FOREST SOIL PRODUCTIVITY ON THE SOUTHERN LONG-TERM SOIL PRODUCTIVITY SITES AT AGE 5

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Abstract—Forest management operations have the potential to reduce soil productivity through organic matter and nutrient removal and soil compaction. We measured pine volume, bulk density, and soil and foliar nitrogen and phosphorus at age 5 on the 13 southern Long-Term Soil Productivity study sites. The treatments were organic matter removal [bole only (BO), whole tree (WT), whole tree and forest floor (WTFF)], and soil compaction (none, moderate, severe). The WT and WTFF treatments reduced pine volume by 18 percent overall compared to the BO plots, with the greatest reductions occurring on the sites with the lowest inherent site quality. Soil compaction had little effect on pine volume, but bulk density of the compacted plots at age 5 was still elevated, by an average of 5 percent, over the noncompacted plots.

INTRODUCTION

The U.S. Department of Agriculture (USDA) Forest Service (National Forest Management Act of 1976) and forest industry in the United States (American Forest and Paper Association 1995) are committed to practicing sustainable forest management. We must understand how forest management operations affect the ability of a site to provide water and nutrients to the growing forest to ensure that forest management is sustainable. If forest management operations reduce available water or nutrients, then the resulting site productivity potential will be decreased. Whereas forest industry often seeks to improve site productivity through more intensive soil manipulation and fertilization, the USDA Forest Service manages its land within the natural limits of site productivity (Powers and others 1996). This management approach requires an even more rigorous understanding of the basic processes controlling site productivity and the mechanisms by which management affects these processes.

Powers and others (1990) reviewed the literature on productivity change and concluded that if forest management were to have negative impacts on future productivity, it would likely do so through the removal of site organic matter or through soil compaction. Using these concepts, the Forest Service initiated a nationwide study on the impacts of organic matter removal and soil compaction on long-term soil productivity (LTSP).

Direct organic matter removals occur due to harvesting, site preparation, and litter harvesting and affect many soil functions that control productivity. Any level of harvesting will remove large quantities of essential plant nutrients from a site. More intensive practices that harvest branches, foliage, and forest-floor organic debris remove a disproportionately large amount of nutrients for the added biomass removed (Johnson and others 1982). Many nutrients, such as phosphorus (P), do not cycle into a given ecosystem from other systems at a rapid rate, so the total nutrient pool cannot recover following harvest removal without amendments (Mann and others 1988). In addition to maintaining nutrient levels, organic matter serves many other important functions in soils. It serves as a substrate for microbial communities, it helps in forming soil structure, and it helps regulate soil water processes.

Soil compaction resulting from machine traffic during harvest and site preparation can increase soil strength and/or decrease aeration porosity. Both processes can reduce root growth, water and air movement, and solute diffusion. Reduced infiltration caused by soil compaction also greatly increases runoff and concomitant erosion.

Loblolly pine (*Pinus taeda* L.) is the most important commercial tree species in the South and is present across much of the region. Therefore, the LTSP study was installed on 13 loblolly pine sites from Texas to North Carolina to test the effects of organic matter removal and compaction across a wide climatic and productivity gradient. The objectives of this paper are to determine (1) loblolly pine productivity, (2) total soil nitrogen (N) and available P, (3) foliar N and P concentrations, and (4) soil bulk density. These tests occurred at age 5 on replicated plots covering a range of organic matter removal and soil compaction levels.

MATERIALS AND METHODS

Study Sites

Thirteen sites were installed across the Southern United States from 1990 to 1998 (table 1). Four sites (statistical blocks) were installed in the Kisatchie National Forest in Louisiana, while three sites each were installed in the DeSoto National Forest in Mississippi, the Davy Crockett National Forest in Texas, and the Croatan National Forest in North Carolina. The soils associated with these installations cover a wide range of soil types and evapotranspiration levels commonly found across the Gulf and Atlantic Coastal Plains.

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Table 1—General site description data for 13 locations of the long-term soil productivity study in the southern region

Location	Louisiana	Mississippi	North Carolina	Texas
National forest	Kisatchie	DeSoto	Croatan	Davy Crockett
Soil series each block	Malbis Glenmora Metcalf Mayhew	Freest Freest Freest	Lynchburg Goldsboro Goldsboro	Kurth Kurth Kurth
Precipitation (cm)	145(LA1) 148(LA2-4)	151	136	105
Mean annual temperature (°C)	19	18	16	23
Year established	1990 1992 1993 1993	1993 1993 1993	1991 1991 1991	1997 1997 1997
Previous species	Loblolly	Slash	Loblolly	Loblolly, shortleaf, longleaf

Malbis = fine-loamy, siliceous, subactive, thermic Plinthic Paleudults; Glenmora = fine-silty, siliceous, active, thermic Glossaquic Paleudalfs; Metcalf = fine-silty, siliceous, semiactive, thermic Aquic Glossudalfs; Mayhew = fine-silty, smectitic, thermic Chromic Dystraquerts; Freest = fine-loamy, siliceous, active, thermic Aquic Paleudalfs; Lynchburg = fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults; Goldsboro = fine-loamy, siliceous, subactive, thermic Aquic Paleudults; Kurth = coarse-loamy, siliceous, semiactive, thermic Oxyaquic Glossudalfs.

Treatments

On each site (block), nine treatments were imposed in a 2- by 3-factorial design following a clearcut harvest of the existing stand, with organic matter removal and compaction as the main treatment factors. The three organic matter removal treatments were bole-only harvest (BO), whole-tree harvest (WT), and whole-tree harvest plus forest floor removal (WTFF). Compaction was induced by pulling a weighted multitire road compactor across the sites. Severe compaction was intended to raise bulk density to 80 percent of the root-limiting level (Daddow and Warrington 1983). Moderate compaction was intended to result in bulk density values midway between ambient and severe compaction. After treatment installation, loblolly pine seedlings were planted at 2- by 2-m spacing. Each treatment plot was split into two 0.2-ha plots. One of the split plots was kept clear from competing vegetation when needed by manual removal and directed-spray applications of glyphosate. Competing vegetation was allowed to grow freely on the other split plot. Volunteer pines were controlled manually on all plots except in North Carolina, where they were only controlled on the competition-free split plots. Measurement plots were the interior 0.1 ha of each split plot.

Measurements

At age 5, we measured pine tree height and diameter at breast height in the 0.1-ha measurement plot with height poles and calipers. Pine volume was calculated using equations from Baldwin and Feduccia (1987). Soil samples were collected with a custom core extractor from random locations throughout each measurement plot. The sampler extracted a 5-cm-diameter by 30-cm-length soil core, which was then separated into 0- to 10-cm, 10- to 20-cm, and 20- to 30-cm sections. Ten cores were collected per split plot in Louisiana, Mississippi, and Texas, while three cores were collected per split plot in North Carolina. The soils were dried at 105 °C to a constant weight, and bulk density was recorded. A subsample was collected from each core, prior to drying, for soil nutrient analysis. Soil N was determined by combustion analysis with a C/N/S analyzer. Available soil P was determined by Mehlich III extraction (Mehlich 1984). Foliage was collected in September or October at each site. Foliar N was determined with a C/N/S analyzer, while foliar P was determined by digestion followed by colorimetric analysis.

Data Analysis

The data were analyzed in two ways. First, each State was considered as a separate study and analyzed as a randomized complete-block design. The main treatment effects were determined with Proc GLM (SAS Institute 2000) and separated using Duncan's Multiple Range Test at $\alpha = 0.1$. A lower alpha was chosen in order to increase the power of the test and avoid type II errors. Interaction effects were included in the design but are not discussed in this report, nor are the split-plot effects. To widen the overall scope of inference, the study was also analyzed as a RCBD with all 13 blocks. Main effects and separations were performed as in the analysis by State.

To determine the relative influence of site quality, defined as the average volume across all treatment plots, on pine response to organic matter removal, we plotted the pine volume of the two most severe organic matter removal treatments (WT and WTFF) relative to the least severe organic matter removal treatment (BO) against the mean pine volume for each site.

RESULTS

Loblolly pine volume at age 5 declined with increasing intensity of organic matter removal, but was unaffected by soil compaction. The organic matter removal treatments had no effect on pine volume in Louisiana, which averaged 11.6 $m^3 ha^{-1}$ at age 5 (table 2). In Mississippi, pine volume was reduced from 8.71 $m^3 ha^{-1}$ on the BO plots by an average of 45 percent by WT and WTFF harvesting. In North Carolina, pine volume was 15 percent greater on the WT-harvested plots than on the BO-harvested plots. The WTFF harvesting, however, resulted in an 18-percent decrease in pine volume compared to BO harvesting. In Texas, WT harvesting (5.13 $m^3 ha^{-1}$) reduced volume by 25 percent, but WTFF-harvested plots (2.42 $m^3 ha^{-1}$) had only a third the volume of the BO-harvested plots (6.88 $m^3 ha^{-1}$). Across the 13 sites, pine volume was decreased by about 18 percent by harvesting more organic matter than just the merchantable boles. Within Louisiana, North Carolina, and Texas, compaction had no effect on pine volume. In Mississippi, pine volume increased from an average of 5.44 $m^3 ha^{-1}$ on the noncompacted and moderately compacted plots to 7.38 $m^3 ha^{-1}$ on the severely compacted plots.

The relative impact that harvest intensity had on pine volume was strongly related to overall site quality as defined by average stand volume (fig. 1). Because all stands were the same age and began with the same initial stocking, stand volume is an accurate assessment of site quality. When all comparisons were made (WT vs. BO and WTFF vs. BO), the linear relationship was significant ($P < 0.0001$) and explained a majority of the variation ($R^2 = 0.57$). When the most intensive treatment (WTFF) alone was compared to BO harvesting, the relationship explained even more variation ($R^2 = 0.66$). Because the 13 sites sampled cover a wide spectrum of loblolly pine site types, this finding has important implications. It shows that the inherent productivity of a soil largely determines its susceptibility to harvesting-induced losses of productivity. High-quality sites, such as in North Carolina and Louisiana, were not affected by WTFF removal, but poor-quality sites, such as Texas and Mississippi, were.

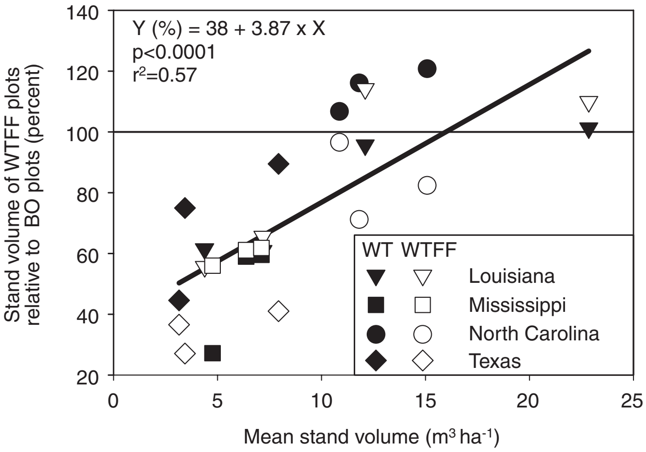

Figure 1—Relative influence of organic matter removal on sites of inherently different quality.

We could not quantitatively compare the average volume estimate of site quality to site index (SI) because the previous stands were not all loblolly pine. However, a cursory examination indicates that SI did not sufficiently indicate which sites were potentially at risk. For example, Texas block 1, one of the poorest sites in terms of average volume, had a SI_{50} for loblolly pine of 26 m. On the other hand, Louisiana block 3, which had a SI_{50} for loblolly pine of 24 m, was one of the most productive sites.

Total soil N and available P were decreased by intensive harvesting in Louisiana and Texas, but not in Mississippi or North Carolina (table 3). In Louisiana, harvesting more than boles only reduced soil N and P by 12 and 23 percent, respectively. In Texas, soil N was reduced 19 percent by WTFF harvesting compared to BO harvesting. In Louisiana and Texas, available soil P was, on average, reduced 22 percent by both increased-intensity harvesting treatments compared to the BO treatment. Over the 13 sites, neither soil N nor P was impacted by harvesting treatments.

Foliar N responded to the organic matter removal treatments much differently than soil N did (table 4). Over the

Table 2—Loblolly pine volume response at age 5 to three levels each of organic matter removal and soil compaction

	Organic matter removal			Compaction			
Location	BO	WT	WTFF	None	Moderate	Severe	Mean
	- - - - - - - - - -	- - - - - -	- - - - - -	*$m^3 ha^{-1}$*	- - - - - -	- - - - - -	- - - - - -
Louisiana	12.33a	10.76a	11.80a	10.59a	12.68a	11.61a	11.63
Mississippi	8.71a	4.33b	5.22b	5.02b	5.85b	7.38a	6.09
North Carolina	12.67b	14.61a	10.49c	12.16a	12.71a	12.90a	12.59
Texas	6.88a	5.13b	2.42c	4.78a	5.13a	5.09a	5.00
Overall	10.32a	8.87b	8.11b	8.42a	9.37a	9.54a	9.11

BO = bole-only harvest; WT = whole-tree harvest; WTFF = whole-tree harvest plus forest floor removal.

Table 3—Soil nitrogen and phosphorus response at age 5 to three levels of organic matter removal

	Total nitrogen			Available phosphorus		
Location	BO	WT	WTFF	BO	WT	WTFF
	- - - - - - g kg^{-1} - - - - - -			- - - - - mg kg^{-1} - - - - -		
Louisiana	0.57a	0.49b	0.51b	1.60a	1.07b	1.40b
Mississippi	0.55a	0.53a	0.54a	1.36a	1.25a	1.33a
North Carolina	0.72a	0.72a	0.80a	9.09a	8.26a	7.68a
Texas	0.47a	0.40ab	0.38b	1.55a	1.29b	1.14b
Overall	0.58a	0.53a	0.56a	3.26a	2.82a	2.86a

BO = bole-only harvest; WT = whole-tree harvest; WTFF = whole-tree harvest plus forest floor removal.

Table 4—Loblolly pine foliar nitrogen and phosphorus response at age 5 to three levels of organic matter removal

	Nitrogen			Phosphorus		
Location	BO	WT	WTFF	BO	WT	WTFF
	- - - - - - - - - - - - - - - g kg^{-1} - - - - - - - - - - - - - - -					
Louisiana	11.4ab	11.5a	11.0b	0.77a	0.74a	0.76a
Mississippi	13.9b	15.1a	13.3b	0.73a	0.72ab	0.71b
North Carolina	9.1b	10.4a	9.1b	0.71a	0.70a	0.67a
Texas	14.8a	15.1a	15.3a	0.95a	0.98a	0.94a
Overall	12.2b	12.9a	11.9b	0.79a	0.78a	0.76b

BO = bole-only harvest; WT = whole-tree harvest; WTFF = whole-tree harvest plus forest floor removal.

13 sites, foliar N concentrations were greatest in plots that had WT harvesting (12.9 g kg^{-1}) compared to BO- and WTFF-harvested plots, which averaged 12.1 g kg^{-1}. In Mississippi and North Carolina, which had the second-highest (14.1 g kg^{-1}) and lowest (9.54 g kg^{-1}) average foliar N concentrations, respectively, the WT-harvested plots had about 11 percent greater foliar N concentrations than the BO and WTFF-harvested plots. In Texas, which had the highest concentrations but the least pine volume, harvest intensity did not affect foliar N. Foliar P concentrations were affected only in Mississippi, where WTFF harvesting reduced foliar P concentrations from 0.73 to 0.71 g kg^{-1}. Although no other significant responses were seen on a State basis, the WTFF treatment reduced the average foliar P concentration from 0.79 g kg^{-1} in BO-harvested plots to 0.76 g kg^{-1}.

Soil compaction was greatly reduced from the first year after treatment to age 5 (table 5). At age 1, the compaction treatments increased bulk density about 12 percent over the noncompacted plots. The lowest increase was 7 percent in Louisiana, while the highest was 22 percent in North Carolina. After 5 years, the average bulk density of the compacted plots was only 4.4 percent greater than the noncompacted plots. Across all sites, the average bulk density of the noncompacted plots was 1.26 Mg m^{-3} at ages 1 and 5. The compacted plots, however, had an average bulk density of 1.41 Mg m^{-3} at age 1, but only 1.31 Mg m^{-3} at age 5, a 7-percent reduction. In North Carolina, which incurred the greatest initial compaction, no effect was detected at age 5. Bulk densities recovered only 2 percent overall in Texas between ages 1 and 5.

DISCUSSION

The results of this study suggest three important findings. First, the removal of organic matter in the form of needles, branches, and litter can be detrimental to early site productivity. Second, treatment responses are site specific. Finally, the data show that elucidating causal mechanisms for productivity change will not be achieved through measurement of static soil properties.

The reduction in early growth caused by organic matter removal is likely due to a reduction in available nutrients. Across Louisiana, Mississippi, and Texas, WT harvesting removed only about 15 percent more biomass than the BO treatment (data not shown). WT harvesting removed about 60 and 78 percent more N and P, respectively, in the biomass removed compared to the BO-harvesting. WTFF harvesting removed about 54 percent more biomass than the BO treatment and about 196 and 240 percent more N and P, respectively. In the western gulf coast sites (Louisiana, Mississippi, and Texas), soil P was inherently low, averaging only 1.5 mg kg^{-1} in the BO-harvested plots. The critical level for loblolly pine is 3 mg kg^{-1} (Wells and others 1973), making these soils quite P deficient. Accelerated removals

Table 5—Soil bulk density (0-10cm) immediately after the application of three levels of soil compaction at age 1 and again at age 5

	Age 1			Age 5		
Location	None	Moderate	Severe	None	Moderate	Severe
	- - - - - - - - - - - - - - - - - - Mg m^{-3} - - - - - - - - - - - - - - - - - -					
Louisiana	1.32b	1.41a	1.43a	1.28b	1.31a	1.32a
Mississippi	1.31b	1.41a	1.42a	1.30b	1.37a	1.35a
North Carolina	1.20b	1.47a	1.45a	1.17a	1.22a	1.28a
Texas	1.18b	1.33a	1.32a	1.23c	1.32a	1.28b
Overall	1.27b	1.41a	1.41a	1.25b	1.30a	1.31a

of P through more intensive biomass harvesting probably exacerbated this deficiency, even though available soil P was not affected in Mississippi. The lack of correlation between soil P change and productivity change at Mississippi is not surprising; the method used to estimate available P was not designed to detect such low concentrations of P, and Mississippi had the lowest available P of any of the sites.

If the observed reduction in productivity was due to a reduction in available P, then long-term findings will likely reflect these early results. Phosphorus becomes available through weathering of parent materials and dissolution from fixed States (McBride 1994) and from atmospheric deposition. Jorgensen and Wells (1986) suggest that on highly weathered soils, deposition provides the only significant input of P. In much of the Coastal Plain, these reactions and deposition inputs occur much more slowly than the expected forest rotations. Since P fertilizer is retained in the mineral soil (Pritchett and Comerford 1982), applications of P fertilizer can easily remedy these P deficiencies. While P fertilization is common on deficient forest industry lands, it is not common on national forest lands in the South.

Harvesting also removed substantial quantities of N, which is limiting throughout much of the South. However, the effect of harvest intensity on soil N availability is more complex than for P. While increased removal of organic matter removes a portion of the total site N, forest management operations may increase N availability in the first few years after harvest. Burger and Pritchett (1984) showed that disturbances that increased temperature, water content, and juxtaposition of soil and organic matter increased N availability, even though total N was reduced. Slash and forest floor insulate soils after harvest, and removing them may have increased soil temperature. Removing the slash and forest floor also may have removed a sink for N immobilization, thereby increasing short-term N availability. Theoretically, if atmospheric deposition and biological fixation does not replace the N removed in harvest, then long-term soil N availability will be reduced.

Foliar analysis indicated that P was much more limiting than N on all sites except in North Carolina. Established critical levels for foliar N and P are 12 and 1 g kg^{-1}, respectively (Wells and Allen 1985). Foliar N in Mississippi and Texas consistently exceeded 12 g kg^{-1} regardless of treatment and was nearly 12 in Louisiana. Only the foliar N in the North Carolina plots indicated a N deficiency. Foliar P, however, was only about 0.7 g kg^{-1} in Louisiana, Mississippi, and North Carolina, and about 0.96 g kg^{-1} in Texas. These results indicate that although N availability may have been limiting for short periods of time, P was the more limiting nutrient.

Soil compaction had much more variable effects on productivity. In Louisiana, North Carolina, and Texas, compaction had no statistically verifiable effect on pine volume production. However, compaction had substantial impacts, both positive and negative, on a block basis. Compaction (average of two compaction treatments) reduced volume production compared to no compaction on four blocks (LA1, LA3, NC3, TX3), but only LA3 and TX3 had reductions > 10 percent. Conversely, LA2, LA4, MS2, MS3, and NC1 had > 10 percent improvement on the compacted plots than on the noncompacted plots. The responses at age 5 to compaction may be due to several factors. First, the Louisiana and Mississippi soils had been compacted previously by unregulated grazing. Second, early root growth may have occurred in root channels and other remnant soil voids (Parker and Van Lear 1996). Finally, as the data indicate (table 5), the compaction has largely been alleviated by age 5 through natural processes such as shrinking and swelling, frost heaving, and biological activity. If root growth in old root channels or other remnant soil voids occurred, then compaction may have a greater effect as the stand ages and remnant root channels are filled and new roots must explore the compacted soil matrix. These results are in direct contrast to several studies that have found significant and substantial reductions in productivity on skid trails and log landings (Aust and others 1998, Hatchell 1981), and raise the question of how similar the experimentally applied compaction of the LTSP study is to traffic-induced compaction. One possibility is that the growth reduction found in previous studies was due to the loss of organic matter rather than compaction. Another factor was that compaction may have reduced competing vegetation, thereby allowing site resources to be allocated to pine trees, which improved growth over the noncompacted plots. Further analysis of the data will help to understand this interaction.

CONCLUSIONS

At age 5, loblolly pine volume production was reduced 18 percent by harvesting practices that removed more than just the merchantable bole. Using the USDA Forest Service guideline for evaluating productivity, which states that 15 percent losses in productivity are nonsustainable (U.S. Department of Agriculture, Forest Service 1987), the whole-tree or total organic matter removal treatments in this study are not sustainable practices. The reductions in productivity were closely related to inherent site productivity: Sites with low inherent productivity were much more sensitive to treatments than highly productive sites. The analysis of soil and foliar nutrients indicate that the loss of productivity was likely due to the removal of P on inherently P-deficient soils. These practices, therefore, are unsustainable without amelioration. This study also indicates that, through age 5, soil compaction does not negatively impact forest productivity on these soils and may be beneficial to pine productivity in some cases. Negative compaction impacts may appear as the stands age, however, and may be more prevalent on other soil types.

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