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Composition, diversity, and height of tree regeneration, 3 years after soil scarification in a mixed-oak shelterwood

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Abstract

This study reports the effects of soil scarification soon after dissemination of northern red oak (*Quercus rubra* L.) acorns on species composition, density, height, and diversity of regeneration in a mixed-oak shelterwood in central Pennsylvania, US. Prior to treatment, the understory of the stand had relatively few large stems of oak reproduction and was dominated by less desirable shade tolerant tree species. Three years after treatment, scarified plots had significantly higher density of northern red oak regeneration (34,262 ha^{-1}) reflecting greater first-year germination and survival of acorns (28%) compared to undisturbed control plots (2447 ha^{-1} and 2%, respectively). Additionally, scarification resulted in 70% lower red maple (*Acer rubrum* L.) density (5751 ha^{-1}) arising from mortality of advance regeneration and reduced recruitment from seed relative to unscarified control. The tallest reproduction (height class >122 cm) had density reduced by 62% in scarified plots compared to undisturbed controls; however, seedlings in this height class were mostly less desirable shade tolerant species present as advance reproduction before treatment. Scarification also tended to reduce densities of *Vaccinium* but increased *Rubus* densities four-fold. Shannon diversity (H') of tree species decreased in scarified plots reflecting increased relative dominance of northern red oak. This decrease in H' occurred despite increased species richness and greater seedling density for 14 of 17 species compared to pretreatment values. Soil scarification soon after acorn dissemination in a mixed-oak shelterwood served to inhibit successional momentum toward shade tolerant species through decreased density and height of red maple and increased density and competitive position of oak reproduction.

Keywords: Acorns; Oak regeneration; Oak silviculture; Red maple; Scarification

1. Introduction

Presently, northern red oak (*Quercus rubra* L.) is a major component of the mature hardwood forests in the eastern North American landscape. However, altered disturbance regimes involving fire suppression, gypsy moth (*Lymantria dispar*) defoliation, white-tailed deer (*Odocoilus virginianus*) browsing, and cutting practices are failing to regenerate oak while succession to shade tolerant species prevails in many oak stands (Crow, 1988; Widmann, 1995; Abrams, 1996). This change holds true in undisturbed stands except on the most xeric sites (Nowacki and Abrams, 1991; Fralish et al., 1999; Spivey, 2000).

One of the most important aspects of oak regeneration ecology is an accumulation of adequate numbers of competitively-sized and well distributed advance reproduction in the understory (Sander et al., 1976; Johnson, 1994). However, in recent decades, vigorous northern red oak advance reproduction has been generally lacking across much of its natural range (Crow,

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1988; Widmann, 1995). What constitutes adequate numbers of oak seedlings is suggested to range from relatively few, approximately 111 ha^{-1} well-placed oak seedlings (Oliver, 1978) to thousands of seedlings per hectare depending on other factors such as seedling size, light, soil moisture, nutrients, micro site differences, and competition (Beck, 1970; Crow, 1992; Harrison and Werner, 1984; Johnson, 1992). Even where the oak advance regeneration is abundant, it is usually suppressed by other less desirable species in a superior competitive position after the overstory is removed (Beck, 1970; McGee and Hooper, 1975). Increasing the density and size of oak advance reproduction relative to shade tolerant competitors is a crucial early step in the complex and often unpredictable process of regenerating oak forests.

Critical steps in the process of developing vigorous oak regeneration occur soon after acorn dissemination and continue through germination and seedling growth during the first several years, when losses to predation and environmental stresses are typically high. Northern red oak acorns are disseminated in autumn just prior to leaf fall, require cold stratification, and do not germinate until the following spring (Young and Young, 1992). Following dissemination, acorns typically fall prey to a variety of animal and insect species with losses often exceeding 90% (Marquis et al., 1976; Sander, 1990; Galford et al., 1991; Young and Young, 1992; DeLong, 1994; Steiner and Joyce, 1999). Furthermore, acorns are sensitive to environmental factors such as desiccation and freezing which can seriously reduce viability (Olson and Boyce, 1971; Young and Young, 1992). As many as 500 or more acorns may be needed to result in a single surviving 1-year-old seedling (Sander, 1990). Steiner (reported in Zaczek, 1994) monitored 2 years of northern red oak seed production in five Pennsylvania mixed-oak stands and found that only 0.6% of viable acorns resulted in live seedlings 18 months after dissemination. Developing effective silvicultural strategies that minimize acorn predation while maximizing germination and oak seedling survival is warranted.

Acorns sown below the soil surface are better protected against exposure to lethal cold temperatures, desiccation, and predation from both large and small mammals than those on the soil surface (Sluder et al., 1961, Bowersox, reported in Zaczek, 1994; DeLong, 1994). Mechanical disturbance (scarification) of the litter and upper horizon(s) of forest soils potentially protects acorns by sowing them below the soil surface while simultaneously reducing the numbers and size of existing competing vegetation. However, results of scarification have been variable depending on the circumstances and methods employed. Various scarification techniques have been shown to be either initially beneficial to oak regeneration but impractical to implement on a operational basis (DiMarcello, 1986), or operationally feasible but of little benefit to oak regeneration (Bundy et al., 1991). Scarification has been shown to increase the abundance of oak regeneration relative to other hardwood species after two growing seasons but much of the advantage was reduced after seven growing seasons when cultured under a relatively intact forest canopy (Scholz, 1959). This suggests that the initial benefits of scarification may not persist unless combined with other silvicultural treatments such as a shelterwood which can encourage the further development and growth of oak reproduction. Logging operations typically scarify the soil but the disturbance pattern is spatially inconsistent and unlikely to coincide with recent dispersal of large numbers of viable acorns. Additionally, little is known about the impact of scarification on species diversity. The objective of this study was to determine the effects of mechanical scarification, applied soon after the dissemination of abundant acorns, on the species composition, height distribution, and diversity of regeneration in a mixed-oak shelterwood.

2. Materials and methods

This study was conducted in a 28 ha mixed-oak stand located on the Pennsylvania State University's Stone Valley Experimental Forest in Huntingdon County, Pennsylvania. The stand was in the process of being regenerated through application of a two-stage shelterwood cutting. Of the total volume ca. 76% was oak (ca. 43% *Quercus velutina* Lam., 13% *Q. rubra* L., 10% *Q. coccinea* Munch., 6% *Q. alba* L., and 5% *Q. prinus* L.), 9% white pine (*Pinus strobus* L.), 7% yellow-poplar (*Liriodendron tulipifera* L.), 5% Virginia pine (*Pinus virginiana* Mill.), 2% red maple, 1% other hardwoods. The stand was whole-tree harvested in the autumn/winter of 1992/1993 leaving a uniform shelterwood of primarily oak with a residual basal area of 11.4 $m^2\,ha^{-1}$. During the subsequent spring, the shelterwood was enclosed in a six-wire electric fence to protect regeneration from white-tailed deer. The fence apparently limited but did not entirely exclude deer as evidenced by browsing damage and other sign within the perimeter.

On 14 October 1993, after mast crop dispersal and just prior to leaf fall in the region, seven relatively stump-free blocks sized approximately $2\,m \times 90\,m$ were established within a poorly regenerating section of the shelterwood. Because of the virtual lack of natural acorn production within the shelterwood, northern red oak acorns recently collected from another location were hand-broadcast across the surface of the leaf litter in all blocks attempting to simulate natural mast crop dispersal. Prior to dissemination, the acorns were float-tested for soundness and the floaters were discarded. Each block was divided into two treatment plots ($2\,m \times 40\,m$ each) with a buffer zone (10 m) located between plots. Scarification (described below) or control treatments were randomly assigned to plots in each block.

Preceding scarification treatment, ca. 19 circular 1.17 m^2 sample plots (122 cm diameter) were randomly located within evenly spaced strata in each treatment and block combination (134 plots total per treatment) to estimate the density (number per hectare) of acorns and tree seedlings. No distinction was made between broadcast seeded acorns and those that may have been present from natural seeding. Regeneration less than 5 cm in diameter at breast height (1.3 m above the ground) was recorded by species and height classes (0–6, 7–32, 33–122, >122 cm). For multi-stemmed plants, only the tallest stem was recorded. At this time, a representative sample of acorns was collected ($n = 93$), stratified in a refrigerator at $-1\,^{\circ}C$ over winter, and sowed in a greenhouse the following spring. Germination was 84% after 3 months. Pre-treatment herbaceous and woody shrub vegetation was not measured.

Prior to leaf fall, scarification of the soil was performed using a brush rake mounted on the blade of a small crawler dozer (John Deere model 350D). The six-toothed brush rake was 180 cm wide with teeth 36 cm apart and 30 cm long. The tracks on the dozer were 36 cm wide and 88 cm apart. Plots were scarified by driving forward with the teeth of the brush rake inserted approximately 10 cm into the soil surface. Control plots were not disturbed.

After the first and third growing seasons, ca. 10 circular 1.17 m^2 sample plots (122 cm diameter) were randomly located within evenly spaced strata in each treatment and block combination (70 plots total for each treatment) to determine the density and height class of tree regeneration by species. First-year tree species data reported in Zaczek et al. (1997a) is included here to elucidate trends in species recruitment. In addition, third-year measurement determined density and height class of other woody plants including: low sweet blueberry (*Vaccinium* angustifolium Ait.), *Rubus* as a combination of highbush blackberry (*Rubus allegheniensis* Porter) and black raspberry (*Rubus occidentalis* L.), and grape vine (*Vitis* spp.).

Pretreatment comparisons of the density of acorns were made between treatments and among blocks using analysis of variance at the $\alpha = 0.05$ level (Steel and Torrie, 1980). For pre- and post-treatment data, comparisons of the density of northern red oak, red maple, and various species groups (all other oaks, other desirable hardwoods, acceptable low value trees, all tree seedlings, *Rubus*, *Vaccinium*, and *Vitis*) across all height classes were made between treatments (and blocks) using analysis of variance at the $\alpha = 0.05$ level. The total number of stems in each height class across all species was compared by treatment in the same manner. Other desirable hardwoods included: white ash (*Fraxinus americana* L.), black cherry (*Prunus serotina* Ehrh.), yellow-poplar, pignut hickory (*Carya glabra* Mill.), and shagbark hickory (*Carya ovata* Mill.). Additionally, eastern white pine, Virginia pine, American beech (*Fagus grandifolia* Ehrh.), sweet birch (*Betula lenta* L.), serviceberry (*Amelanchier arboria* Michx. f.), hawthorne (*Crataegus* spp.), flowering dogwood (*Cornus florida* L.), blackgum (*Nyssa sylvatica* Marsh.), Eastern hophornbeam (*Ostrya virginiana* Mill.), sassafras (*Sassafras albidum* Nutt.), and bigtooth aspen (*Populus grandidentata* Michx.) were considered acceptable low value tree species for maintenance of diversity. Summaries and results are estimates of the numbers and height of regeneration presented on a per hectare basis. Species diversity of the tree seedling community was estimated using the Shannon–Weiner (H') index (Barbour et al., 1987).

3. Results

3.1. Regeneration density

In 1993, prior to scarification treatment, the number of acorns on the ground did not significantly differ ($P = 0.600$) between control (122,823 ha^{-1}) and scarified (116,682 ha^{-1}) treatments or among replicates ($P = 0.234$). Additionally, plots designated for control and scarification treatment did not differ ($P > 0.05$) in the numbers of northern red oak, red maple, other oaks, other desirable hardwoods, acceptable low value tree species (Fig. 1), and total regeneration (9545 and 10,646 ha^{-1}, respectively). Significant replicate differences were found only for the other oaks ($P = 0.040$) and total stems groups ($P = 0.011$). Of total pre-treatment reproduction, red maple was most common (45% of all stems), followed by low value species (24%), other oaks (22%), northern red oak (5%), and other desirable hardwoods (4%).

One year after treatment, every species or species group in both control and scarified areas had increased densities compared to the previous year except for red maple which decreased ($P = 0.016$) by 1611 ha^{-1} in the scarification treatment (Fig. 1). Despite the decrease of red maple, the density of all tree regeneration in areas disturbed by scarification (41,686 ha^{-1}) was greater ($P = 0.019$) than in undisturbed areas (23,756 ha^{-1}). This difference was largely caused by more ($P = 0.001$) northern red oak in scarified plots than in controls (28,654 ha^{-1} versus 2476 ha^{-1}, respectively). However, scarification also resulted in fewer other oaks compared to undisturbed plots ($P = 0.009$). Density of other desirable hardwoods and low value species remained not statistically different between treatments.

Seedling recruitment continued from years 1 to 3 within most species or species groups for both treatments (Fig. 1) with the density of tree regeneration increasing by 14,358 ha^{-1} in disturbed plots compared to 19,562 ha^{-1} in undisturbed areas. Recruitment of northern red oak during this period increased by 20% in treated plots but was essentially lacking in controls. Densities of northern red oak continued to be significantly ($P = 0.001$) higher (14 times more) and red maple significantly ($P = 0.010$) lower (70% less) in scarified relative to undisturbed areas. Differences in density of the other oak and total tree regeneration groups between treatments were no longer detected.

Among shrub and woody vine species, scarified plots had more *Rubus* reproduction (60,449 ha^{-1}) compared to control (22,638 ha^{-1}) plots ($P = 0.001$).

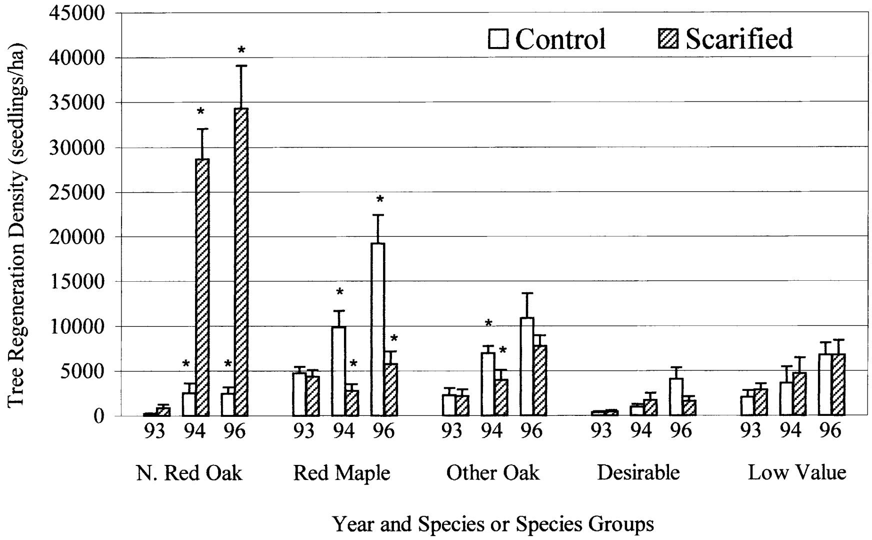

Fig. 1. The density (seedlings per hectare) of tree regeneration (and standard error bars) for species and species groups in control and scarified plots prior to (1993), 1 year after (1994), and 3 years after (1996) treatment. Paired bars within a year and species combination with asterisks indicate significant treatment differences ($P < 0.05$).

Treatment differences could not be detected for *Vitis* with statistically similar densities for disturbed and undisturbed plots (1224 and 1468 ha^{-1}, respectively). The same was true for *Vaccinium* despite control plots averaging nearly twice the density (15,418 ha^{-1}) of scarified plots (8076 ha^{-1}).

3.2. Height distribution

Prior to treatment, 95% of the tree regeneration was less than 32 cm tall and 1% taller than 122 cm (Fig. 2). Within height classes, both treatments had similar numbers of reproduction except in the 7–32 cm class where there were more ($P = 0.026$) in scarified plots (8260 ha^{-1}) versus controls (6450 ha^{-1}). A significant replicate effect was present only in this height class, indicating unequal distribution of 7–32 cm tall stems across the study site.

One year later, more regeneration ($P = 0.007$) was present only in the 7–32 cm height class within scarified plots (32,998 ha^{-1}) compared to control (15,616 ha^{-1}) plots (Fig. 2). Northern red oak accounted for 74% of the seedling density of this size in scarified plots. This occurred without a significant replicate effect suggesting that scarification resulted in a more even distribution of stems within this height class. Although control plots tended to have more regeneration in the tallest height class (>122 cm), 79% were either red maple or low value species.

Three years after treatment, continued height growth of the regeneration in the shelterwood was reflected by increases in numbers of taller reproduction with the most occurring in the 33–122 cm class (Fig. 2). In this height class, soil scarification resulted in more total regeneration (28,268 ha^{-1}) compared to unscarified controls (17,499 ha^{-1}) but the difference was not statistically significant ($P = 0.053$). Of the 33–122 cm tall seedlings, 71% was northern red oak (Table 1). Analyses by species in this height class determined that fewer red maple ($P = 0.005$) and more northern red oak ($P < 0.001$) were present in scarified areas than in undisturbed areas. In the 7–32 cm tall height class, scarified plots had more ($P = 0.011$) northern red oak than controls. Density did not significantly differ between treatments in all other comparisons by species or species groups within height classes.

3.3. Tree species diversity and richness

Over time, species diversity (H') for tree species regeneration increased in control plots but was

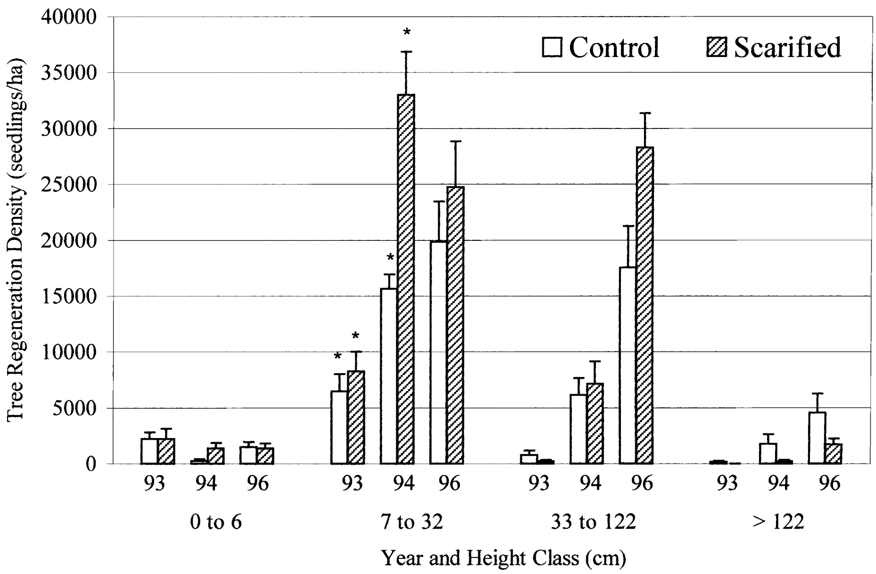

Fig. 2. The density (seedlings per hectare) of all tree regeneration (and standard error bars) by height class for control and scarified plots prior to (1993), 1 year after (1994), and 3 years after (1996) treatment. Paired bars within a year and height class combination with asterisks indicate significant treatment differences ($P < 0.05$).

Table 1
The density of tree seedlings (# per ha) in various height classes for control and scarified treatments across species and species groups 3 years after treatment (1996)

Species treated	Seedling density (# per ha)									
	0–6 cm		7–32 cm		33–122 cm		>122 cm		Height class totals	
	Control	Scarified	Control	Scarified	Control	Scarified	Control	Scarified	Control	Scarified
Northern red oak	122	0	1713[a]	13950[a]	612[a]	19946[a]	0	367	2447[a]	34262[a]
Red maple	367	489	8566	3671	9545[a]	1591[a]	734	0	19212[a]	5751[a]
Other oak	489	734	6118	4405	2937	2203	1346	367	10890	7709
Other desirable	245	0	1835	612	1713	979	245	0	4038	1591
Low value	245	122	1591	2080	2692	3549	2203	979	6731	6731
Total	1468	1345	19823	24718	17499	28268	4528	1713	43318	56044

[a] Indicates significant differences ($P < 0.05$) between control and scarified treatments within a species and height class.

Table 2
Tree regeneration species diversity (H') and richness for control and scarified plots immediately prior to treatment (1993) and 1 (1994) and 3 (1996) years after treatment

Response	1993		1994		1996	
	Control	Scarified	Control	Scarified	Control	Scarified
Species diversity (H')	1.73	1.96	1.81	1.30	1.94	1.47
Species richness	14	14	13	15	19	17

reduced in response to scarification (Table 2). However, tree species richness increased for both treatments by the third year.

4. Discussion

The density of northern red oak acorns disseminated by hand across all plots in this study (average 119,753 ha^{-1}) was slightly higher than a 4-year average (103,238 ha^{-1}) and well within the range (from 1334 to 490,527 ha^{-1}) found previously in five mature uncut mixed-oak stands in Pennsylvania (Steiner, 1995). Considering this stand was a shelterwood with ca. 50% residual basal area of mostly oak, the number of acorns present at the time of treatment could be considered above average but well below the potential maximum mast production in oak stands.

In this study, a considerably greater percentage of acorns successfully germinated and survived the first year in the scarification treatment (28%) versus control (2%) when allowing for pretreatment advance regeneration of northern red oak and the estimated viability of the sown acorns. Visual observations indicated that scarification buried the majority of acorns under the soil surface. Other studies report that surface-seeded acorns produced fewer germinants, were preyed-upon more often by deer, insects, and small mammals (Auchmoody et al., 1994; DeLong, 1994; Steiner, 1995) and experienced more severe micro-environmental temperature and desiccation extremes (Bowersox, reported in Zaczek, 1994) than acorns seeded at least 2.5 cm below the soil surface. However, planting depths below 10 cm can reduce oak seedling emergence (Smiles and Dawson, 1995). In a recently harvested red pine (*Pinus resinosa* Ait.) plantation, DiMarcello (1986) reported higher percentage germination of hand-seeded northern red oak acorns in rototilled versus undisturbed plots. Additionally, scarified soils under an uncut hardwood-hemlock stand were found to be between 3.3 and 5.6 °C warmer and experienced a longer duration of optimum temperatures during spring and early summer compared to unscarified areas in the same stand (Godman and Mattson, 1980). Considering that the electric fence in the current study limited deer feeding, predation was likely ascribed to small mammals, birds, or insects. It seems apparent that germination rates were higher in the current study for acorns incorporated into the soil because of increased protection from predation, improved environmental conditions for overwintering and earlier onset of germination because moisture conditions were more favorable.

Without sufficient numbers of desirable advance reproduction, planting seedlings or direct-seeding can be used to reestablish an oak component in harvested mixed-oak stands (Zaczek et al., 1993, 1997b; Johnson, 1994). Compared to planting seedlings, sowing acorns has been shown to be a more cost effective way of establishing or supplementing oak (Bullard et al., 1992; Countryman et al., 1996) on intensively prepared sites or old-fields. Countryman and others (1996) concluded that hand sowing northern red oak acorns is economically superior to hand planting purchased seedlings if more than 12% of planted purchased acorns were successful in establishing seedlings. Additionally, they found that machine sowing can be from 11 to 27 times less expensive than hand sowing acorns. In the present study, acorn germination was 28% in machine scarified plots suggesting that scarification-sowing is a cost effective regeneration technique. Since over half the cost of machine sowing acorns is for the purchase of seed (Countryman et al., 1996), coupling scarification with naturally disseminated acorns during an abundant mast year in a forested situation should result in an even more economical way of establishing oak regeneration.

Many oak species are episodic but unpredictable seed producers, bearing large mast crops every 2–6 years and, at times, failing to produce seed in the intervening years (Downs and McQuilkin, 1944; Sander, 1990; Cecich, 1991; Koenig et al., 1991; Sork et al., 1993; Steiner, 1995). Under natural conditions, acorns do not accumulate in the soil seed bank and are generally considered to be viable only for the first growing season after seed fall (Crow, 1988), though a small percentage of subsurface seeded acorns may germinate more than 1 year after sowing (Steiner et al., 1990). This may, in part, account for the slight increase in northern red oak recruitment after the first year in disturbed plots. Thus, to be most cost-effective for increasing oak regeneration, scarification must be thoughtfully implemented in years with abundant acorn crops of high viability.

In central Pennsylvania, though ripening and dissemination appear to be weather dependent, northern red oak seed fall is typically completed by the end of October. Leaf fall usually occurs during the following several weeks. Large losses of acorns to predation can occur rapidly. Steiner (1995) reported that 53.5% of the average annual production of viable acorns remained on the ground in November. Of the 46.5% lost, 38.6% was removed by vertebrates and 7.9% was directly attributed to insect attack or fungal/bacterial infection following insect damage. Deer predation accounted for nearly half of the removal by vertebrates. Scarification after leaf fall could disrupt natural protection of acorns by disturbance of the leaf litter layer (Bundy et al., 1991). It was also observed that subsequent leaf fall tended to cover up exposed mineral soil and obscure visual differences between scarified and control areas. Therefore, it appears that optimal timing of soil scarification is soon after acorn dissemination, but prior to completion of leaf fall. If implemented during this interval, the exposure of the seed to animal predation and unfavorable environmental conditions is minimized and site protection is maximized.

Scarification tended to break stems and uproot some of the advance regeneration in place at the time of treatment. This resulted in either resprouting or mortality, as has been previously reported using an aboveground scarification technique that did not intentionally disturb the soil surface (Bundy et al., 1991). In the current study, density of red maple decreased significantly in scarified areas 1 year after treatment. Additionally, except for northern red oak, other oaks had reduced recruitment during the first year in response to soil disturbance suggesting seedbed conditions must favor germination and viable seed must be present to germinate into new seedlings to offset losses from mortality and uprooting of existing seedlings.

The density of advance regeneration of all tree species prior to treatment was relatively low (10,094 ha^{-1}) and was primarily red maple less than 33 cm in height. Even with abundant acorns and the relative lack of red maple seed source within the shelterwood, red maple increased by 14,465 ha^{-1} and dominated regeneration in control plots (44% of total) 3 years later. Increases in red maple reproduction in control plots may reflect the seed's ability to either germinate immediately after dissemination on moist mineral soil, with or without a thin layer of leaf litter, or remain dormant for one or more years (Peroni, 1996; Tremblay et al., 1996; Walters and Yawney, 1990; Young and Young, 1992). Furthermore, wind dissemination of maple samaras may allow for seed to enter the shelterwood from considerable distances.

Three years after treatment, species composition of regeneration in the scarified plots (75% oak and 10% red maple) more closely resembled that of the trees in the uncut mature stand than did undisturbed controls. Scarification not only increased the density of northern red oak but also reduced the density of red maple by 70% compared to control plots. Advance regeneration of red maple has a higher shoot:root ratio than northern red oak (Loach, 1970), perhaps predisposing the species to increased susceptibility to scarification-induced damage or mortality through dislodging. Additionally, red maple seed should be sown at depths from 0.5 to 1.0 cm (Young and Young, 1992). Resultant seedbed conditions in this study, created by scarifying the soil to a depth of 10 cm, appear to be unfavorable for red maple germination. Thus, the considerable reduction of red maple density in scarified treatments likely resulted from the cumulative effects of reductions of advance regeneration and relatively low levels of recruitment of new seedlings from seed.

Interspecific competition to northern red oak reproduction was reduced by scarification as densities and height of nearly all species declined or remained similar to controls, except for *Rubus* which increased by 267%. However, competing vegetation in the shrub layer can be important in protecting against frost and deer browse (Buckley et al., 1996) and *Rubus* has been shown to provide less competition to tree reproduction than advance regeneration of other trees (Roberts and Dong, 1993). *Rubus* species are preferred deer browse during spring (Harlow and Hooper, 1972), providing an alternative food source to tree seedlings. Advance regeneration may also be protected by dense *Rubus* thickets that present a physical barrier to encroachment by browsers. Additionally, *Rubus* are shade intolerant early successional species that rapidly colonize and stabilize disturbed sites, typically persisting at high levels of importance for 5 years or less (Marks, 1974; Reich et al., 1990). In this shelterwood, and perhaps after completion of overstory removal, the presence of *Rubus* may be beneficial overall to oak reproduction.

The lower diversity (H') value of 1.47 in the disturbed area 3 years after treatment may indicate that scarification is detrimental to the diversity of the regeneration in the stand (Table 2). However, the decrease in H' for disturbed areas is a functional result of the disproportionately large increase in northern red oak regeneration relative to all other tree species. In fact, reducing the density of northern red oak in scarified plots to levels found in control plots would increase H' to 2.18. Additionally, scarification increased total numbers of tree regeneration by 29%, did not significantly affect densities of regeneration for most other tree species or species groups, shifted dominance toward oak, and undercut red maple dominance of the regeneration to levels proportional to the species composition of the preharvest mature forest. Considering these results, care must be taken when interpreting calculated diversity values relative to the regeneration in managed oak forests.

There is no universal constant defining the ideal density of seedling reproduction to ensure the continued dominance of northern red oak in future mature stands. Oliver (1978), estimating initial stand composition from current living and remaining dead stems of three stands (33, 45, and 60 years old) in central New England, concluded that placement of only a few, approximately 111 ha^{-1}, well-placed seedlings (or seedling sprouts) were sufficient to stock these stands with northern red oak. Other research has shown that greater numbers may be necessary. The potential of oak advance reproduction to become a component of a new stand's overstory after a regeneration harvest or other disturbance is not determined by abundance of oak advance reproduction alone but by their size and distribution as well (Sander et al., 1976; Loftis, 1990). Additionally, the probability that newly established oak seedlings will continue to survive and grow varies greatly with levels of light, soil moisture, nutrients, competition, and other factors (Beck, 1970; Crow, 1992; Johnson, 1994). The variability of these factors can influence the rate of survival of 5-year oak seedlings from less than 20% to greater than 80% (Johnson, 1994, adapted from Beck, 1970; Crow, 1992; Loftis, 1988; Scholz, 1955). Considering this, application of scarification should be carefully considered and likely is unnecessary for or detrimental to regenerating oak where there are sufficient numbers of competitively-sized oak advance regeneration.

Besides affecting density and species composition, scarification also tended to reduce the size and numbers of larger well-established advance regeneration of shade tolerant and low value species, diminishing their competitive advantage over more recently established germinants of oak. The negative effect of scarification on height appeared to be caused by the mechanical disturbance at the time of treatment and did not appear to persist into later years as evidenced by increasing density of regeneration (primarily northern red oak) in the taller height classes by year 3. In this mixed-oak shelterwood with a relatively open canopy, scarification tended to arrest succession and divert successional momentum away from shade tolerant regeneration, increasing the potential of maintaining significant numbers of competitively-sized oak reproduction within the stand after removal of the overstory.

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