CONTRASTING THE EFFECTS OF ORGANIC MATTER REMOVAL AND SOIL COMPACTION ON ROOT BIOMASS OF 9-YEAR-OLD RED OAK, WHITE OAK, AND SHORTLEAF PINE IN A MISSOURI OZARK FOREST

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Abstract.—Nine-year old artificially regenerated red oak (*Quercus rubra* L.), white oak (*Q. alba* L.), and shortleaf pine (*Pinus echinata* Mill.) trees were excavated from plot borders of a U.S. Forest Service long-term soil productivity study in the Carr Creek State Forest near Ellington, MO, to quantify treatment effects on above- and belowground tree biomass. The study consists of factorial combinations of soil compaction and organic matter removal treatments that are replicated three times. Seventy-two trees were removed from treatments containing two levels each of soil compaction (SC) and organic matter removal (OMR) with weed control (WC) and without weed control (NWC). Except for red oak, neither SC nor OMR alone affected root or shoot biomass production (weights) for trees in the study. However, biomass for both root and shoot were affected by interactions between SC and OMR with and without weed control. Regardless of the SC or OMR treatments, root biomass was higher with WC than NWC. Only the root:shoot ratio of red oak was affected by treatments, where it was higher for trees in the severe SC treatment than for trees in the no soil compaction treatment. Overall, measurements of above- and belowground biomass on plot border trees indicate that after nine growing seasons, site productivity has been affected more by the WC treatment than by SC or OMR.

INTRODUCTION

Roots utilize space in the soil. The more space roots control, the more potential resources they control. Coarse root (>2 mm in diameter) production reflects the vigor of the tree's growth (Theodorou and Bowen 1993) and it increases with increasing resource availability (Albaugh and others 1998). However, soil disturbance can influence the behavior of tree roots, thereby impacting forest productivity. Reductions in soil porosity through compaction and losses in nutrients through site organic removal are considered potentially detrimental consequences of forest operations (Kozlowski 1999, Kranabetter and others 2006). Kranabetter and others (2006) go on to say, "Quantifying the effects of these disturbances on soil properties and tree growth is an ongoing objective of the long-term soil productivity (LTSP) studies" (Powers 2006). While soil disturbance treatments will likely affect specific chemical and physical properties that can be characterized by measurement of soil properties, tree responses to disturbance treatments will be based on impacts seen in aboveground biomass rather than in belowground biomass.

Early LTSP treatment responses were noted by differences in tree growth associated with differences in soil compaction (SC) and understory control (WC) and/or their interactions; organic matter removal (OMR)

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resulted in fewer responses (Fleming and others 2006, Page-Dumroese and others 2006). Moderate soil disturbance has been found to create better growing conditions for some, but not all, tree species on medium- or coarse-textured soils (Brais 2001, Gomez and others 2002, Kabzems and Haeussler 2005, Ponder 2007). The main objective of this study was to assess the root and shoot biomass of trees planted in the Missouri LTSP study in plots treated with two levels of soil compaction (none and severe), two levels of organic matter removal (bole only and whole tree plus forest floor removed), and two levels of understory control or weed control (with and without weeds) using trees excavated from plot borders.

METHODS AND MATERIALS

SITE AND STUDY DESCRIPTION

This work was conducted using trees in the LTSP Study, on the Missouri Department of Conservation's Carr Creek State Forest in Shannon County. The study is located on upper slopes (slopes range from 20 to 28 percent) of two north-facing parallel ridges (Ponder and Mikkelson 1995). Soils are predominately Clarksville (loamy-skeletal, mixed, mesic Typic Paleduits). The soil is primarily derived from Ordivician and Cambrian dolomite with some Precambrian igneous rock (Missouri Geological Survey 1979). Mean annual precipitation and temperature are 112 cm and 13.3 °C, respectively. Moisture drains easily through the soil to subsurface channels. The pre-harvest forest was occupied by a mature, second-growth oak-hickory forest type. Site index ranged from 74 to 80 based on *Quercus velutina* Lam. at 50 years (Hahn 1991). The Missouri LTSP study has three levels of OMR—bole only (BO), whole tree (WT), and whole tree plus forest floor (WTFF)—and three levels of SC: none (NC), medium (MC), and severe (SSC). The factorial design was replicated three times. One-year-old red oak (*Quercus rubra* L.), white oak (*Q. alba* L.), and shortleaf pine (*Pinus echinata* Mill.) were planted 3.66 m apart in rows 3.66 m apart at a ratio of three oaks of each species to one shortleaf pine in spring 1994. For the first 2 years, a manually operated backpack sprayer was used to spray all plots annually in late spring with a mixture of glyphosate [N-(phosphonomethyl) glycine] and simazine (6-chloro-*N'*,*N'*-diethyl-1,3,5-triazine-2-4-diamine) at the recommended rate of 3 and 3.6 kg a.i. ha^{-1}, respectively, to control weeds and to enhance the establishment of 1-year-old planted tree seedlings. Beginning in year 3, the understory (weeds) in half of all plots was controlled while the other half of the plot had no weed control.

For this experiment, fewer treatments were used from the original nine in the LTSP study. Treatments were as follows:

- two levels of OMR: merchantable boles only (BO) and WTFF
- two levels of SC: no soil compaction (NSC) and SSC
- two levels of WC: half of each plot treated to control weeds (WC) and the other half untreated so weeds were free to grow (NWC)

Plots are approximately 0.4 ha in size and randomly selected trees in the border rows from 12 of the 27 plots were used.

Excavating Trees

Trees selected for excavation were located within the treated buffers surrounding the core measurement plots. Heights and diameters were determined and trees were excavated using a backhoe in the fall after several killing frosts and after their ninth growing season. Intact trees (above- and belowground parts) were excavated to recover maximum root (root crowns) volume (3 trees x 2 subplots x 12 plots = 72 trees, or 24 each of red oak, white oak, and shortleaf pine) with minimal damage to remaining trees. Trees were excavated within a 1.5- x 1.5-m square about 1 m deep. The goal was to maximize the removal of roots in the 2.25-sq m area. For most trees, the backhoe disturbed the soil within the measured area sufficiently to allow trees to be lifted from the soil matrix by two individuals. For the larger trees, soil was removed around trees before the backhoe bucket was able to successfully remove the tree. Before roots and shoots were put into separate bags, the excavated trees, including root ball (soil and root) and shoot were cut into lengths when necessary; put in large, clear, thick-walled plastic bags; labeled according to date, plot, subplot, tree number, and name; and closed with plastic ties for transport to the U.S. Forest Service Laboratory at Lincoln University in Jefferson City, MO. Excavations and areas of disturbed soil were filled and/or leveled to initial ground height.

Preparation for Drying and Weighing Roots and Shoots

At the laboratory, bags containing shoot parts were opened and positioned on benches in the greenhouse for air drying. Roots were washed in a gentle stream of tap water from a garden hose after roots were soaked in garbage containers containing tap water overnight. After washing, roots were placed in newly labeled plastic bags and positioned on benches in the greenhouse for air drying. Roots and shoots were allowed to air dry in the greenhouse for approximately 6 months (last week in December 2003 to third week of June 2004). Greenhouse temperature was kept at 71 °C for five days during the third week in June 2004 before root and shoot weights were determined using an Ohaus digital scale (Ohaus Corporation, Pine Brook, NJ).

Statistical Analysis

Root and shoot biomass (weights) and growth measurements were analyzed as a 2 x 2 factorial split-plot for weed control treatments replicated three times using PROC GLM procedure (SAS 9.1, SAS Institute, Cary, NC) and root and shoot means are reported. Statistical significance was set at $\alpha = 0.05$.

RESULTS

MAIN TREATMENT EFFECTS

After 9 years, controlling the understory (weeds) on plots of planted trees contributed significantly to increases in shoot diameter for all three species excavated in the border of plots in this study compared to border trees on plots not treated to control weeds. Root and shoot weights were higher for trees in WC plots by 80 and 82 percent, by 68 and 71 percent, and by 64 and 43 percent, respectively for red oak, white oak, and shortleaf pine compared to these species in the NWC treatment (Table 1). But shoot height increases attributed to weed control for trees in WC treatment were insignificant compared to NWC treatment (Table 2). Also, neither shoot height nor diameter was affected by OMR or SC. Except for the shoot dry weight of red oak, however, there were significant interactions between OMR and WC and/or SC, thus yielding two- or three-way interactions.

Treatment Interactions for Organic Matter Removal

Shoot dry weight was not affected by OMR alone for any tree species, but there was a significant three-way interaction (WC x OMR x SC, *P=0.0184*) for white oak (Table 1). Shoot dry weight was higher with WC than without, regardless of the level of OMR and SC. Total root biomass was higher for red oaks in the BO treatment than for red oaks in the WTFF treatment, but the two-way interaction (WC x OMR, *P=0.0172*) showed that the mean root dry weight was higher for the BO with WC than with the WTFF treatment with WC. Neither OMR alone nor interactions with WC or SC affected shoot or root weight of shortleaf pine (Table 2).

Table 1.—Dry weights of stem and root biomass and root:shoot ratio (mean ± standard deviation) for excavated red oak, white oak, and shortleaf pine planted in a Missouri clear-cut with organic matter removal, soil compaction, and understory control treatments.

Treatment	Biomass		Root/shoot ratio
	Stem (kg)	Root (kg)	
Red oak			
Organic matter removal (OMR)			
Bole only (BO)	6.4(1.4)a*	4.3(4.4)a	0.8(0.2)a
WT + forest floor (WTFF)	4.4(2.4)a	2.6(2.6)b	0.9(1.8)a
Soil compaction (C)			
No soil compaction (NSC)	6.5(1.7)a	4.5(4.5)a	0.8(0.3)a
Severe soil compaction (SSC)	4.2(2.1)a	2.4(2.4)b	1.0(0.6)b
Weed control (WC)			
Weed control (WC)	8.0(2.1)a	6.3(5.5)a	0.8(0.2)a
No weed control(NWC)	1.4(0.2)b	1.3(1.2)b	0.9(1.3)a
p-values for treatment interactions‡			
OMR x C	0.8054	0.1158	0.4814
WC x OMR	0.8884	0.0253	0.4243
WC x SC	0.3165	0.0013	0.5751
WC x OMR x SC	0.0675	0.4171	0.6159
White oak			
Organic matter removal (OMR)			
Bole only (BO)	3.7(0.9)a	3.8(1.1)a	1.4(0.4)a
WT + forest floor (WTFF)	3.7(1.1)a	3.3(0.9)a	1.0(0.3)a
Soil compaction (C)			
No soil compaction (NSC)	3.5(0.8)a	3.3(0.8)a	1.4(0.2)a
Severe soil compaction (SSC)	4.0(1.3)a	3.7(1.3)a	1.0(0.4)a
Weed control (WC)			
Weed control (WC)	6.0(1.4)a	5.4(1.4)a	0.9(0.5)a
No weed control (NWC)	1.6(0.6)b	1.7(0.7)b	1.4(0.3)a
p-values for treatment interactions‡			
OMR x C	0.4564	0.4070	0.4701
WC x OMR	0.1333	0.3009	0.6441
WC x SC	0.3954	0.3545	0.3512
WC x OMR x SC	0.0002	0.0160	0.0881
Shortleaf pine			
Organic matter removal (OMR)			
Bole only (BO)	15.3(5.9)a	5.5(1.3)a	0.4(0.8)a
WT + forest floor (WTFF)	17.5(6.3)a	6.9(1.7)a	0.6(0.8)a
Soil compaction (C)			
No soil compaction (NSC)	19.0(6.0)a	6.3(1.4)a	0.4(0.3)a
Severe soil compaction (SSC)	13.9(6.4)a	6.0(0.9)a	0.5(1.2)a
Weed control (WC)			
Weed control (WC)	26.0(8.5)a	9.0(1.7)a	0.4(0.3)a
No weed control (NWC)	9.8(5.0)b	3.3(1.1)b	0.5(0.8)a
p-values for treatment interactions‡			
OMR x C	0.5633	0.2317	0.2252
WC x OMR	0.5407	0.1398	0.3040
WC x SC	0.0158	0.0014	0.9309
WC x OMR x SC	0.3225	0.4029	0.5488

*Within each column, mean values for treatment differences for a treatment category with the same letter are not significantly differently at α = 0.05 according to Tukey test.

‡*p-values* for treatment interactions greater than 0.05 are not significantly different.

Table 2.—Dry weights of stem and root biomass (mean ± standard deviation) for excavated red oak, white oak, and shortleaf pine planted in a Missouri clearcut with organic matter removal, soil compaction, and understory control treatments.

Treatment	Red oak Stem	Red oak Root	White oak Stem	White oak Root	Shortleaf pine Stem	Shortleaf pine Root
			kg			
Organic matter removal (OMR)						
Bole only	6.4(4)a*	4.3(2)a	3.7(2)a	3.8(1)a	13.6(5)a	5.5(1)a
WT + forest floor	4.4(2)a	2.6(1)b	3.7(1)a	3.3(1)a	14.0(5)a	6.9(1)a
Soil compaction (C)						
No compaction	6.5(3)a	4.5(2)a	3.5(1)a	3.8(1)a	16.5(6)a	6.3(1)a
Severe compaction	4.2(1)a	2.4(1)b	4.0(1)a	3.3(1)a	11.1(4)a	6.0(1)a
Weed control (WC)						
Weed control (WC)	8.0(5)a	6.3(2)a	5.7(2)a	5.4(1)a	17.1(5)a	9.0(2)a
None (NWC)	1.4(1)b	1.3(1)b	1.6(1)b	1.7(1)b	9.8(5)b	3.3(1)b
p-values for treatment interactions‡						
OMR x C	0.5143	0.6621	0.4035	0.1437	0.2348	0.2562
WC x OMR	0.9283	0.2892	0.4997	0.3009	0.9688	0.1398
WC x C	0.5302	0.0652	0.6662	0.3545	0.0769	0.0014
WC x OMR x C	0.3819	0.8167	0.1094	0.0160	0.9180	0.4029

*Within each column, mean values for treatment differences for treatment categories with the same letter are not significantly differently at α = 0.05 according to Tukey test.

‡*p-values* for treatment interactions greater than 0.05 are not significantly different.

Treatment Interactions for Soil Compaction

While shoot dry weights for both red oak and shortleaf pine tended to be higher for trees in the NC treatment than in the SSC treatment, soil compaction alone did not significantly affect shoot dry weights for any of the three species (Table 2). There was a significant interaction for shortleaf pine between WC and SC (*P=0.0074*). With NC and WC, shortleaf pine shoot dry weights were nearly two times higher than that for shoots in the SSC treatment with or without WC. The root weights of red oak and shortleaf pine were significantly affected by the interaction between SC and WC (*P=0.0007* and *0.0017*, respectively). Both had higher total root biomass in the NC + WC treatment than in the SSC + NWC treatment. But with NWC, root weights were similar regardless of SC treatment for red oak and heavier for shortleaf pine roots in the SSC + NWC treatments than in the NC + NWC. Root weights of white oak were affected by a three-way interaction (WC x OMR x SC, *P=0.0160*). Regardless of the compaction and organic matter removal treatment, root weights were higher with WC than with NWC.

Among tree species, the root:shoot ratio determinations between treatments were significant (*P=0.05*) only for SC for red oak (Table 1). The allocation of aboveground and belowground biomass among tree species responded differently to OMR and SC. With no soil compaction, red oak in the BO treatment had a distribution of 64 to 36 percent aboveground to belowground biomass (root:shoot ratio = 0.55) compared to 53 and 47 percent for aboveground and belowground biomass with severe compaction (root:shoot ratio = 0.90). In the WTFF treatment with no compaction, the percent biomass distribution aboveground and belowground for red oak was 53/47 (root:shoot ratio = 0.89) and was 77/23 (root:shoot ratio = 0.30) with severe compaction.

DISCUSSION

Soil bulk density measurements reported for the LTSP study 5 years after establishment showed that soil compaction had effectively increased bulk density of severe compaction treatments by 22, 29, and 26 percent for the 10-, 20-, and 30-cm depth increments over no compaction treatments (Ponder and others 1995). However, the duration of effects of soil compaction on bulk density increases for the fine-textured cherty soil on this site is not known (Ponder 2004). Research has shown that substantial increases in bulk density of fine-textured soils may (Powers and others 2005) or may not (Sanchez and others 2006) affect tree growth.

For the present study, except for the root dry weight of red oak and significant interactions between treatments, there were no main treatment differences for either OMR or SC (Tables 1 and 2). Fleming and others (2006) conducted a regional comparison of tree growth at age 5 for all the replicates of the LTSP study at the various locations, including the Missouri site, and reported that growth for trees in the Missouri study plots was not affected by OMR, but SC increased shortleaf pine diameter. By age 9, differences between NC and SSC for the diameter at breast height of shortleaf pine remained significant based on measurement of core plot trees (Ponder 2007). However, this treatment difference for shortleaf pine growth in the larger LTSP study is not reflected in the biomass of excavated border trees. In the present study, one reason for some of the lack of biomass difference of excavated trees in OMR and SC treatments was likely due to restricting excavated trees to border rows; as border trees, some trees apparently did not meet all criteria of core plot trees. Sample trees in the border rows were preselected, taking precautions to minimize erosion and not cause damage to core plot trees from excavating equipment. However, in another LTSP study in North Carolina (Ludovici 2008), 18 planted loblolly pine trees were excavated in the border rows of plots. While tree growth measurements for excavated trees were not significantly different for OMR or SC treatments, growth measurements of excavated trees were consistent with plot tree measurements, which also showed no growth differences between treatments (Sanchez and others 2006).

Soil moisture can often be limited by the presence of understory competition (Gautam 1998). Soil moisture data collected 3 years before trees were excavated showed that soil moisture stress was highest in the NWC plots (Ponder 2004). Soil moisture stress was also higher for NC with NWC than for SSC with NWC treatments. Soil compaction can adversely impact root penetration and create water stress in trees. Blouin and others (2008) in a greenhouse study using lodgepole pine (*Pinus contorta* Dougl. Ex. Loud. var. *latifolia* Engelm.) seedlings reported that compaction influenced seedling growth and biomass at dry water content, but not at wet water contents. In another greenhouse study, Siegel-Issem and others (2005) grew ponderosa pine (*Pinus ponderosa* var. *scopulorum* Dougl. Ex. Laws), shortleaf pine (*Pinus echinata* Mill.), and loblolly pine (*Pinus taeda* L.) seedlings in PVC cylinders and reported that root growth decreased with compaction, with water regulating the effect of compaction on all species. In the present study, the greater root biomass for all three tree species in the WC treatment compared to the NWC treatment can likely be attributed to higher soil moisture and nutrient availability.

The root:shoot ratio was not altered significantly by weed control treatments for any species, despite the difference in growth patterns for above- and belowground biomass between the two treatments (Table 1), suggesting a functional equilibrium between root and shoot (Drew and Ledig 1980, Clinton 1990). Coyle and Coleman (2005) concluded that biomass accumulation does not favor shoots in developing stands, even with favorable soil resources. Other studies show that resource availability in developing stands has little or no effect on relative belowground biomass accumulation (Drew and Ledig 1980, Gebauer and others 1996, Coleman and others 1998). In simply reporting total root biomass in the present study, the author did not account for the more responsive measurement of root activity—biomass allocation—as in the results of a similar study reported by Ludovici (2008).

CONCLUSIONS

Root and shoot biomass (weights) were affected by interactions between soil disturbance treatments consisting of two levels of OMR and SC with and without WC. All significant interactions involved weed control. Results from this work demonstrate that controlling understory vegetation in forest stands can increase root and shoot growth. Except for red oak, neither OMR nor SC alone affected root or shoot biomass production for trees in the study. These findings suggest that growth rates of regenerating red oak stands could be reduced when significant amounts of biomass are removed and when soils are compacted during harvesting operations. Also, these results suggest that because white oak appears less sensitive to disturbance caused by organic matter removal and soil compaction compared to red oak, regenerating severely disturbed sites to white oak could be advantageous.

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