to 146 SPA in the 4 ft to 1.5 in. dbh class, while oaks in this same size class increased to 106 SPA, representing 12% of SPA in this size class. Oak species accounted for only 4% (by density) of the reproduction ≤ 1.5 in. dbh, and 16% of trees > 1.5 in. dbh. This certainly represents a drastic reduction in oak dominance from original conditions in the parent stand where oak was ≥ 75% of the stand basal area.

There are few studies on long-term regeneration development on the Cumberland Plateau, but comparisons of our results with other research in the Central Hardwood Forest Region can be made to discern general regional trends and highlight local variations in the competitive relations between oak and other species. In the Missouri Ozarks, Kabrick et al. (2008) found that oaks comprised 13% of all stems of reproduction in the > 3.3 ft tall to < 1.4-in.-dbh size class 10 years after clearcutting oak-hickory forests where originally oak species accounted for > 70% of stand basal area. Red maple is less competitive in these Missouri Ozark ecosystems than in other eastern mesophytic forests, and the forests occur outside of the natural range of yellow-poplar. Nonetheless, the role of oak in the composition of reproduction is similar at these young stand ages. They further reported that the density of red oaks (i.e., scarlet oak and black oak) in this size class increased more rapidly and attained higher levels over the 10 years on sites of lower site index (< 65 ft oak); and density of competing species was greatest on the high quality sites.

Hilt (1985) observed interesting patterns in reproduction development and oak dominance following clearcutting of mature oak forests (i.e., oak species > 60% by volume) in the Ohio Valley that varied by site index and time since harvesting. In stands that were less than 15 years old, he found that the proportion of oak was consistently around 22–31% of the total stem count regardless of site index (range 50–80 ft for oak). In older stands, there was a significant change in stand development and composition as the oaks assumed dominance (> 64% of total stem density) on site index < 60 ft sites. In contrast, oak species had dropped to just 11% of stem density on higher quality sites (site index > 70 ft) in stands older than 15 years. Similarly, the proportion of oak reproduction was low (10% of all dominant and codominant stems) in 5–17-year-old stands that had originated after clearcutting oak-dominated forests in southern Indiana (Fischer 1987), but the relative density of dominant oak increased over time in those same stands predominantly on the drier, more xeric and less productive stands (Morrissey et al. 2008). Heiligmann et al. (1985) reported that the proportion of oak in the reproduction following clearcutting ranged from 13% on north slopes to 54% on south slopes 28 years after harvesting oak forests in southeastern Ohio. They concluded that red maple had reduced oak stocking from levels in the original stand on north slopes (site index 66 ft black oak) and that stands on south slopes (site index 63 ft black oak) would remain predominantly oak-hickory in composition. Groninger and Long (2008) inventoried 15–26-year-old clearcuts of upland oak forests in southern Illinois and found that 16% of the stems were oak, that oaks were being outcompeted by red maple and yellow-poplar, and that sustaining the original stocking of oak would require silvicultural intervention, for example, crop-tree thinning. They too noted that oaks were more prevalent and competitive on the lower quality sites, but wherever yellow-poplar was present the future dominance of oak was questionable.

In this study, yellow-poplar competition was similar to that of red maple based on density by reproduction size class. Seed-origin yellow-poplar increased from 0 to 193 SPA in the 4 ft to 1.5-in.-dbh class after 8 years. In the reproduction, the largest trees were oaks and yellow-poplar, with an average of 16 SPA of oak and 10 for yellow-poplar. However, McGee (1986) found that yellow-poplar height growth on Plateau surface sites was poor, and few yellow-poplar in the reproduction cohort were free to grow. Therefore, the competitiveness (growth rates and survival) of yellow-poplar (Elliott and Swank 1994, Morrissey et al. 2008) and perhaps red maple (Lorimer 1984) may be reduced or limited on xeric sites over time by the occurrence of severe drought that acts to release the more drought-tolerant oaks through mortality of these two competing species.

Although reproduction origin data were not collected, red maple reproduction from stump sprouting was observed to be prominent. Red maple diameter distribution ranged between 1.8–9.6 in. dbh, with a quadratic mean diameter of 4.7 in. Red maple stump sprouts have been shown to exhibit rapid height growth on productive sites (Nowacki et al. 1990, Palik and Pregitzer 1992). Tift and Fajvan (1999) found that 50% of codominant maples on a dry site were of stump sprout origin. However, oaks have also been shown to be prolific and competitive stump sprout producers (Wendell 1975, Johnson 1977, McGee 1978, Dey et al. 2008). Morrissey et al. (2008) reported that 45% of the dominant oak stems in 21–35-year-old clearcuts in southern Indiana were of stump sprout origin. Weigel and Peng (2002) found stump sprouting probabilities for oaks decreased with increasing dbh. However, for white oaks, decreasing site quality was associated with a greater likelihood of stump-sprouting success because of reduced competition on the poorer sites. For upland sites on the Cumberland Plateau, oak stump sprouting has great potential to contribute to the stocking of the next stand because current stands are oak-dominated and the xeric nature of the sites contributes to reduced competition.

Clearcutting with mechanical harvesting equipment on an upland hardwood site located on the surface of the Cumberland Plateau did not result in oak seedlings being physically pulled from the ground. The competitiveness of oaks on these lower quality sites (site index 60 ft upland oaks) with well-drained, low-fertility soils is probably sufficient to maintain oak dominance in the future stand based on results of other studies of stand development following clearcutting. The minor amount of competition from other species, the relatively high numbers of advance reproduction of oaks, and the potential contribution of oak stump sprouts contribute to a desirable postharvest species composition in these stands. Foresters and logging contractors have some control over the severity and extent of soil disturbance and should continue to take harvesting season into account, limiting operations during high soil moisture conditions and employing specific harvest planning techniques.

Endnote

1. Remote site data are transmitted to a master station, where they are checked for completeness and then made available online at www.wcc.nrcs.usda.gov/nwcc.

Literature Cited

Abrams, M.D. 2005. Prescribing fire in eastern oak forests: Is time running out? *North. J. Appl. For*. 22(3):190–196.

American Forests and Paper Association. 1994. Sustainable forestry principles and implementation guidelines. American Forest and Paper Association, Washington, DC. 9 p.

Aust, W.M., J.A. Burger, E.A. Carter, D.P. Preston, and S.C. Patterson. 1998. Visually determined soil disturbance classes used as indices of forest harvesting disturbance. *South. J. Appl. For*. 22(4):245–250.

Aust, W.M., M.D. Tippett, J.A. Burger, and W.H. McKee Jr. 1995. Compaction and rutting during harvesting affect better drained soils more than poorly drained soils on wet pine flats. *South. J. Appl. For*. 19(2):72–77.

Beck, D.E., and R.M. Hooper. 1986. Development of a Southern Appalachian hardwood stand after clearcutting. *South. J. Appl. For*. 10(3):168–172.

Black, B.A., H.T. Foster, and M.D. Abrams. 2002. Combining environmentally dependent and independent analyses of witness tree data in east-central Alabama. *Can. J. For. Res*. 32:2060–2075.

Dey, D.C., R.G. Jensen, and M.J. Wallendorf. 2008. Single-tree harvesting reduces survival and growth of oak stump sprouts in the Missouri Ozark Highlands. P. 26–37 in *Proceedings of the Sixteenth Central Hardwood Forest Conference*, Jacobs, D.F., and C.H. Michler (eds.). USDA For. Serv., Gen. Tech. Rep. NRS-P-24, Norther Research Station, Newtown Square, PA.

Dryness, C.T. 1965. Soil surface condition following tractor and high-lead logging in the Oregon Cascades. *J. For*. 8(1):15–17.

Elliott, K.J., and W.T. Swank. 1994. Impacts of drought on tree mortality and growth in a mixed hardwood forest. *J. Veg. Sci.* 5:229–236.

Fischer, B.C. 1987. The regeneration response to clearcutting on the US Forest Service Hoosier National Forest. Wayne-Hoosier National Forest, USDA For. Serv., Contract No. 53-52B1-5-01086. 95 p.

Greacen, E.L., and R. Sands. 1980. Compaction of forest soils: A review. *Aust. J. Soil Res*. 18:163–189.

Green, W.D., and W.B. Stuart. 1985. Skidder and tire size effects on soil compaction. *South. J. Appl. For*. 9(3):154–157.

Groninger, J.W., and M.A. Long. 2008. Oak ecosystem management considerations for central hardwood stands arising from silvicultural clearcutting. *North. J. Appl. For*. 25(4):173–179.

Hart, J.L., and H.D. Grissino-Mayer. 2008. Vegetation patterns and dendroecology of a mixed hardwood forest on the Cumberland Plateau: Implications for stand development. *For. Ecol.* 255:1960–1975.

Hatchell, G.E., C.W. Ralston, and R.R. Foil. 1970. Soil disturbance in logging: effects on soil characteristics and growth of loblolly pine in the Atlantic Coastal Plain. *J. For*. 68:772–775.

Heiligmann, R.B., E.R. Norland, and D.E. Hilt. 1985. 28-year-old reproduction on five cutting practices in upland oak. *North. J. Appl. For*. 2:17–22.

Hix, D.M., and C.G. Lorimer. 1991. Early stand development on former oak sites in southwestern Wisconsin. *For. Ecol. Manage*. 42:169–193.

Hinkle, C.R., W.C. McComb, J.M. Safely Jr., and P.A. Schmalzer. 1993. Mixed mesophytic forests. P. 203–253 in *Biodiversity of the Southeastern United States: Upland Terrestrial Communities*, Martin, W.H., S.G. Boyce, and A.C. Echternacht (eds.). John Wiley and Sons, New York.

Hilt, D.E. 1985. Species composition of young central hardwood stands that develop after clearcutting. P. 11–14 in *Proceedings of the Fifth Central Hardwood Forest Conference*, Dawson, J.O., and K.A. Majerus (eds.). Agricultural Experiment Station and Society of American Foresters, University of Illinois, Springfield, IL.

Incerti, M., P.F. Clinnick, and S.T. Willatt. 1987. Changes in the physical properties of a forest soil following logging. *Aust. J. For. Resourc*. 17:91–98.

Johnson, P.S. 1977. Predicting oak stump sprouting and sprout development in the Missouri Ozarks. USDA For. Serv., Res. Pap. NC-149, North Central Forest Experiment Station, St. Paul, MN. 11 p.

Johnson, P.S., S.R. Shifley, and R. Rogers. 2009. *The Ecology and Silviculture of Oak*, 2nd ed. CABI Publishing, New York. 580 p.

Jordon, D., F. Ponder Jr., and V.C. Hubbard. 2003. Effects of soil compaction, forest leaf litter and nitrogen fertilizer on two oak species and microbial activity. *Appl. Soil Ecol.* 23:33–41.

Kabrick, J.M., E.K. Zenner, D.C. Dey, D. Gwaze, and R.G. Jensen. 2008. Using ecological land types to examine landscape-scale oak regeneration dynamics. *For. Ecol. Manage*. 255: 3051–3062.

King, T., and S. Haines. 1979. Soil compaction absent in plantation thinning. USDA For. Serv., Res. Note SO-251, Southern Research Station, New Orleans, LA. 4 p.

Kluender, R.A., and B.J. Stokes. 1994. Productivity and costs of three harvesting methods. *South. J. Appl. For*. 18(4)168–174.

Kolb, T.E., K.C. Steiner, L.H. McCormick, and T.W. Bowersox. 1990. Growth response of northern red-oak and yellow-poplar seedlings to light, soil moisture, and nutrients in relation to ecological strategy. *For. Ecol. Manage.* 38:65–78.

Loftis, D.L. 1983. Regenerating southern Appalachian mixed hardwoods with the shelterwood method. *South. J. Appl. For*. 7(4):212–217.

Loftis, D.L. 1985. Preharvest herbicide treatment improves regeneration in Southern Appalachian hardwoods. *South. J. Appl. For*. 9(3):177–180.

Loftis, D.L. 1990. A shelterwood method for regenerating red oak in the southern Appalachians. *For. Sci*. 36(4):917–929.

Lorimer, C.G. 1984. Development of the red maple understory in northeastern oak forests. *For. Sci*. 30(1):3–22.

McDonald, T.P., B.J. Stokes, and W.M. Aust. 1995. Soil physical property changes after skidder traffic with varying tire widths. *J. For. Eng*. 6(2):41–50.

McGee, C.E. 1967. Regeneration in southern Appalachian oak stands. USDA For. Serv., Res. Note SE-72, Southeastern Forest Experiment Station, Asheville, NC. 6 p.

McGee, C.E. 1975. Regeneration alternatives in mixed oak stands. USDA For. Serv., Res. Pap. SE-125, Southeastern Forest Experiment Station, Asheville, NC. 8 p.
McGee, C.E. 1978. Size and age of tree affect white oak stump sprouting. USDA For. Serv., Res. Note SO-239, Southern Research Station, New Orleans, LA. 2 p.
McGee, C.E. 1986. Regeneration after shear felling and chipping of upland hardwoods. USDA For. Serv., Res. Pap. SO-224, Southern Research Station, New Orleans, LA. 13 p.
McGee, C.E., and R.M. Hooper. 1970. Regeneration after clearcutting in the southern Appalachians. USDA For. Serv., Res. Pap. SE-70, Southeastern Forest Experiment Station, Asheville, NC. 12 p.
Miller, G.W., J.N. Kochenderfer, and K.W. Gottschalk. 2004. Effect of pre-harvest shade control and fencing on northern red oak seedling development in the central Appalachians. P. 182–189 in *Upland Oak Ecology Symposium: History, Current Conditions, and Sustainability*, Spetich, M.A. (ed.). USDA For. Serv., Gen. Tech. Rep. SRS-73, Southern Research Station, New Orleans, LA.
Miller, J.H., and D.L. Sirois. 1986. Soil disturbance by skyline yarding versus skidding in a loamy hill forest. *Soil Sci. Soc. Am. J*. 50:1579–1583.
Moehring, D.M., and I.W. Rawls. 1970. Detrimental effects of wet weather logging. *J. For*. 68:166–168.
Morrissey, R.C., D.F. Jacobs, J.R. Seifert, B.C. Fischer, and J.A. Kershaw. 2008. Competitive success of natural oak regeneration in clearcuts during the stem exclusion stage. *Can. J. For. Res*. 38:1419–1430.
Morrissey, R.C., D.F. Jacobs, J.R. Seifert, and J.A. Kershaw. 2010. Overstory species composition of naturally regenerated clearcuts in an ecological classification framework. *Plant Ecol*. 208:21–34.
Nowacki, G.J., M.D. Abrams, and C.G. Lorimer. 1990. Composition, structure, and historical development of northern red oak stand along an edaphic gradient in northcentral Wisconsin. *For. Sci*. 36:276–292.
Palik, B.J., and K.S. Pregitzer. 1992. The age and height structure of red maple (*Acer rubrum*) populations in northern Michigan bigtooth aspen (*Populus grandidentata*) forests. *Can. J. For. Res*. 22:1449–1462.
Reisinger, T.W., P.E. Pope, and S.C. Hammond. 1992. Natural recovery of compacted soils in an upland hardwood forest in Indiana. *North. J. Appl. For*. 9(4):138–141.
Reisinger, T.W., G.L. Simmons, and P.E. Pope. 1988. The impact of timber harvesting on soil properties and seedling growth in the South. *South. J. Appl. For*. 12(1):58–67.
Sander, I.L. 1971. Height growth of new oak sprouts depends on size of advance reproduction. *J. For*. 69(11):809–811.
Sander, I.L. 1972. Size of oak advance reproduction: key to growth following harvest cutting. USDA For. Serv., Res. Pap. NC-79, North Central Forest Experiment Station, St. Paul, MN. 6 p.
Sander, I.L., and F.B. Clark. 1971. Reproduction of upland hardwood forests in the central States. USDA For. Serv., Agriculture Handbook 405, Washington, DC. 25 p.
Sander, I.L., P.S. Johnson, and R.F. Watt. 1976. A guide for evaluating the adequacy of oak advance reproduction. USDA For. Serv., Gen. Tech. Rep. NC-23, North Central Forest Experiment Station, St. Paul, MN. 7 p.
SAS Institute, Inc. 2000. SAS Version 8.01. SAS Institute, Inc., Cary, NC. 1,686 p.
Schaefer, G.L., M.H. Cosh, and T.J. Jackson. 2007. The USDA Natural Resources Conservation Service Soil Climate Analysis Network (SCAN). *J. Atmos. Ocean. Tech*. 24(12):2073–2077.
Schweitzer, C.J., and D.C. Dey. 2011. Forest structure, composition, and tree diversity response to a gradient of regeneration harvests in the mid-Cumberland Plateau escarpment region, USA. *For. Ecol. Manage*. 262: 1729–1741.
Shostak, D., M.S. Golden, and M.R. Dubois. 2002. Oak regeneration: four years after three harvesting treatments in a north Alabama upland hardwood stand. P. 383–389 in *Proceedings of the Eleventh Biennial Southern Silvicultural Research Conference*, Outcalt, K.W. (ed.). USDA Forest Serv., Gen. Tech. Rep. SRS-48, Southern Research Station, Asheville, NC.
Smalley, G.W. 1982. Classification and evaluation of forest sites on the Mid-Cumberland Plateau. USDA For. Serv., Gen. Tech. Rep. SO-38, Southern Forest Experiment Station, New Orleans, LA. 58 p.
Soil Survey Series. 1954. Jackson County, Alabama. Soil Conservation Service, USDA For. Serv. 1941(8):96–103.
Soil Survey Staff, Natural Resources Conservation Service, USDA. 2010. Available online at http://websoilsurvey.nrcs.usda.gov/; last accessed Apr. 19, 2012.
Stringer, J.W. 2006. Effect of ground skidding on oak advance regeneration. P. 535–537 in *Proceedings of the Thirteenth Biennial Southern Silvicultural Research Conference*, Connor, K.F. (ed.). USDA For. Serv., Gen. Tech. Rep. SRS-92, Southern Research Station, Asheville, NC.
Tift, B.D., and M.A. Fajvan. 1999. Red maple dynamics in Appalachian hardwood stands in West Virginia. *Can. J. For. Res*. 29:157–165.
Tsegaye, T.D., R. Metzl, X. Wang, M. Schamschula, W. Tadesse, D. Clendenon, K. Golson, T.L. Coleman, F. Archer, and G. Schaefer. 2005. Near real time variability of soil moisture and temperature under different land use and cover: the Alabama Mesonet. *J. Env. Hydrol*. 13(13):1–13.
Tworksosi, T.J., J.A. Burger, and D.W. Smith. 1983. Soil texture and bulk density affect early growth of white oak seedlings. *Tree Planters' Notes* 34(2):22–25.
Wang, J., C.B. LeDoux, P. Edwards, and M. Jones. 2005. Soil bulk density changes caused by mechanized harvesting: a case study in central Appalachia. *For. Prod. J*. 55(11):37–40.
Weigel, D.R., and C.-Y. J. Peng. 2002. Predicting stump sprouting and competitive success of five oak species in southern Indiana. *Can. J. For. Res*. 32:703–712.
Wendell, G.W. 1975. Stump sprout growth and quality of several Appalachian hardwood species after clearcutting. USDA For. Serv., Res. Pap. NE-329, Northeastern Forest Experiment Station, Upper Darby, PA. 9 p.