# Nine-Year Response of Hardwood Understory to Organic Matter Removal and Soil Compaction

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ABSTRACT

The effects of three levels of organic matter removal (OMR) and three levels of soil compaction (SC) on the development of understory vegetation in a central hardwood forest were evaluated 9 years after treatments were applied as part of a national program of long-term soil productivity research. The three levels of biomass removal (OMR) were removal of merchantable boles only (OM0), removal of the whole tree (OM1), and removal of the whole tree plus forest floor (OM2). The three levels of soil compaction (SC) were none (C0), medium (C2), and severe (C2). Weeds were controlled in all plots for the first 2 years. Understory vegetation within 81 7.9-$m^2$ subplots was inventoried by species and quantified into plant groups of woody (trees, shrubs, and woody vines) and herbaceous (annuals, perennials, and grasses) at year 5 (after 3 years of no weed control) and year 9 (after 7 years of no weed control). Vegetation was analyzed for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). OMR did not significantly affect the overall number of plants over the 5-year measurement period, but there were differences for both woody vines and grasses, which were highest in the OM0 treatment in 1999, but by 2003, they were not different. There were no differences in plant numbers among plant groups for SC in the 1999 measurement period between treatments for any plant group, but there were significantly fewer trees and woody vines in the C2 treatments than in the C0 or C1 treatments in 2003; the opposite was true for herbaceous annuals, which were highest in C1 and C2 treatments. Over the 5-year measurement period, only the height of woody vines was significantly affected by OMR, but SC significantly affected the height of all plant groups over the 5-year measurement period. Annually, however, trees were tallest in the OM0 and C0 treatment than in OM2 and C2 treatments. The annual height of other plants, excluding trees, was affected only 1 year of 5 by OMR. Fewer trees and shorter trees in the severe compaction treatment suggest that, in the short term, soil productivity has been affected on the site.

**Keywords:** soil disturbance, artificial regeneration, species diversity, forest floor

Forest soil disturbance, whether caused by nature or humans, impacts both belowground and aboveground environments of the forest stand. Problems with soil quality and maintenance of soil productivity occur when management activities are improperly planned and performed. Soil quality may be defined as the capacity of a soil to accept, store, and recycle water, nutrients, and energy; sustain biological productivity; maintain environmental quality; and promote plant and animal health (Doran and Parkin 1994). Timber harvesting and similar activities can create adverse soil disturbances such as rutting, compaction, erosion, and surface soil displacement. These disruptions, depending on magnitude, can significantly reduce the soil's ability to provide nutrients, moisture, and a friable growth medium for plant roots. They can reduce plant vigor, resulting in increased susceptibility to insects and disease and reduced biomass production and storage. In addition, compaction and other surface disturbances can reduce rainfall infiltration, thereby increasing runoff and erosion.

Physical soil properties determine the total quantity of soil available for root growth and the ability of the soil to store and supply nutrients. Most of the nutrients for tree growth in a forest stand are contained in the soil organic matter and in the biomass on the site. The introduction of whole-tree harvesting in the early 1970s created concern about the potential for long-term site degradation because of the disproportionately high rates of nutrient removal associated with harvesting of branches and foliage. Since then, studies of nutrient budgets with conventional (sawlog harvesting) versus whole-tree harvesting have been completed (Hornbeck and Kropelin 1982, Silkworth and Grigal 1982, Hornbeck et al. 1986, Crow et al. 1991,). Johnson (1995) reported that the soil nitrogen (N) in the forest floor at Hubbard Brook, New Hampshire, 8 years after harvesting, was reduced by 17%. In another study, using the same soil from Hubbard Brook, Johnson et al. (1997) found no statistically significant changes in exchangeable soil pools of calcium ($Ca^{2+}$), potassium ($K^+$), or magnesium ($Mg^{2+}$). When changes in soil nutrients do occur, similar differences usually occur in the vegetation growing on the site. Johnson and Todd (1998) reported that differences in the foliage nutrient concentrations of mixed oak species were consistent with differences in soil nutrient concentrations. Changes in soil nutrient concentration, physical properties, and the surface soil environment (shading and temperature) could affect the composition and development of future regenerating vegetation. Of particular importance is the understory vegetation because it is a significant portion of the total site carrying capacity and will make up most of the plant diversity on the site, posing a significant source of competition to trees in the developing stand after disturbances that are typically associated with timber harvesting.

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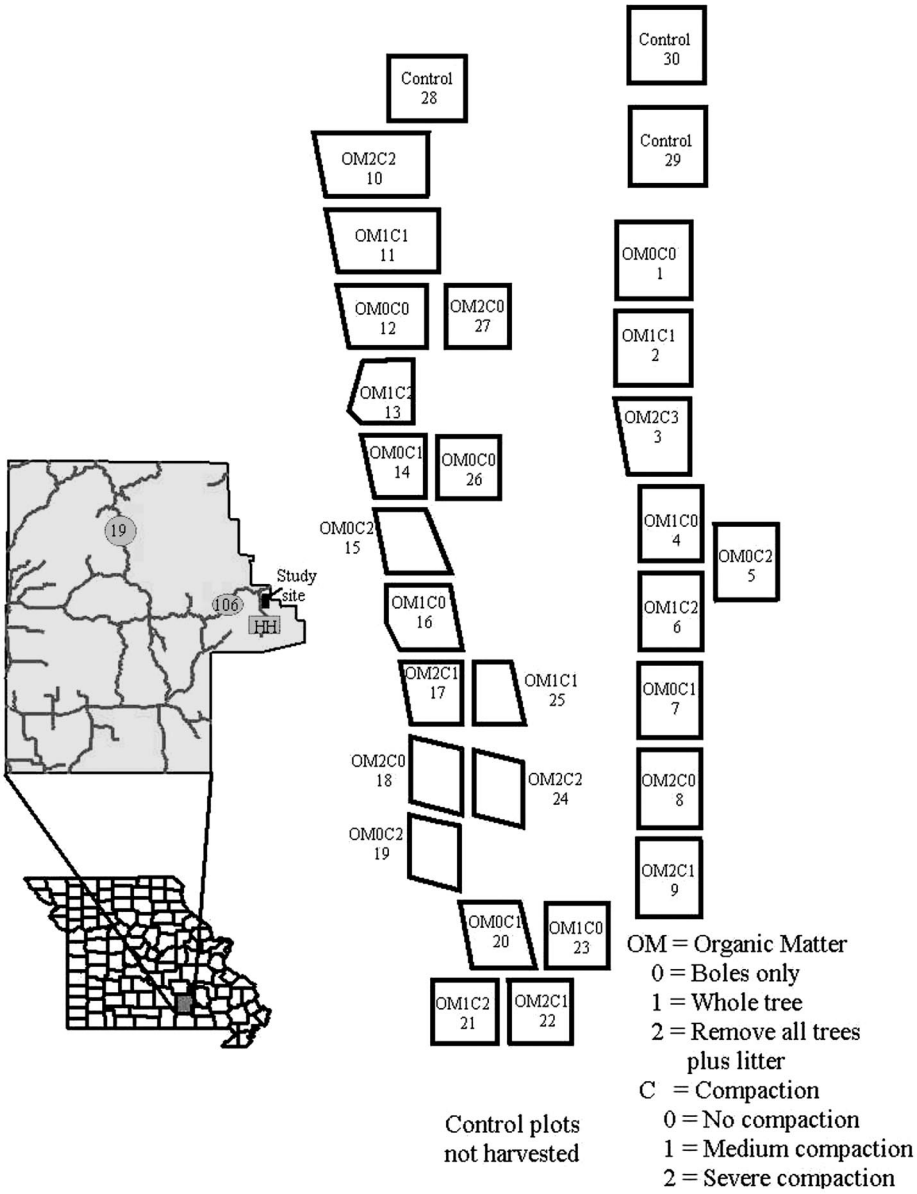


**Figure 1. Location and schematic diagram of field layout of the Missouri long-term soil productivity (LTSP).**

A series of federal mandates including the Multiple Use–Sustained Yield Act of 1960, National Environmental Policy Act of 1969, Forest and Rangeland Renewable Resources Planning Act of 1974, and the National Forest Management Act of 1976 require the US Forest Service to maintain and protect the productivity of federal forest system lands and provide the research and monitoring necessary for this protection (Powers et al. 1990). The US Forest Service Long-Term Soil Productivity (LTSP) Study program was developed to address this need (Powers et al. 1990). The LTSP study, which is replicated on lands supporting major forest types in the United States and Canada, was initiated to study the impact of soil compaction (SC) and organic matter removal (OMR) on the growth, development, and LTSP of forested lands. The overall purpose of this study was to compare the understory development and foliar nutrient concentrations several years after timber harvesting and application of soil disturbance treatments of soil compaction and OMR.

## Materials and Methods

The Missouri LTSP study was implemented in 1994 in the Ozark Region of southeastern Missouri on the Carr Creek State Forest in Shannon County, on upper side slopes with northeastern aspect on two ridges (Figure 1). Before harvesting, the study site was occupied by a mature, second-growth oak-hickory forest. Site index ranged from 74 to 80 for black oak (*Quercus velutina* Lam.) at 50 years (Hahn 1991). Slopes of 20–28% are characteristic of the site. Soils are silt loams derived from cherty residuum primarily of the Clarksville series (loamy skeletal mixed mesic Typic Paleudults; Gott [1975]). Mean annual precipitation and temperature is 112 cm and 13.3°C, respectively. The soils are well drained and highly permeable with 40–70% angular fragments by volume less than 15 cm in diameter.

The study has three levels of biomass removal and three levels of SC in a factorial design. Treatments were replicated three times in 0.4-ha plots (Figure 1). The three levels of biomass removal were

**Table 1. Macronutrient concentrations in the forest floor after OMR and SC treatments.[a]**

| | OMR | | | SC | | |
|---|---|---|---|---|---|---|
| Nutrient | OM0 (%) | OM1 (%) | OM2 (%) | C0 (%) | C1 (%) | C2 (%) |
| Year 5 (1999) | | | | | | |
| N | 1.28 | 1.35 | 1.27 | 1.34 | 1.31 | 1.26 |
| P | 0.09 | 0.09 | 0.08 | 0.10a[b] | 0.09ab | 0.07b |
| K | 1.15 | 1.30 | 1.17 | 1.36 | 1.25 | 1.03 |
| CA | 0.77 | 0.87 | 0.66 | 0.87 | 0.72 | 0.72 |
| Mg | 0.15 | 0.18 | 0.16 | 0.19 | 0.16 | 0.14 |
| Year 9 (2003) | | | | | | |
| N | 1.65 | 1.65 | 1.64 | 1.65 | 1.62 | 1.67 |
| P | 0.11 | 0.11 | 0.12 | 0.11 | 0.12 | 0.11 |
| K | 1.21 | 1.39 | 1.24 | 1.29 | 1.30 | 1.26 |
| Ca | 1.08 | 1.31 | 1.02 | 1.00a | 1.30b | 1.13ab |
| Mg | 0.22 | 0.23 | 0.22 | 0.22 | 0.23 | 0.22 |

[a] Stem-only harvest = OM0, whole-tree harvest = OM1, and whole-tree harvest plus forest floor removal = OM2; and three levels of soil compaction, none = C0; moderate = C1; and severe = C2.
[b] Means in a row for SC treatments followed by different letters are significantly different at $P = 0.05$.

removal of merchantable boles only (OM0), removal of the whole tree (OM1), and removal of the whole tree plus forest floor (OM2). The three levels of SC were none (C0), medium (C1), and severe (C2). Because heavy logging equipment was not permitted on C0 plots, skyline logging was used to remove merchantable boles. For C1 and C2 plots, logging equipment was allowed only on designated skid trails. Soil was compacted by driving a 14-tn vibrating sheep-foot roller over the plots for different numbers of times and measuring bulk density (Soil Survey Staff 1984) after each pass. Preliminarily, it was determined that two and three passes did not compact the soil as much as five and eight passes. Thus, all medium compacted plots received three passes and the severe compacted plots received eight passes. Mean soil bulk density ranged from 1.26 g $cm^3$ for C0 treatments to 1.72 and 1.82 g $cm^3$ for C1 and C2 treatments, respectively. In the spring of 1995, 1–0 red oak (*Quercus rubra* L), white oak (*Quercus alba* L), and shortleaf pine (*Pinus echinata* Mill.) were planted 2.5 m apart in rows spaced 2.5 m apart in a 3:3:1 ratio mixture (three red oak plus three white oak to one shortleaf pine) to mimic the ratio of these species before the harvest.

For the first 2 years after planting, 1995 and 1996, a 0.9-m-radius area around each planted seedling was sprayed in the spring with a mixture of glyphosate and simazine to control weeds in all plots. In the 3rd year, treatment plots were divided in half; in one half herbicides were used to control weeds and in the other half weeds were free to grow. A complete description of the site and the LTSP installation are provided elsewhere (Ponder and Mikkelson 1995).

Beginning in 1999 and continuing annually, understory plants were inventoried in 7.9-$m^2$ permanent circular subplots where weeds were not controlled. Three subplots were established in each of the 3 replicates for the 9 treatments for a total of 81 subplots. All plants within the 7.9-$m^2$ subplots were inventoried by species and origin; they were then counted, and their heights were measured. Data were collected between early July and mid-August. Plants were later quantified into groups of woody (trees, shrubs, and woody vines) and herbaceous (annuals, perennials, and grasses) plants. Plots were sampled randomly by blocks each measurement period. For this report, data are presented for 1999 (year 5), 3 years after weed control stopped, through 2003 (year 9), 7 years after weed control stopped. For nutrient analyses, vegetation was clipped in three 0.30-$m^2$ sample areas located adjacent to each inventory subplot. Samples were oven-dried and separated into leaves and stems, and the stems were discarded before leaves were ground in a Wiley mill to pass through a 2-mm sieve. Samples were analyzed for N, phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) at the University of Arkansas Agricultural Diagnostic Laboratory (Fayetteville, Arkansas).

The principal measure of species diversity was species richness, defined here as the number of species present in a plant group in a particular treatment (Magurran 1988, Wade et al. 2003). Repeated measures restricted maximum likelihood using PROC MIXED (SAS Institute, Inc., 2004) was performed on the mean number of plants in each of six plant groups and their height for OMR and SC treatments. OMR and compaction were factorial fixed effects in the model. Year also was a fixed effect and block was a random effect. To model the correlation between years, unstructured, compound symmetry, and autoaggressive order 1 [AR(1)] covariance structures were evaluated. In most cases, the finite population–corrected Akaike information criterion and the Schrwarz Bayesian criterion were the smallest for the AR(1) covariance structure, meaning observations closer in years were more correlated with one another than observations further apart. Analysis of variance (ANOVA) was performed on leaf nutrient concentrations for OMR and SC treatments. Tukey's test was used to compare means ($P < 0.05$) for statistically significant differences for the MIXED models and ANOVA.

## Results

### Foliar Nutrients

Nutrition of understory plants was not affected consistently by OMR or SC treatments during the two sample periods (Table 1). Among nutrients (N, P, K, Ca, and Mg) in leaf samples from understory vegetation, only P and Ca were significantly affected ($P = 0.002$) by SC in different sample periods. Phosphorus concentration was lower in C2 treatment than in C0 and C1 treatments in year 5. However, there was no difference in P among SC treatments in year 9. Calcium was higher in the C2 treatment in year 9 but was not significantly different in year 5.

### Number of Plants over a 5-Year Period

Overall, the number of plants quantified into plant groups exhibited OM × C interactions for woody vines and herbaceous annuals during the 5-year measurement period (Table 2). Both woody

**Table 2. ANOVA *P*-values for plant number and height of understory vegetation over a 5-yr period (between yr 1999 and 2003) in OMR and SC treatments and year effects.**

| Treatment | Plant group | | | | | |
|---|---|---|---|---|---|---|
| | Trees | Shrubs | Woody vines | Annuals | Perennials | Grasses |
| Number of plants | | | | | | |
| OM | 0.577 | 0.728 | 0.056 | 0.728 | 0.542 | 0.599 |
| C | **0.053**[a] | **0.023** | **0.001** | **0.023** | **0.032** | **0.001** |
| OM × C | 0.807 | **0.016** | **0.008** | **0.016** | 0.176 | 0.779 |
| Year | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **<0.001** |
| Year × OM | 0.059 | 0.917 | 0.875 | 0.917 | 0.683 | 0.018 |
| Year × C | 0.670 | 0.393 | 0.339 | 0.393 | **0.024** | **<0.001** |
| Year × OM × C | 0.425 | 0.867 | 0.523 | 0.867 | 0.514 | 0.863 |
| Plant height | | | | | | |
| OM | 0.843 | 0.248 | **0.047** | 0.877 | 0.489 | 0.560 |
| C | **0.012** | **0.121** | **0.001** | **0.023** | **0.004** | **0.001** |
| OM × C | 0.909 | 0.357 | **0.035** | 0.056 | 0.218 | 0.886 |
| Year | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **<0.001** |
| Year × OM | 0.198 | 0.694 | 0.886 | 0.921 | 0.437 | 0.418 |
| Year × C | **0.039** | **0.001** | 0.106 | 0.410 | 0.415 | 0.129 |
| Year × OM × C | 0.979 | 0.714 | 0.183 | 0.461 | 0.588 | 0.996 |

[a] *P* values in bold print are significant for treatments and treatment interactions for a plant group.

**Table 3. Mean number of plants per group occurring in 7.9-m$^2$ subplots in 1999 and 2003.**

| Treatment[a] | Mean number of plants per group | | | | | | |
|---|---|---|---|---|---|---|---|
| | Trees | Shrubs | Woody vines | Annuals | Perennials | Grasses | Total |
| 1999 | | | | | | | |
| OMR | | | | | | | |
| OM0 | 34a[2] | 26a | 39a | 34a | 25a | 50a | 208 |
| OM1 | 45a | 31a | 37a | 50a | 31a | 12b | 206 |
| OM2 | 43a | 29a | 23b | 42a | 29a | 18b | 184 |
| Total | | | | | | | 598 |
| SC | | | | | | | |
| C0 | 54a | 28a | 39a | 38a | 28a | 23a | 210 |
| C1 | 36a | 28a | 39a | 54a | 28a | 30a | 215 |
| C2 | 32a | 31a | 19a | 37a | 30a | 27a | 176 |
| Total | | | | | | | 601 |
| 2003 | | | | | | | |
| OMR | | | | | | | |
| OM0 | 36a | 22a | 39a | 28a | 22a | 11a | 158 |
| OM1 | 31b | 25a | 29a | 21a | 25a | 15a | 146 |
| OM2 | 37a | 26a | 28a | 29a | 26a | 15a | 161 |
| Total | | | | | | | 465 |
| SC | | | | | | | |
| C0 | 44a | 20a | 39a | 16b | 20a | 10a | 149 |
| C1 | 34ab | 25a | 37a | 33a | 25a | 12a | 166 |
| C2 | 26b | 28a | 21b | 30a | 28a | 19a | 152 |
| Total | | | | | | | 467 |

[a] OMR treatment levels (OM0 = bole only removal, OM1 = whole tree removal, and OM2 = whole tree plus forest floor removal). SC levels (C0 = no compaction, C1 = medium compaction, and C2 = severe compaction).
[b] Means in a column for a treatment within a year followed by the same letter are not significantly different at the 0.05 level based on Tukey's test.

vines and herbaceous annuals were highest in the C1 treatment level and lowest in the reatment level regardless of the OM treatment level. Also, there was a year × SC interaction for grasses because of their number being higher in the C2 treatment for years 2000, 2001, 2002, and 2003 but not for 1999, where their number in the C1 treatment level was highest. Alone, both SC and year significantly affected the number of plants in all groups, but OMR alone did not significantly affect the number of plants in any plant group (Table 2).

### Number of plants at Year 5 (1999) and at Year 9 (2003)

Although OMR did not significantly affect the overall number of plants over the 5-year measurement period, there were differences for some plant groups for the 1999 and 2003 measurement periods (Table 3). Both woody vines and grasses were highest in the OM0 treatment in 1999, but by 2003, they were not different. Also, except for trees, which were higher in the OM1 treatment than in the OM0 and OM2 treatments, differences for OMR treatment levels were not different in 2003. There were no differences in plant numbers among plant groups for SC in the1999 measurement period between treatments for any plant group, but there were for 2003. Significantly fewer trees and woody vines were present in the C2 treatments than in the C0 or C1 treatments; the opposite was true for herbaceous annuals.

Except for woody vines, the mean number of plants in all plant groups declined from 1999 to 2003 (Table 3). Although the pattern of the data was not consistent with treatment levels over the two sample periods, there were some similarities, especially for SC. Medium compaction plots had the highest total number of plants across all plant groups for both sampling periods. The number of woody plants followed the order C0 > C1 > C2 for the 1999 and 2003 measurement periods. Herbaceous

**Table 4. Mean height of understory vegetation for OMR and SC treatments.**

| Treatment | Year | | | | |
|---|---|---|---|---|---|
| | 1999 | 2000 | 2001 | 2002 | 2003 |
| | (m) | | | | |
| Trees | | | | | |
| OMR | | | | | |
| OM0 | 1.73a[1] | 1.71a | 2.07a | 2.34a | 2.58a |
| OM1 | 1.77a | 1.65a | 1.97ab | 2.10b | 2.58a |
| OM2 | 1.42b | 1.44b | 1.81b | 1.89c | 2.38a |
| CS | | | | | |
| C0 | 1.75a | 1.68a | 2.04a | 2.10a | 2.67a |
| C1 | 1.60ab | 1.54ab | 1.98a | 2.23a | 2.46a |
| C2 | 1.49b | 1.49b | 1.76b | 1.90b | 2.32a |
| All other plants[b] | | | | | |
| OMR | | | | | |
| OM0 | 0.69a | 0.65a | 0.66a | 0.55a | 0.60a |
| OM1 | 0.67a | 0.63a | 0.62a | 0.45ab | 0.53a |
| OM2 | 0.62a | 0.57a | 0.57a | 0.42b | 0.48a |
| SC | | | | | |
| C0 | 0.64a | 0.64a | 0.62a | 0.48a | 0.59a |
| C1 | 0.63a | 0.66a | 0.63a | 0.47a | 0.53a |
| C2 | 0.70a | 0.58a | 0.44a | 0.44a | 0.51a |

[a] Means in a column for a treatment within a year followed by the same letter are not significantly different at the 0.05 level based on Tukey's test.
[b] Include plants in all groups except trees.

plants were least abundant in the C0 treatment compared with C1 and C2 treatments.

### Height over 5-Year Period

The height of understory vegetation was affected by an OM × C interaction for woody vines and a year × C interaction for trees and shrubs (Table 2). Woody vines were taller in the whole tree plus forest floor removed treatment with either moderate or severe compaction. The interaction between year and SC showed that trees and shrubs were taller in C0 or C1 treatments for all years. Also, the effect of year was significant for all plant groups. Main treatment effect of OMR over the 5-year period was significant only for woody vines, which were taller in the OM2 treatment compared with OM0 and OM1 treatments.

### Annual Height for 1999 through 2003

There were differences between OMR treatment levels for trees (Table 4). For example, except for 2003, trees during the 5 years of measurements were significantly shorter in the OM2 treatment for all years including 2002 when trees in each OMR treatment differed from each other. When the annual height of all other plants excluding trees was compared according to OMR treatments, the only difference was for 2002, which showed vegetation in the bole-only treatment to be taller than vegetation in the whole tree plus forest floor removal treatment.

The effect of SC on tree height was significant for all years except 2003 (Table 4). Trees were taller in the C0 plots than in C2 plots. SC did not significantly affect the annual height of other plants in the understory.

## Discussion

Leaf macronutrient concentrations for understory vegetation were not consistently affected by treatment for either sample year. This may be because the nutrient concentrations reported were for understory samples composed of herbaceous and woody materials consisting of different plant species and covering different developmental stages, even with sampling being done about the same time of the year. Perhaps, trees and perennial plant species would have provided more consistent samples for analysis. Johnson and Todd (1998), using samples from trees, found no statistically significant differences in nutrient concentrations for woody tissue because of OM0 and OM1 harvesting treatments, but did find significant differences in foliar nutrient concentrations that were consistent with differences in soil nutrient concentrations. Soil nutrient analysis was not done in this study, but earlier work on the same soil type, landscape, and in the proximity of the study area indicated that these soils generally have low nutrient status (King 1997).

After tree harvesting in the Central Hardwood Region, woody sprouts, tree seedlings, and herbaceous vegetation fiercely compete with planted hardwood seedlings in clearcuts (Ponder 1987). Normally, woody sprouts can grow several feet in height the 1st year (Johnson 1976). Thus, it was necessary to control the understory for 2 years after treeplanting to achieve successful artificial regeneration on the present study site, delaying the succession of plants in the understory.

The higher number of species in the first sample period (1999) compared with the second (2003), 5 years earlier, was probably caused by, in part, the initial opportunity for seedlings to become established (Table 3). Overall, trees and shrubs decreased in number by 15% from 1999 to 2003. Trees in the highest number of plots in the first sample period continued to be in the highest number of plots in the second sample period (data not shown). However, SC did not affect all trees the same. For example, the presence of shortleaf pine and redcedar (*Juniperus virginiana*) tended to increase with increasing compaction levels, whereas hickory (*Carya* spp.) and black gum (*Nyssa sylvatica*) decreased with increasing SC levels. Among shrub types, sumac (*Rhus* spp.) increased as SC increased. Because of their low occurrence, little or no apparent pattern existed for such species as elm (*Ulmus* spp.), dogwood (*Cornus* spp.), and hawthorn (*Crategus* spp.).

Among herbaceous plants, legumes, such as beggar weed (*Desmodium* spp.) and hog peanut (*Amphicarpa bractea*), tended to decrease with compaction in the second sample period with little change in the first, whereas Lespedeza (*Lespedeza* spp.) and New Jersey tea (*Ceanothus americans*) tended to do better with compaction in the second sample period with little change in the first. Grasses decreased in number by nearly 50% from 1999 to 2003

(Table 3). Neither *Panicum communtatumn* (a panic grass) nor little bluestem (*Schizachyrium scoparium*) were present in the first sample period but were present in the second sample period. The opposite was true for poverty grass (*Danthonia spicata*). Panic grass (*Panicum* spp.) was present in both measurement periods.

The 2 years of weed control likely influenced what plant species inhabited the plots. Spraying herbicides around each tree in 0.9-m circles for 2 years means that a little over one-third of the area was kept weed-free during that time. Two years of weed control probably reduced the number of some species that regenerate by sprouting, increasing the opportunity for regeneration from seeds.

Initially, it was thought that the mechanical activity associated with the compaction process might contribute to a reduction in species that could regenerate by sprouting and that the compaction process would damage stumps and root systems of harvested trees, likely making them more susceptible to pathogens and desiccation. It was estimated that the overall mean regeneration that developed from sprouts was less than 1% across all treatments for both measurement periods (Kenneth R. Davidson, data not presented, Superintendent, Salem Experimental Forest, Salem, Missouri [retired]). Another reason for the low percentage of regeneration recognized as stems developed from sprouts may have been the difficulty in determining whether plants developed from sprouts or seed. Easily viewable indicators of plant origin were likely no longer present in year 9.

Seedling development from sprouts was investigated in a bottomland hardwood forest in Texas (Messina et al. 1997). One year after harvesting, species diversity comparisons between control, partial cut, and clearcut showed the only difference between treatments was for clearcut when compared with preharvest values. These authors reported that before harvest, sprouts made up 37, 65, and 48% of the inventory in the control, partial cut, and clearcut, respectively. Sprouts that developed after harvest made up 23, 46, and 83% of the inventory in the control, partial cut, and clearcut, respectively. They concluded that treatment effects (harvesting intensity) on species diversity were relatively minor, with the effects of clearcut being most apparent. The lack of pretreatment data on understory origination in the current report adds little to better understanding how OMR and SC impact tree development from sprouts.

Volunteer pines and redcedar compete for resources year-round compared with hardwood trees, thus giving them an advantage, especially over hardwoods developed from seeds. It appears that root systems on tree species such as these (evergreen type) are more adaptive to compacted soil conditions than many hardwood species (Foil and Ralston 1967). Alban et al. (1994) reported that within 3 years the number of plant species increased by 14 in response to SC compared with 6 for the no compaction treatment in the Lake States. In their study as in the present study (Table 3), although not significant, the highest number of plants was in the "mild" or medium level of SC. In another report, using disk scarification in the Lake States, the increased establishment of northern red oak over oak in the nonscarified treatment was not evident 7 years later because cultural treatments had been neglected (Lhotka et al. 2004). The implication is that soil disturbance can initially increase the number of plants. However, the difference between treatment application for C1 and C2 is the number of passes with the compacting equipment. Few passes (three) tended to stimulate plant richness more than more passes (eight) did and was more favorable to plant establishment. Fulbright (2003) reported that disturbing the site by discing temporarily increased herbaceous plant richness. Plant recruitment is limited by water availability and sunlight and success increases with an increase in gap size (Aguilera and Lauenroth 1995). However, gaps can be short-lived. Conditions created by OMR and SC exposed soil previously covered by litter, exposing seeds that germinated later.

Earlier, Kabzems (2000) reported that forest floor removal in a boreal forest, where removal included removing all woody material from the plot plus removing the forest floor with an excavator to mineral soil, decreased the number of woody species but increased the number of herbaceous species. The increase in herbaceous species was attributed to the exposure of mineral soil made possible by scalping the forest floor, which reduced the number of tree and shrub species, but the exposed mineral soil on these plots created suitable conditions for a number of early succession species. The establishment of early succession species, as in the case of shortleaf pine and redcedar, could quickly reduce the opportunity for other plants to become established.

The heights of trees in the understory were affected by OMR and SC treatments in year 5 but not in year 9 (Table 3). However, the general trend was for the shorter trees to be in the most severe treatments (OM2 and C2). The poorer growth in the OM2 may be caused by soil moisture loss during the growing season. During droughts, the most pronounced drying of bare mineral soil occurs near the surface although soil at deeper depths may have higher water content. Forest floor removal also increases soil temperature, drying out soils further. Adverse effects of compaction on reduced plant growth usually are associated with poor root development, limited nutrient supply, and insufficient aeration. Corns (1988) speculated that negative effects of compaction continue for a time, but as soils gradually revert to precompaction levels, growth effects may subside. By the 8th year of this study, surface soil (0–10 cm) bulk density had recovered to precompaction level. Bulk density differences between CO and C2, however, continue to exist for the 10- to 20-cm depth (data on file at 208 Foster Hall, Lincoln University, Jefferson City, Missouri).

The mean height of naturally regenerated trees in OMR and SC treatments was 2.60 m in year 9. The mean height of trees planted in this study that received only 2 years of weed control was 2.69, 2.16, and 5.90 m for northern red oak, white oak, and shortleaf pine, respectively, after 9 years of growth. In another study on Clarksville soil in an Ozark forest, where trees were planted but received no weed control, the average height of the woody vegetation within 1.5 m of planted trees was 1.68 m 5 years later (Ponder 2002). In this study, trees in the understory were 1.6 m tall for OMR and SC treatments after 5 years (Table 4).

## Management Implications

When changes in the soil occur, similar differences usually occur in the vegetation growing on the site. Differences in foliar nutrient concentrations in plants growing on the study site were minor, suggesting that no major changes in soil nutrient content were caused by OMR or SC treatments. Applying a mixture of glyphosate and simazine in the spring for 2 years did not significantly affect the ability of plots to regenerate naturally in the understory. Although, treatments did affect the number of plants in some plant groups, the successional trend in forest revegetation was not significantly altered. Over the study period, fewer plants occupy the site and proportionately fewer herbaceous plants remain in the understory.

The reduction in tree height, which was significant at year 5 and not present at year 9, species adaptation, and fewer trees in the severe

compaction treatment indicate that soil disturbance in this study did affect understory development. The immediate affect of OMR on foliar nutrient concentration and overall plant richness appear to be minor. Nine years is a short time in the overall development of a forest, but species richness has a great influence on stand composition during stand development. Nutritional impacts will likely be most apparent at crown closure.

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