A BRIEF OVERVIEW OF THE 25-YEAR-OLD LONG-TERM SOIL PRODUCTIVITY STUDY IN THE SOUTH

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Abstract—The international Long-Term Soil Productivity experiment began in 1989 in response to the need for Forest Service, U.S. Department of Agriculture managers to understand and monitor the impacts of forest management on site productivity given the expected increase in timber harvesting at the time. It grew to include many other cooperators across the U.S. and Canada and today represents the largest coordinated study of forest management and soil productivity in the world. Twenty-five years after its inception, the Gulf Coastal Plain locations provide many important findings and lessons for management. Overall, soil compaction did not reduce early loblolly pine (*Pinus taeda* L.) survival or growth. In fact, pine volume was increased due to reduced competing vegetation in compacted plots. Intensive organic matter removal (whole-tree harvesting and complete organic matter removal), however, reduced stand volume growth, but only on nutrient-deficient sites. These findings raise questions about current guidelines related to compaction and intensive harvesting. Continued monitoring will help determine how resilient the soils and forests are to these one-time disturbances.

INTRODUCTION

The Long-Term Soil Productivity (LTSP) study began in 1989 as a joint effort between the Forest Service, U.S. Department of Agriculture's National Forest System (NFS) and Research and Development (R&D) branches, but quickly expanded to include cooperators with forest industry, the Canadian Forest Service, and the provincial forestry agencies in Ontario and British Columbia. The study was initiated to determine the fundamental impact of forest management on inherent site productivity and support standards for maintaining soil productivity in managed forests. The research and standards were critically needed because many anecdotal or short-term studies at the time indicated that intensive forestry was potentially detrimental to inherent site productivity, but managers had neither solid research nor defensible standards upon which to act.

The 1980s were a time of major transitions in forest management across all land ownerships, but especially on NFS lands. Timber harvesting on NFS lands had greatly increased from less than 3 billion board feet (bbf) in 1946 to 10-12 bbf from 1960 to 1980 (U.S. Dept. Agriculture Forest Service 2015), and harvesting on NFS lands was projected to reach 20 bbf by 2030 (Thomas 2011). At the same time, however, the rise of the environmental movement of the 1960s and 1970s and new policies, e.g., the National Forest Management Act of 1976 (NFMA), resulted in a much greater concern for the impact of harvesting and forest management in general on other resources such as soil, water, wildlife, and aesthetics. Other forestry and environmental stressors, such as elevated ozone, acid rain, and the fledgling bioenergy movement initiated in the wake of the 1973 and 1979 energy crises were also influencing forest science related to sustainability. Finally, concerns were increasing regarding the sustainability of multiple forest rotations, especially for stands managed intensively for timber production.

Thus, in the late 1980s, a group of scientists and managers from Forest Service R&D and NFS came together to discuss how forest management might impair the inherent productivity of the site (as required by the NFMA), what evidence was available at that time, and finally, how to study it and provide better guidelines to managers. This work resulted in the LTSP's seminal publication at the 7th North American Forest Soils Conference and marked the beginning of the LTSP network. The review concluded that of all the possible mechanisms whereby forest management might alter the inherent productivity of the land, those with the greatest potential were reductions in site organic matter or losses of soil porosity (Powers and others 1990).

The following year, Allan Tiarks of the then-Southern Forest Experiment Station installed the first set of treatment plots on the Palustris Experimental Forest within the Kisatchie National Forest in Louisiana (Tiarks

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Citation for proceedings: Schweitzer, Callie J.; Clatterbuck, Wayne K.; Oswalt, Christopher M., eds. 2016. Proceedings of the 18th biennial southern silvicultural research conference. e–Gen. Tech. Rep. SRS–212. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 614 p.

and others 1990). Over the next 8 years, twelve more sets of treatment plots were installed from North Carolina to Texas. These plots all had the same basic core design, as did another ca. 50 locations throughout the U.S. and an additional ca. 40 in Canada. They were designed to test the effect of fundamental factors involved in forest management, not any one particular or current treatment. This approach was able to provide experimental bounds beyond those actually employed by management, but it also received criticism because it was not directly relevant to the current practices of the time.

The objectives of this manuscript are to provide a summary of lessons learned over the past 25 years with respect primarily to loblolly pine (*Pinus taeda* L.) responses to organic matter removal and soil compaction and to provide inference to current management questions.

MATERIALS AND METHODS

Site Descriptions

The methods used to install the LTSP study in Louisiana, Mississippi, and Texas have been published previously (Scott and others 2004, Scott and Dean 2006). Briefly, two main treatments, organic matter removal and soil compaction, with three levels of each were installed in a factorial design at 10 separate locations across these three states. Three additional southern sites are located in North Carolina, but this analysis will focus on the Gulf Coastal Plain study sites. The locations were chosen specifically to represent productive sites suitable for intensive pine timber production. Moreover, they were placed on a gradient of potential water deficit: the North Carolina sites had essentially no modeled water deficit (difference between potential evapotranspiration and precipitation), while the Texas sites had the highest deficit in the loblolly pine range. All the sites were dominated by southern pines prior to harvesting. The locations were grouped by state as individual randomized complete block experiments, but similarities among treatments allow results to be grouped across all blocks.

Experimental Design

The three levels of organic matter removal were bole-only harvest (OM0), whole-tree harvest (OM1), and complete organic matter removal, which included all forest floor to the bare mineral soil (OM2). Stumps were not removed from any treatment. The compaction treatments were no machine traffic (C0), moderate compaction (C1), and severe compaction (C2). The treatment plots were 0.4 ha in size, and vegetation composition and biomass and soil characteristics were characterized preharvest. The stands were clearcut harvested and the treatments were imposed. On most sites, the compaction was imposed preharvest because it was more efficient to conduct when the wobble-wheel compactor was not running over unseen stumps. Each main plot was split, with one half receiving multiple herbicide applications (H1) and the other receiving no herbicide (H0). Herbicides varied by site and understory vegetation present but included glyphosate and triclopyr. Volunteer loblolly pine trees were controlled manually for the first few years on all plots except in Texas, where planted pine survival was so poor that volunteer pines were allowed to restore stocking levels. For this analysis, only whole-plot data are reported.

A separate study was conducted on one additional plot on the MS2, LA1, and LA3 sites. These three individual plots were whole-tree harvested (OM1) with operational compaction, i.e., standard feller buncher and skidder operations. These plots were then split in half, with one side receiving no additional treatment (F0). The other side received 243 kg ha^{-1} of diammonium phosphate (DAP, 18-46-0) providing 44 kg ha^{-1} N and 56 kg ha^{-1} P, respectively, at age 4.

Following initial harvesting and treatment, containerized loblolly pine from 10 known half-sib families were planted at a 2.5- by 2.5-m spacing (1600 trees ha^{-1}). The measurement subplots for most measurements consisted of 20 rows of 8 trees on each half-plot (320 trees per whole plot). Every 5 years (and some additional time periods), vegetation was measured for height (10 percent sample for ages 15 and 20) and diameter. Volume (or biomass) was calculated using similar methods as Scott and others (2014). Soil bulk density was sampled every 5 years using the same equipment for all measurements (Grossman and Reinsch 2002).

Design and Analysis

Each treatment was replicated within a state. Mississippi and Texas locations each had three replications located within close proximity and on the same respective soil series. Louisiana had four replications, but the replicate blocks were not all in close proximity to each other and were each on a different soil series. Thus, for the 10 replicate blocks, 6 soil series were represented (table 1). The data were analyzed by a mixed-model analysis of variance where the overall affect was assessed (Federer and King 2007) and effects were considered significant at α=0.10.

RESULTS AND DISCUSSION

Compaction

Many misconceptions abound with respect to terms describing soil disturbance caused by forest management. Frequently, foresters (and others) consider soil "compaction" to be a general term encompassing all soil damage associated with any ground-based harvest operation. Compaction is one

Table 1—Site characteristics of the 10 locations of the Long-Term Soil Productivity study in the Gulf Coastal Plain

Site name	Location	Soil series	Soil texture (surface/subsurface)
LA1	Palustris Experimental Forest	Malbis	sandy loam/loam
LA2	Catahoula RD, Kisatchie NF	Glenmora	sandy loam/clay loam
LA3	Catahoula RD, Kisatchie NF	Metcalf	silt loam/silty clay
LA4	Catahoula RD, Kisatchie NF	Mayhew	silt loam/silty clay loam
MS1-3	Chickasawhay RD, DeSoto NF	Freest	loam/loam
TX1-3	Davy Crockett NF	Kurth	loamy fine sand/sandy clay loam

particular type of soil disturbance and consists of a reduction in porosity. It can be present without vertical mixing or soil shear, in which case many preferential flow paths for water may not be drastically disturbed. Rutting usually includes a compaction component, but also incorporates soil shearing and vertical mixing of the soil as the soil flows under pressure. Churning may or may not result in porosity loss because fully saturated soil cannot be compacted, but flow paths and pore sizes are drastically affected and vertical mixing is maximized. These different disturbances affect both dynamic and static soil properties and processes quite differently. This study focused on the impacts of compaction only, not rutting or churning.

Soil compaction has two primary impacts on properties that affect plant roots: increasing soil strength and reducing aeration. Strength (the resistance a plant root receives as it penetrates soil) is increased because friction is increased due to the closer soil particles. Aeration is reduced due to fewer and smaller pores. Root growth can be limited by both of these, and obviously both are dynamically related to water content (Siegel-Issem and others 2002, Scott and Burger 2013). This study was designed with an earlier conceptual model of compaction and root growth in mind, however. It was called the root-growth-limiting bulk density (RGLBD), and it incorporated two metrics: soil texture and bulk density (Daddow and Warrington 1983). Bulk density is a static measure that is closely related to strength at a given water content and is relatively easy to measure. The goal of the study design was to achieve 80 percent of the root-growth-limiting bulk density with the severe compaction treatment and a geometric mean between the uncompacted and severe treatments with the moderate treatment. However, based on the preharvest conditions, the six soils tested ranged from 68 to 93 percent of the RGLBD (mean of 82 percent) without any compaction in the surface 10 cm. Moderate compaction (C1) increased the mean to 89 percent, while severe compaction (C2) reached a mean of 90 percent RGLBD (data not shown). The sandier soils (Kurth, Glenmora) generally achieved a greater absolute amount of compaction than the heavier textured soils (Metcalf, Mayhew). Actual posttreatment bulk density averaged 1.29 Mg m^{-3} across all 10 locations in the C0 plots, and 1.37 and 1.39 Mg m^{-3} in the C1 and C2 plots, respectively (fig. 1).

This compaction was hypothesized to reduce early survival and growth of planted pines through increased soil strength when the soils were dry (growing season) and reduced aeration when wet (dormant season). However, soil compaction had no effect at any site on early survival of planted pines (data not shown). First year survival averaged 94 percent and second year survival averaged 80 percent across the 10 blocks (values included year 3 data from Mississippi, where year 2 data were not available). Survival was relatively stable after the second growing season, at which point normal stand development mortality occurred.

Age 5 volume growth of planted pines was not affected overall by compaction, but volume growth was about 16 percent higher on compacted plots at age 10 (fig. 2), and this increase was sustained through age 15 (and age 20 on the LA and MS sites). This finding was unexpected. One possibility is that the compaction increased the soil water-holding capacity by reducing the size of very large pores. This effect has been seen in coarse volcanic-origin soils in the West, where bulk densities may be relatively low (Gomez and others 2002). These soils simply have too many large pores to hold much water. Given the relatively highly compacted nature of the soils before treatment in this study, it is unlikely that soil water-holding capacity was improved. A second hypothesis is that bulk density recovered very quickly so that growth was unaffected. The data show that while surface soil (0-10 cm) bulk density of compacted plots declined precipitously after initial treatment, reaching pretreatment levels by age 5, the uncompacted soil bulk density was declining at a similar rate (fig. 1). Thus, relative differences were essentially maintained. A third hypothesis is that the compaction had a relatively greater impact on the rooting and growth of competing vegetation. At age 5, competing vegetation biomass on the compacted plots was only 60 percent of that on the uncompacted plots (fig. 3).

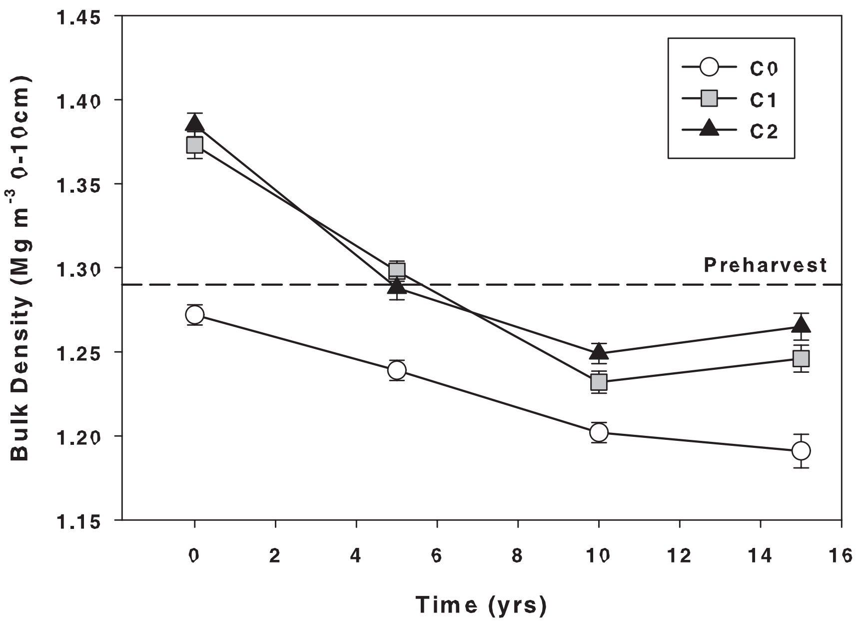

Figure 1—Soil bulk density (0-10 cm) before and after harvest and three levels of applied compaction [no machine traffic (C0), moderate compaction (C1), and severe compaction (C2)] on seven soil series (10 total blocks) across Mississippi, Louisiana, and Texas. Time=0 represents the year of harvest and treatment.

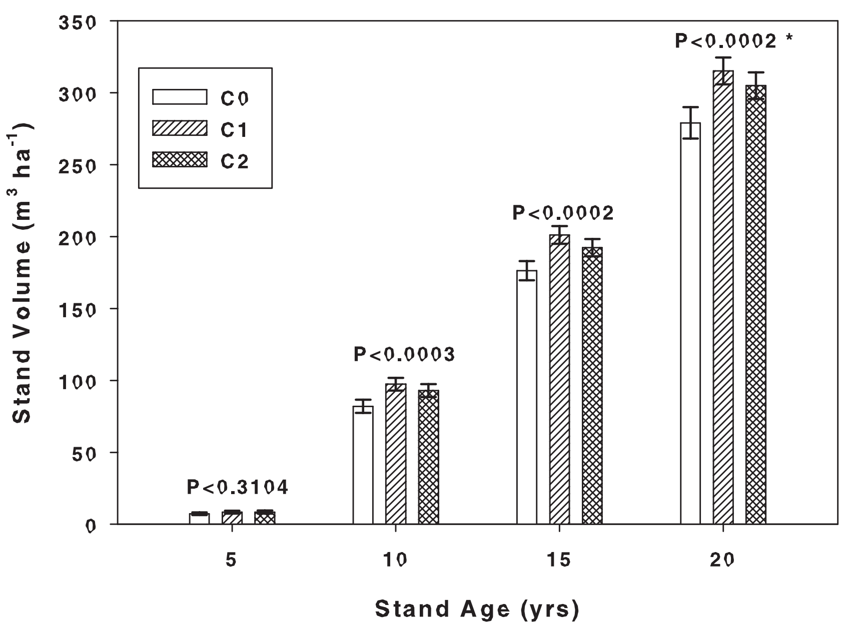

Figure 2—Loblolly pine volume following three levels of compaction [no machine traffic (C0), moderate compaction (C1), and severe compaction (C2)] across 10 blocks of the southern LTSP study in Mississippi, Louisiana, and Texas. *Indicates n=7 because Texas blocks had not reached 20 years old.

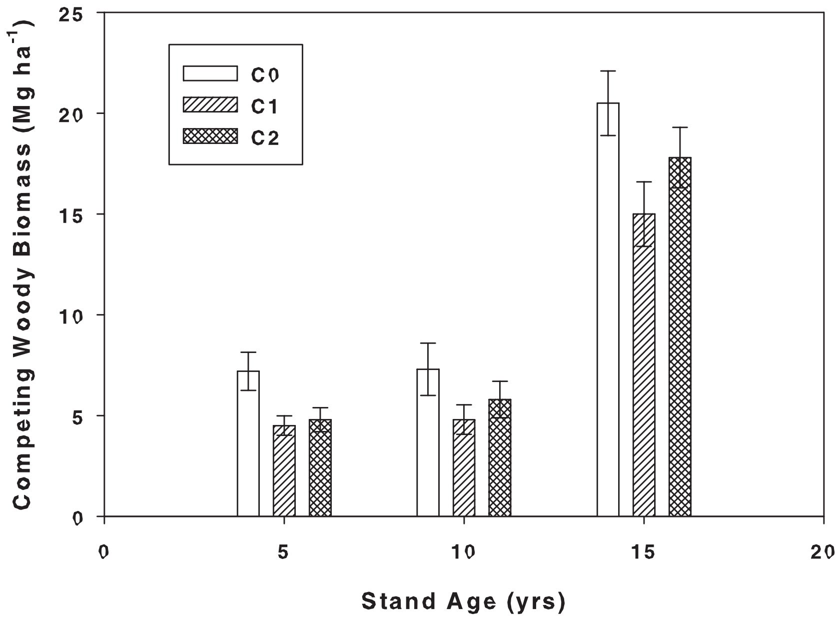

Figure 3—Biomass of competing woody vegetation following three levels of compaction [no machine traffic (C0), moderate compaction (C1), and severe compaction (C2)] across 10 blocks of the southern LTSP study in Mississippi, Louisiana, and Texas.

Apparently the compacting effect reduced the ability of naturally regenerated vegetation to seed, sprout, or achieve root growth in the first few years, giving the planted pines a competitive advantage.

These results, which indicate simple compaction reduced naturally regenerated hardwoods and shrubs but not planted pines, challenge the prevailing management paradigm of restricting traffic to skid trails to avoid the total area disturbed in forests. This paradigm is based on the generally accepted finding that the majority of compaction occurs following the first few equipment passes (Steinbrenner 1955, Hatchell and others 1970, Sidle and Drlica 1981, Greene and Stuart 1985, Han and others 2006). Therefore, it has been widely accepted that reducing compaction is best achieved 1) by avoiding traffic except on dry soils, 2) by using slash to distribute loads, or 3) by minimizing the area compacted. Rutting and churning on moderately well or somewhat poorly drained sites has a much greater potential for reducing site productivity (Aust and others 1995). This raises the question—if we encourage less concentrated traffic, might we both reduce the potential negative effects of more severe disturbance related to multiple passes and disrupted soil structure as well as potentially improve tree productivity through controlling interspecific competition? The Farm Forestry Forties at Crossett Experimental Forest, Arkansas (Guldin 2002), the Hope Demonstration Forest, Arkansas (Farrar Jr. and others 1984), and the Escambia Experimental Forest in Alabama (Barlow and others 2011) provide support for such an approach. The Crossett Farm Forties are naturally regenerated, uneven-aged loblolly and shortleaf pine (*Pinus echinata* Mill.) stands that were harvested annually for >30 years and then on a 5-year cycle for the past 40 years. The Hope Demonstration Forest is also an uneven-aged loblolly and shortleaf pine stand and was harvested six times from 1966 to 1981. The Escambia Farm Forty is a >60-year-old uneven-aged longleaf pine (*Pinus palustris* L.) stand, harvested six times since 1948. Skid trails were never designated, and the uneven-aged, naturally regenerated character necessitated distributed traffic, yet productivity is still high (Guldin 2002, Barlow and others 2011). In fact, the scarification provided by harvesting equipment is useful for preparing seedbeds for naturally regenerated southern pine (Guldin 2004). For landowners with limited resources, this approach might be more useful than designated skid trails that may require costly ripping or bedding site preparation to ameliorate.

Organic Matter Removal

The treatments used in this experiment were not intended to replicate any specific harvesting intensity exactly as conducted within the operational conditions present in 1990; they were intended to provide a clear gradient of organic matter and nutrient removal. Because harvesting technology often changes faster than a long-term study can be conducted, this approach enables the results to be applicable regardless of current technology. These treatments resulted in an average relative organic matter removal increase of 16 and 54 percent in the OM1 and OM2 treatments, respectively (table 2). Aboveground nitrogen (N) removals were 67 and 134 percent greater in the OM1 and OM2 treatments, respectively, than the OM0 treatment. Phosphorus (P) removals were 78 and 199 percent greater in the OM1 and OM2 treatments, respectively.

When the study was established, it was hypothesized that the primary impacts to site productivity would be observed after the stand reached canopy closure, when overall nutrient demand is highest and supply declines. Survival was not expected to be affected by organic matter removal, as nutrient availability is generally elevated following harvesting. In general, early survival was not greatly affected (data not shown). However, second year survival on the Texas sites was drastically reduced in the OM2 plots (Scott and Stagg 2013). The TX sites not only were at the western (driest) edge of loblolly pine natural range, but the soils in TX were sandy loams (nearly loamy fine sand), and the TX sites experienced a drought between 1 and 2 years postplanting. Apparently, the forest floor provided an insulating effect on soil water content and temperature on these sites.

The organic matter removal effect was significant, however, at every age measured (fig. 4) on average, but the OM2 treatment had no additional effect on volume relative to the OM1 treatment. However, treatment effects were very site specific; volume response has been correlated with site-level productivity and the initial nutrient availability of the site (Scott and others 2004, 2007, 2014, Scott and Dean 2006). These results present a few important implications.

First, and most importantly, removing more than tree boles can reduce site productivity, and our data so far do not indicate a convergence of stand volume through age 20. It is possible that natural processes may restore productivity over longer times, but nothing indicates these processes are having a positive effect yet. The degree of organic matter removal was not important in determining site productivity impact. Removing the hardwoods, understory, and forest floor (OM2) removed over 40 percent more N and 68 percent more P than removing pine boles and tops (OM1) (table 2), yet the relative impact on site productivity was not significant compared to removing whole pine trees. Secondly, productivity lost by intensive organic matter removal was restored with limited rates of fertilizer (fig. 5). On the LA1 and MS3 locations, pine volume on the fertilized halves of whole-tree harvested plots was 56 percent greater than on the unfertilized plot. In LA3, pine volume did not respond to fertilizer application. The overall volume response (37 percent) was thus not significant ($p<0.11$). However, the plot on LA3 only had 73 percent of the mean volume for the other nine plots, and productivity was not reduced by intensive organic matter removal on this site. LA1 and MS3 were both sites in which pine volume was reduced by whole-tree harvest.

Thus, whole-tree harvesting by itself has the potential to reduce site productivity on infertile pine sites in the South, but several soils showed no reductions in productivity with complete organic matter removal. This finding is especially important given the increase in concern for biomass harvesting guidelines, especially for limited-resource landowners or those who choose not to use nutrient amendments (NFS lands, many State lands, naturally regenerated forests, etc.). Most biomass harvest guidelines focus on determining the percentage of initial slash (generally, noncommercial trees and tops) to be retained on site. From a site productivity perspective, this approach is precisely the opposite of the best approach. On very highly productive sites, where slash and organic matter is likely very high, our results did not indicate that a one-time removal of all aboveground organic matter affected productivity negatively, but on infertile soils productivity was affected. Slash and surface organic matter serve purposes other than simply maintaining productivity, however, and these functions should be considered when designing guidelines. But the use of a single percentage based on existing stand volume or biomass may fail to protect productivity on infertile sites and unnecessarily restrict harvest on highly fertile sites. These data also show that conservative rates of

Table 2—Quantities of biomass, nitrogen, and phosphorus removed in three organic matter removal treatments [bole-only harvest (OM0), whole-tree harvest (OM1), and complete organic matter removal (OM2)] from 10 blocks of the southern LTSP study across Mississippi, Louisiana, and Texas

Treatment	Biomass (Mg ha^{-1})	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})
OM0	127.5 (23.5)	130.1 (51.6)	8.6 (4.72)
OM1	148.0 (24.9)	216.8 (61.7)	15.3 (5.57)
OM2	196.6 (54.3)	304.1 (117)	25.7 (13.4)

Note: values are means with standard deviations in parentheses.

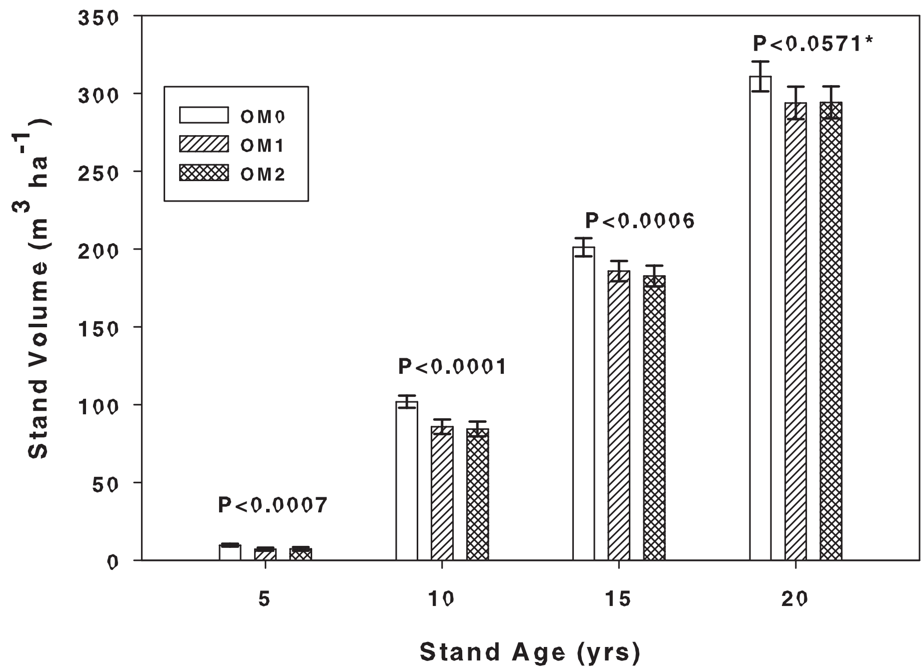

Figure 4—Pine volume following three levels of organic matter removal [bole-only harvest (OM0), whole-tree harvest (OM1), and complete organic matter removal (OM2)] across 10 blocks of the southern LTSP study in Mississippi, Louisiana, and Texas. *Indicates n=7 because Texas blocks had not reached 20 years old.

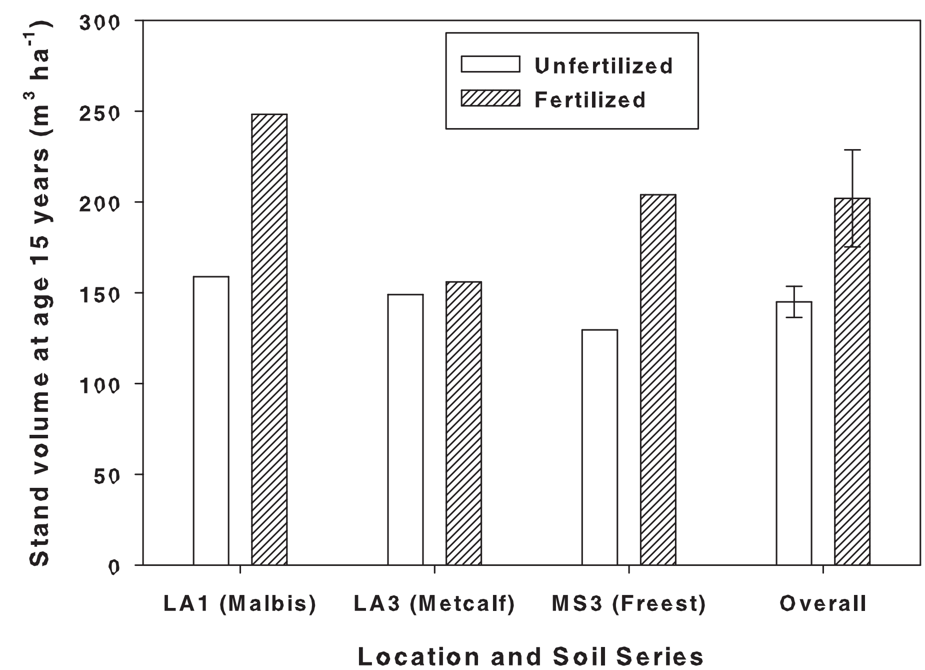

Figure 5—Pine volume response to fertilizer (56 and 44 kg ha^{-1} of phosphorus and nitrogen, respectively, applied at age 4) on three whole-tree harvested plots with operational compaction at age 15 (see table 1 for location information).

traditional fertilizers restore lost productivity, at least on these site types. Concerns have been raised about potential productivity loss from calcium depletion in the South (Huntington 2000), which could be exacerbated by biomass harvesting, but these data provided no indication of a calcium depletion.

CONCLUSIONS

Forest harvesting has the potential to affect long-term site productivity primarily through two mechanisms: removing organic matter and nutrients from the site and altering soil porosity and the air-water balance. Planted loblolly pine productivity through 15-20 years was not negatively affected by soil compaction across six soil series, including two soils with heavy clay subsoils. Soils were not rutted or churned, but the absence of any negative impact was both surprising and important for understanding the resilience of forest soils to impacts. Conversely, removing more organic matter than just the boles reduced long-term pine growth on infertile soils, including loamy textured soils. Removing all aboveground organic matter did not reduce growth on the more fertile soils, illustrating that assessing site capacity for intensive harvesting is likely more important than harvest intensity for maintaining long-term site productivity. The southern LTSP study has been a vital component of the international LTSP network, and continued monitoring and process-level research will continue to assess how resilient these forests are to harvesting.

ACKNOWLEDGMENTS

The international LTSP network currently comprises well over two dozen scientists and a similar number of forest managers, and the continued progress on any one study location is intimately related to the much greater value of the overall network than of any one region. For that, I wish to thank all current and past participants for their collaborations. A special recognition goes to Allan Tiarks, the scientist who installed all 10 locations covered in this manuscript and completed the early measurements. Similarly, Rick Stagg deserves extraordinary praise as the forester in charge of actual ground operations for both installation and all measurements since 1991. Jerry Ragus and Emanuel Hudson, soil scientists from Region 8, and many employees of the individual National Forests were essential for establishing and maintaining the study. Finally, I offer a special gratitude to Felix Ponder and Bob Powers. Felix installed LTSP plots in Missouri, and his collaborations with Purdue University led to my first job as an undergraduate research technician and my initial interest in the LTSP program. Bob was the guiding force behind the entire program from its inception until his retirement in 2008, and specifically mentored and encouraged me greatly from my first day with the Forest Service until his untimely passing.

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