EFFECT OF SITE TREATMENTS ON SOIL TEMPERATURE AND MOISTURE AND OAK AND PINE GROWTH AND NUTRIENT CONCENTRATIONS

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ABSTRACT.—Five years after planting, measurements of soil moisture and temperature, leaf nutrient concentrations and growth, were compared for plots of northern red oak, white oak, and shortleaf pine for treatment combinations that included two levels each of harvesting intensity (organic matter removal), site disturbance (soil compaction), and weed control (control of the understory). There were significant interactions between organic matter removal and soil compaction for height, height growth, and d.b.h. of northern red oak, and for the height of white oak, but not for shortleaf pine. Controlling the understory contributed to a marked increase in height, height growth, and d.b.h. of northern red oak and white oak, but only the d.b.h. of shortleaf pine. Mean soil moisture and temperatures were significantly higher for treatment combinations without an understory. Also, with some exceptions, leaf nutrient concentrations were higher for treatment combinations without an understory compared to treatment combinations with an understory. The two-way and three-way interactions for the effect of treatments on variables increased the difficulty of sorting out dominant influences among main effects. However, at age 5, interactions involving understory vegetation seemed to impact soil moisture and temperature, tree nutrition, and growth as much or more than organic matter removal or soil compaction on this site.

The effects of soil compaction and organic matter removal (above ground biomass) on soil moisture and temperature which alter tree growth are not well understood; even less is known about how soil compaction and organic matter removal affect nutrient uptake. Forested ecosystems contain large amounts of nutrients in woody biomass that may exist either as standing material, on the soil surface, or within the soil profile. Whole-tree harvesting and debris removal remove considerable amounts of nutrients (Ponder and Mikkelson 1995); and the disturbance caused by the process may sometime later, if not immediately, affect nutrients left on the site by increasing soil erosion, mineralization, and leaching.

Wells and Jorgensen (1979) concluded that because soil nutrient supply and productivity in forests change relatively slowly, biomass-harvesting practices could be used for several rotations without serious risk of decline in soil productivity. However, an increase in the amount of biomass harvested can be expected to increase soluble nutrient losses and increase transport of particulate matter. Also, increasing the amount of biomass removal reduces the quantity of organic residue that would ordinarily decompose and release nutrients. If forest floor temperature and moisture are increased by biomass removals, there could be a nutrient flush from accelerated forest floor decomposition.

Soil compaction can contribute to poor root health and reduce root response time to localized nutrient concentrations (Shierlaw and Alston 1984, Chaudhary and Prihar 1974). Soil compaction has been shown to cause reductions

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in soil volume, soil porosity, aeration, water infiltration, and saturated hydraulic conductivity (Graecen and Sands 1980), or increase bulk density, which limits root growth (Daddow and Warrington 1983).

Castillo and others (1982) reported that mechanical stress to soil while pea seedlings (*Pisum sativum* L. cv. Alaska) were actively growing, decreased the uptake of Ca, Mg, and Mn, but the uptake of Cu was increased. These authors also observed differences in nutrient uptake associated with differences in soil water potential. Compressing soil around growing roots during field operations may reduce root length and nutrient uptake to a greater extent than will occur when plants are grown in initially more compacted soil.

The USDA Forest Service initiated research to study the impact of soil compaction and organic matter removal on the growth and development of regenerating vegetation and long-term soil productivity (LTSP) of forested lands in the United States (Powers and others 1989, 1990). Similar studies have been established in Ontario and British Columbia, Canada. The study has two major objectives. The first is to determine how changes in soil porosity and organic matter affect soil processes controlling productivity and sustainability and secondly, to compare results from similar replicated studies among major forest types. For this report, only the low and high treatments were used. This report compares measurements of soil moisture and temperature, as well as growth and leaf nutrient concentrations of planted northern red oak, white oak, and shortleaf pine after five growing seasons in treatments that included two levels each of organic matter removal, soil compaction, and weed control at the Missouri site.

MATERIALS AND METHODS

Study Site

The study is located at the Carr Creek State Forest in Shannon County, MO. Shannon County is located in the southeastern Missouri Ozarks. Mean annual precipitation in the area is 112 cm and mean annual temperature is 13.3°C (Barnton 1993). The study site is located on the upper northeastern-facing side slopes (20 to 28 percent slopes) of two parallel ridges. The weathering of the Ordovician and Cambrian dolomite has resulted in a deep mantle of cherty residuum (Gott 1975). Soils derived from this residuum are primarily of the Clarksville series (loamy-skeletal, mixed, mesic, Typic Paleudults). Prior to harvest, the site had a well-stocked, mature, second-growth oak-hickory forest. The site index for 50-year-old black oak (*Quercus velutina* Lam.) ranged from 22.5 to 24.3 m (74 to 80 feet) (Hahn 1991).

Experimental Design

The LTSP study includes nine treatments derived from combinations of three levels each of organic matter removal and soil compaction. The three levels of organic matter removal included:

1) merchantable boles removed (boles only, OM_0),
2) all living vegetation removed (whole tree, OM_1), and
3) all living vegetation plus forest floor removed, exposing mineral soil (whole tree + forest floor, OM_2).

Merchantable boles included trees with diameters at breast height (d.h.b.) of 25 cm or larger. The three levels of compaction included:

1) no compaction (C_0),
2) moderate compaction (C_1), and
3) severe compaction (C_2).

The targeted bulk density of severe compaction treatment was an increase of 30 percent more than the bulk density of the no compaction treatment. The moderate soil compaction treatment was intermediate between the severe compaction and no compaction treatments. Each of the nine treatment combinations was replicated three times in plots approximately 0.4 ha in size before trees were harvested.

Trees were harvested from February through May 1994. On plots designated as no compaction (C_0), all trees with a d.b.h. of 25 cm or larger (merchantable trees) on OM_0, OM_1, and OM_2 plots were directionally felled and removed with a skyline cable logging system. Merchantable trees on plots where the soil was to be compacted (OM_1 and OM_2), plot borders, and the area within the study boundary were directionally felled and removed with a skidder that traveled only on designated paths within the plots and in plot borders. After the removal of merchantable trees in OM_0 plots, the remaining trees were felled. This standing biomass included trees with d.b.h. less than 25 cm (unmerchantable trees), crowns from merchantable trees, standing dead and live snags, and stems of tree species and shrubs in the herbaceous layer with basal diameters greater than 2 cm or at least 25 cm tall. Trees were cut into lengths that permitted material to be either hand carried off plots or distributed over the plots, depending on the OM removal treatment.

Except for crowns, which were retained on the OM_0 plots, but not on OM_1 plots, the remaining biomass on OM_1 plots was treated the same as biomass on OM_0 plots.

On OM_2 harvested plots, all biomass remaining after harvest was removed. This included all understory vegetation plus the forest floor was raked away to the mineral soil. For OM plots requiring compaction, it was necessary to remove and replace these materials (except the leaf/litter layer) before and after compaction. Skidders and tractors were permitted on compacted plots, but not on plots that were not to be compacted. A 14-ton vibrating sheep-foot roller was used to compact soil. The roller made passes over the severe compaction treatment until there was no change in bulk density after roller passes.

For bulk density measurements, soil cores (30 cm in length x 9.2 cm in diameter) were extracted from each plot using a soil-coring device (Ponder and Alley 1997). The cores were divided into 10-cm depth increments, oven dried at 105°C, and weighed. Bulk density for each sample was calculated according to the method of the Soil Survey Staff (1984). Soil bulk density measurements were taken after the roller made one, three, five, and eight passes over plots that received the severe compaction treatment. Initial soil chemical properties of the 0 to 20 cm depth were: 5.33 percent OM, 3.29 percent total C, 0.11 percent total N, 16 $\mu g\ kg^{-1}$ P, 789 $\mu g\ kg^{-1}$ Ca, 61 $\mu g\ kg^{-1}$, and pH of 5.7.

In late spring of 1994, each of the 27 plots were planted to a mixture of 1-0 red oak (*Quercus rubra* L.), white oak (*Q. alba* L.), and shortleaf pine (*Pinus echinata* Mill.) in a 3:3:1 ratio, (three red oak seedlings plus three white oak seedlings to one shortleaf pine seedling), using hoedads. Seedlings were planted in rows at 2.5 m x 2.5 m apart. A 1-m radius area around each seedling was sprayed with a glyphosate and simazine mixture to control weeds for the first 2 years. Beginning in the third growing season, half of each plot was kept weed-free (U_-) to permit planted trees to grow freely. Weeds were not controlled (U_+) in the other half of the plot.

Seedling diameters at 2.5 cm above ground and heights were measured after planting and annually thereafter. Diameter at breast height (d.b.h.) was measured when trees reached 1.4 m tall or taller. Leaf samples were collected the fifth year of the study and analyzed for nutrient element concentrations. Soil moisture and temperature at 10, 20, and 30 cm deep were measured monthly during the growing season using Soiltest™ moisture cells. For this report, measurements for the 20 cm depth were selected without bias. All measurements, leaf sampling, preparation, and analyses were done according to standard procedures. Here, soil moisture and temperature measurements for 2 years at the 20 cm depth, and two levels each of organic matter removal and soil compaction, with and without understory control, and their impact on seedling growth after 5 years are reported.

Statistical Analyses

The experiment was analyzed as a split-plot design with three replications, with organic matter removal and compaction treatments as the main plots and the weed control treatments as the subplots. Analysis of variance procedures were conducted with the PROC GLM procedures in SAS (Version 6, SAS Institute, Cary, NC). All statistical tests were performed at the α = 0.05 level of significance.

RESULTS AND DISCUSSION

Soil Temperature

Statistics for treatment effects on soil moisture and temperature for the fourth and fifth growing seasons are presented in table 1. The greatest difference in soil temperature between treatments was between U treatments. However, there was a significant interaction between OM and U. Soil temperatures were higher in the OM_2 treatment when the U was absent. The significance three-way interaction for year 4 between OM removal, C and U treatments showed that compacted plots tended to have higher temperatures than plots not compacted when the OM removal level was OM_0; and temperatures were always higher when the U was present compared to when it was absent.

The three-way interaction was not significant in year 5, but a two-way interaction between OM removal and U control was (table 1). Likely, considerably more heat was absorbed in U_- plots compared to U_+ plots because of the higher soil moisture content. In a regenerating clearcut such as this, most of the sunlight reaches the forest floor. Seasonal soil temperature differed little between OM removal and C treatments in year 4. However, soil temperature variations between treatment levels were much more apparent for each treatment throughout the measurement period for year 5 (data not presented).

Table 1.—*Mean soil moisture and temperature measurements and their p value if greater than 0.05 for significant interactions at the 20 cm depth, according to treatments for the fourth and fifth growing season in the Missouri LTSP study*

Treatment[1]	Soil moisture Year 4	Soil moisture Year 5	Soil temperature Year 4	Soil temperature Year 5
	-------- Percent------		----------- ºC -----------	
Organic matter removal				
OM_0	28.33 a	23.23 a[2]	18.08 a	11.62 a
OM_2	25.81 a	20.84 a	18.19 a	14.88 b
Compaction				
C_0	29.29 a	25.29 a	17.89 a	11.88 a
C_2	24.81 b	19.30 b	18.38 a	14.21 a
Understory				
U_-	27.65 a	33.54 a	16.45 a	16.30 a
U_+	24.85 a	6.31 b	19.56 b	10.48 b
OM x C	NS	0.0035	0.0002	NS
OM x U	NS	NS	0.0243	0.0012
C x U	NS	NS	NS	NS
OM x C x U	NS	NS	0.0001	NS

[1]Organic matter removal = bole only (OM_0) and whole tree plus forest floor (OM_2). Soil compaction = none (C_0) and severe (C_2). Understory = understory absent (U_-) and understory present (U_+).

[2]Means followed by the same letter are not significantly different (NS) from each other ($P \geq 0.05$) within a column and treatment by Tukey's test.

The increase in soil temperature for OM_2 plots over OM_0 plots in year 5 may be attributed to exposure of the forest floor to sunlight and the lack of a forest floor litter layer in the OM_2 treatment to insulate the soil compared to OM_0 where the forest floor and litter was not removed. Carey and others (1981) observed that harvest residues created an insulating layer over the site. Messina and others (1997) reported that in addition to sunlight reaching the forest floor, microbial and root activity may also cause higher temperatures, especially following forest disturbance.

Soil Moisture

Soil moisture at the 20 cm depth differed significantly between compaction levels in year 4 (table 1), averaging almost 4 percent higher in the C_0 treatment than in the C_2 treatment. In year 5, there was a significant interaction between OM removal and soil C treatments which showed that soil moisture was highest for OM_0C_0, decreased more by the combination of OM_0C_2 than by OM_2C_2 or OM_2C_0. Also, in year 5, soil moisture differed between levels of U control. Soil in U_- treatments had 27 percent more moisture than soil in U_+ treatments. Undoubtedly, U made a major difference in soil moisture at the 20 cm depth on this site. Fifth year soil moisture data showed wider differences between treatment levels, and low, rather than high treatment levels, plus controlling the U produced higher soil moisture at the 20 cm depth.

The insulating effect of debris remaining after harvest on OM_0 plots reduced moisture loss from evaporation. Also, the degree of variation in soil moisture is also dependent on type and amount of vegetative cover, particularly in both clearcut hardwood and pine stands (Haines and Cleveland 1981).

Soil moisture was lower for treatment combinations in C_2 plots than for C_0 plots for both year 4 and for year 5. These results indicate that compaction reduced soil moisture at the 20 cm depth for this site. Soil bulk density at planting at the 20 cm depth was 1.49 g/cm^3 for C_0 plots compared to 1.88 g/cm^3 for C_2 plots (Ponder 1997).

Understory did not affect soil moisture in year 4 but did in year 5 (table 1). The lack of effect in year 4 may be due to the greater than usual rainfall for that year and over the measurement period. The plots received approximately

65.3 cm of rain during May through August and 137.1 cm for the year compared to year 5 when plots received 20.3 cm and 79 cm for the year. This indicates that when soil moisture is high, treatment effects are less likely to be significant.

Major Leaf Nutrients

Statistics for the effects of treatments on leaf nutrient levels for all tree species are presented in table 2. For northern red oak, there was a significant interaction for N between OM removal and U which showed that N was lower (1.83 percent) for OM_0U_+ than for OM_2U_+ (2.04 percent), but was the same (2.30 percent) for OM_2U_- and OM_0U_-treatments, which had the higher N levels. A similar interaction affected the P concentration. Phosphorus concentrations were highest in U_- plots, but it was slightly lower in OM_0U_+ plots. The interaction between OM removal and soil C on K was the lowering of K concentration in compacted treatments. Calcium was significantly higher in northern red oak leaves for U_- plots than for U_+ plots, but the opposite was true for Mg.

White oak leaf nutrient concentrations (N, P, K, C, and Mg) were significantly affected by U treatments (table 3). The interaction between OM removal and soil C showed a decrease in P and K concentrations for the OM_2C_0 treatment compared to OM_2C_2, but for Ca, treatment combination had the highest concentration. In the three-way interaction, Ca concentrations were higher in the $OM_2C_0U_+$ treatment than for $OM_2C_0U_-$ treatment.

As for shortleaf pine, controlling the U significantly increased N, P, and K concentrations in shortleaf pine needles. There were significant interactions for N, Ca, and Mg concentrations. Leaf N was higher for treatment combinations OM_0C_0 and OM_2C_2 than for OM_0C_2 and OM_2C_0. In the three-way interaction, both Ca and Mg levels were highest for the severe compaction treatment (C_2), but these nutrients either increased or decreased with severe compaction in combination with the different levels of OM removal and U.

Minor and Trace Nutrients

Statistics for leaf concentrations of S, Fe, Mn, Zn, and B, are presented in table 3. For northern red oak, there was an interaction for S between OM removal and U, which showed that S concentrations were highest for the OM_0U_- treatment and progressively decreased for OM_2U_-, OM_2U_+, and OM_0U_+ treatments. The three-way interaction between organic matter removal, compaction, and understory for Zn and B showed that concentrations were highest when the understory was controlled, but was also higher when combined with severe compaction compared to no compaction. The contribution of organic matter removal followed no general pattern.

For white oak, there was an interaction between OM removal and soil C, which showed that the higher levels of Mn were associated with the higher level of compaction (table 3). Interactions for S, Fe, and Zn showed that U and OM removal were major contributors to the concentration level. Mean leaf concentrations of S, Fe, and Zn were lower when OM_2 was part of the treatments compared to OM_0. Also, concentrations were higher when U was absent compared to when the U was present.

For shortleaf pine, there was an interaction for S between OM removal and soil C, which showed the order for treatment combinations was $OM_2C_2 > OM_0C_0 > OM_0C_2 > OM_2C_0$. The effects of U were also significant for Fe. It was higher for U_+ than for U_- treatments (table 3). The significant interaction between soil C and U showed that Mn concentrations were higher for trees with U than without U. The order of treatment combinations for decreasing Mn were in the sequence $C_2U_+ > C_0U_+ > C_0U_- > C_2U_-$. Both Zn and B were affected by a two-way interaction between soil C and U and a three-way between the three treatments. The two-way interaction showed that both Zn and B were higher for treatment combinations C_0U_- and C_2U_+ than for C_2U_- or C_0U_+. The three-way interaction for Zn and B showed that levels were higher for the treatment combination OM_2C_2 than for OM_0C_0 with no clear trend for the contribution of U treatments.

Soil nutrient levels are not presented in this report. However, Johnson and Todd (1998), who investigated the long-term changes in nutrient pools of a mixed oak forest following saw log harvesting vs. whole-tree harvesting, reported that significant differences found in foliar nutrient concentrations were consistent with differences in soil nutrient concentrations. Also, some differences or trends in leaf nutrient concentrations may be due to higher rates of organic matter decomposition from stand residues.

There were few significant leaf nutrient concentrations that could be attributed to main effects alone (OM removal and soil C). However, soil C can reduce aeration and cause poor root ramification, thus reducing the uptake of nutrients. Limited water and nutrient availability to plants due to compaction are major constraints to plant growth. Youngberg (1959) concluded that soil K and P fixation occurs more readily as moisture availability decreases as reported for this study for soils in C_2 plots.

The big effect that tended to be common for many leaf nutrients was the importance of understory (tables 2 and 3). Leaf nutrient concentrations were not always highest for treatment combinations for U_- plots. Weeds reduce the amount of water and nutrients available to trees growing in their vicinity. Understory competition for nutrients and water can increase seedling mortality and decrease foliar nutrient concentrations. Périé and Munson (2000), who evaluated scarification,

Table 2.—*Leaf macro nutrient concentrations and p value if greater than 0.05 for significant interactions for 5-year-old northern red oak, white oak, and shortleaf pine in the Missouri Long-Term Soil Productivity study*

		Nutrient				
Species	**Treatment**[1]	**N**	**P**	**K**	**Ca**	**Mg**
		g/kg				
N. red oak	OM_0	20.80 a[2]	1.09 a	6.31 a	8.88 a	1.90 a
	OM_2	21.51 a	1.18 b	6.18 a	8.20 a	1.95 a
	C_0	21.69 a	1.17 a	6.42 a	8.80 a	1.93 a
	C_2	20.63 a	1.10 a	6.08 a	8.26 a	1.46 a
	U_-	22.98 a	1.13 a	6.01 a	9.20 a	1.65 a
	U_+	19.34 b	1.16 a	6.48 b	7.86 b	2.21 b
	OM x C	NS	NS	0.053	NS	NS
	OM x U	0.046	0.022	NS	NS	NS
	C x U	NS	NS	NS	NS	NS
	OM x C x U	NS	NS	NS	NS	NS
White oak	OM_0	19.11 a	1.03 a	5.75 a	9.73 a	1.47 a
	OM_2	18.94 a	1.08 a	5.92 a	10.03 a	1.34 a
	C_0	19.62 a	1.01 a	5.62 a	10.27 a	1.35 a
	C_2	18.43 b	1.10 a	6.05 a	9.50 a	1.56 a
	U_-	20.03 a	0.97 a	5.31 a	9.20 a	1.25 a
	U_+	18.01 b	1.14 b	6.35 b	10.57 b	1.56 b
	OM x C	NS	0.049	0.002	0.006	NS
	OM x U	NS	NS	NS	NS	NS
	C x U	NS	NS	NS	NS	NS
	OM x C x U	NS	NS	NS	0.042	NS
Shortleaf pine	OM_0	14.97 a	1.07 a	5.60 a	2.03 a	0.85 a
	OM_2	14.90 a	1.08 a	5.84 a	1.93 a	0.93 a
	C_0	14.52 a	0.94 a	6.43 a	1.76 a	0.72 a
	C_2	14.91 a	1.00 a	6.51 a	2.21 b	1.70 a
	U_-	16.57 a	1.12 a	5.99 a	1.90 a	0.86 a
	U_+	13.29 b	1.03 b	5.20 b	2.05 a	0.91 a
	OM x C	0.002	NS	NS	NS	0.023
	OM x U	NS	NS	NS	NS	NS
	C x U	NS	NS	NS	0.004	0.035
	OM x C x U	NS	NS	NS	0.001	0.001

[1]Organic matter removal = bole only (OM_0) and whole tree plus forest floor (OM_2). Soil compaction = none (C_0) and severe (C_2). Understory = understory absent (U_-) and understory present (U_+).

[2]Means between treatment levels followed by the same letter are not significantly different from each other (P ≥ 0.05) within a column and treatment by Tukey's test.

fertilization, and herbicide treatments, applied alone and in combinations on white pine (*Pinus strobus* L.) in Ontario, Canada, reported that many of the effects of understory control that were present at age 4 were present at age 10.

Tree Growth

There were significant interactions between OM removal and soil C for height, height growth, and d.b.h. of northern red oak, and for the height of white oak, but not for shortleaf pine (table 4). Also, there were significant interactions between U and soil C for all species. For northern red oak, height, height growth, and d.b.h. were less in plots that received the combination of OM_0 and C_2 treatments compared to trees in plots receiving OM_0 and C_0 treatments. But height, height growth, and diameter of

Table 3.—*Some minor and trace leaf nutrient concentrations and p value if greater than 0.05 for significant interactions of 5-year-old northern red oak, white oak, and shortleaf pine in the Missouri Long-Term Soil Productivity study*

Species	Treatment[1]	S	Fe	Mn	Zn	B
		Nutrient				
		g/kg		µg/kg		
N. red oak	OM_0	0.124 a[2]	93.17 a	962.54 a	34.95 a	35.75 a
	OM_2	0.117 a	87.17 a	1,200.33 b	35.08 a	32.59 a
	C_0	0.123 a	85.50 a	1,033.17 a	34.26 a	33.54 a
	C_2	0.119 a	94.83 a	1,129.71 a	35.77 a	34.69 a
	U-	0.129 a	109.25 a	1,094.88 a	38.57 a	34.60 a
	U+	0.113 b	71.08 b	1,068.00 a	31.45 b	33.73 b
	OM x C	NS	NS	NS	0.035	NS
	OM x U	0.015	NS	NS	NS	NS
	C x U	NS	NS	NS	NS	NS
	OM x C x U	NS	NS	NS	0.010	0.025
White oak	OM_0	0.116 a	65.63 a	742.46 a	16.70 a	47.17 a
	OM_2	0.123 a	75.38 a	804.96 a	16.63 a	47.37 a
	C_0	0.116 a	67.54 a	679.08 a	16.91 a	43.61 a
	C_2	0.113 a	73.46 a	868.33 b	16.42 a	50.94 a
	U-	0.118 a	68.50 a	618.13 a	18.11 a	50.00 a
	U+	0.121 a	72.50 a	929.29 b	15.23 b	44.54 a
	OM x C	NS	NS	0.029	NS	NS
	OM x U	0.049	NS	NS	NS	NS
	C x U	NS	NS	NS	NS	NS
	OM x C x U	NS	0.051	NS	0.042	NS
Shortleaf pine	OM_0	0.087 a	68.46 a	305.29 a	42.21 a	13.92 a
	OM_2	0.086 a	48.00 a	369.46 a	39.93 a	14.29 a
	C_0	0.088 a	70.79 a	302.08 a	39.84 a	14.97 a
	C_2	0.083 b	45.67 a	372.67 a	42.33 a	3.24 a
	U-	0.092 a	41.92 a	248.29 a	41.33 a	14.75 a
	U+	0.079 b	74.54 b	426.46 b	40.81 a	13.45 a
	OM x C	0.001	NS	NS	NS	NS
	OM x U	NS	NS	NS	NS	NS
	C x U	0.020	NS	0.003	0.001	0.003
	OM x C x U	NS	NS	NS	0.001	0.001

[1]Organic matter removal = bole only (OM_0) and whole tree plus forest floor (OM_2). Soil compaction = none (C_0) and severe (C_2). Understory = understory absent (U_-) and understory present (U_+).

[2]Means between treatment levels followed by the same letter are not significantly different (NS) from each other ($P \geq 0.05$) within a column and treatment by Tukey's test.

northern red oak in OM_2 treated plots with either C_0 or C_2 followed the order of OM_0C_0 > $OM_2C_0 \geq OM_2C_2 > OM_0C_2$. The d.b.h. for white oak was largest for trees in the combination OM_0C_2, followed by OM_0C_0, OM_2C_2, and OM_2C_0. The height growth and d.b.h. of northern red oaks in the C_0U_- treatment were largest followed by C_2U_-, C_2U_+, and C_0U_+.

The three-way interaction showed that plots with the treatment combination of no compaction, bole only removal, and no understory

Table 4.—*Planted height and diameter at 1 centimeter above the ground, height and d.b.h. after 5 years, and total growth difference between treatments along with p value if greater than 0.05 for significant treatment interactions for northern red oak, white oak, and shortleaf pine for the Missouri Long-Term Soil Productivity study*

Tree and	**Planted**		**After 5 years**			**Treatment difference**		
Treatment[1]	**Ht.**	**Dia.**	**Ht.**	**Ht. growth**	**d.b.h**	**Ht.**	**Ht. growth**	**d.b.h.**
	cm	**mm**	**cm**	**cm**	**mm**	---------- **Percent** ----------		
N. red oak:								
OM_0	34.22 a[2]	4.53 a	101.07 a	65.98 a	15.64 a			
OM_2	33.04 a	4.90 a	97.87 a	64.87 a	15.34 a	3	2	2
C_0	34.11 a	4.61 a	103.79 a	70.11 a	15.57 a			
C_2	34.24 a	4.72 a	94.45 b	60.22 b	15.37 a	9	14	1
U_-	33.69 a	4.84 a	104.52 a	70.74 a	18.16 a			
U_+	34.28 a	4.63 a	94.23 b	60.13 b	12.86 b	10	15	29
OM x C_-	--------	--------	0.0003	0.0435	0.0071			
U x OM	--------	--------	0.0221	NS	NS			
U x C	--------	--------	NS	0.0110	0.0134			
U x OM x C	--------	--------	NS	0.0471	NS			
White oak:								
OM_0	16.56 a	4.53 a	81.76 a	65.10 a	14.75 a			
OM_2	15.93 a	4.44 a	71.34 b	55.13 b	13.46 b	13	15	9
C_0	16.44 a	4.54 a	76.08 a	59.43 a	14.44 a			
C_2	15.96 a	4.50 a	75.87 a	59.70 a	13.63 b	<1	<1	6
U_-	16.27 a	4.48 a	81.42 a	65.02 a	16.81 a			
U_+	16.24 a	4.58 a	70.37 b	53.94 b	11.18 b	14	17	33
OM x C	--------	--------	0.0394	NS	NS			
U x OM	--------	--------	NS	NS	NS			
U x C	--------	--------	NS	NS	0.0021			
U x OM x C	--------	--------	NS	NS	NS			
Shortleaf pine:								
OM_0	15.58 a	3.06 a	188.98 a	170.30 a	38.10 a			
OM_2	14.78 a	3.07 a	185.26 a	165.41 a	35.84 a	2	3	6
C_0	15.06 a	2.75 a	173.02 a	157.32 a	33.07 a			
C_2	14.49 a	2.93 a	200.79 b	185.55 b	40.94 b	14	15	19
U_-	14.87 a	3.01 a	193.87 a	169.61 a	42.84 a			
U_+	15.43 a	3.01 a	180.86 a	173.67 a	31.49 b	7	2	26
OM x C	--------	--------	NS	NS	NS			
U x OM	--------	--------	NS	NS	NS			
U x C	--------	--------	0.0028	0.0019	0.0095			
U x OM x C	--------	--------	NS	NS	NS			

[1]Organic matter removal = bole only (OM_0) and whole tree plus forest floor (OM_2). Soil compaction = none (C_0) and severe (C_2). Understory = understory absent (U_-) and understory present (U_+).

[2]Means between treatment levels followed by the same letter are not significantly different (NS) from each other ($P \geq 0.05$) within a column and treatment by Tukey's test.

($OM_0C_0U_-$) had the most height growth followed by plots with severe compaction, whole tree plus forest floor removal, and no understory ($OM_2C_2U_-$). Plots with the lowest amount of height growth were those with severe compaction and an understory (C_2U_+) plus only boles removed or the whole tree plus forest floor removed.

The effect of the significant interaction for white oak height showed that the tallest trees were in OM_0C_0 plots followed by OM_0C_2, OM_2C_2 and OM_2C_0. White oak trees with the largest d.b.h. were in the C_0U_- and C_2U_- treatment combinations followed by C_2U_+ and C_0U_+. The interaction effects of soil C and U were somewhat different for height and d.b.h. of shortleaf pine. The tallest trees were in treatments receiving the highest level of soil C with and without U control followed by C_0U_- and C_0U_+. But shortleaf pines in C_2U_- treatment had the most height growth, followed by C_0U_-, C_2U_+, and C_0U_+. Treatment combinations with the largest d.b.h. for shortleaf pine were in plots with U control, in the order of C_2U_-, C_0U_-, C_2U_+, and C_0U_+.

Overall, soil C decreased the height and height growth of northern red oak, the d.b.h. of white oak, and increased the height, height growth, and d.b.h. of shortleaf pine. Apparently soil conditions created by soil C were more favorable for the growth of shortleaf pine than for northern red oak or white oak. Perhaps differences in root morphology and physiology of shortleaf pine compared to the oaks could account for some of the better growth.

Controlling the U caused a marked increase in all growth variables for northern red oak and white oak, but only the d.b.h. of shortleaf pine. Undoubtedly, trees benefited from the absence of U. In general, more of the leaf nutrients were higher for all species in U_- plots compared to U_+ plots. However, these nutrient data must be interpreted with some caution because they do not take plant biomass into account, which if considered, could indicate a dilution effect for faster or slower growing trees. For example, white oak grew significantly better in the U_- treatment, but the U_+ treatment had, with few exceptions, higher leaf nutrient concentrations (tables 2 and 3). Foliar nutrient levels were in the sufficiency range for all species (Mills and Jones 1996).

SUMMARY

Differences in soil moisture and temperature, leaf nutrient concentrations, height, height growth, and d.b.h. after 5 years, can be, in part because of significant interactions, attributed to OM removal and soil C treatments. With some exceptions, soil C decreased the height and height growth of northern red oak, the d.b.h. of white oak, and increased the height, height growth, and d.b.h. of shortleaf pine. Apparently soil conditions created by soil C were more favorable for the growth of shortleaf pine than for northern red oak or white oak. Furthermore, these results indicate that although there were indications of soil C and OM removal evident at age 5, the effect of understory vegetation impacted soil moisture and temperature, tree nutrition, and growth as much or more than organic matter removal or soil compaction on this site. The full impact of organic matter removal and soil compaction may not be realized until there is crown closure in these tree stands.

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