Ten-Year Results from the North American Long-Term Soil Productivity Study in the Western Gulf Coastal Plain

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Forest management operations have the greatest potential to reduce soil productivity through altered soil fertility and air/water balance, which are most affected by organic matter removal and compaction, respectively. The objectives of this study were to assess the early growth response to compaction, organic matter removal, and weed control on the ten locations of the Long-Term Soil Productivity study on the Kisatchie, DeSoto, and Davy Crockett National Forests (Louisiana, Mississippi, and Texas). Three levels of compaction (none, moderate, severe) and three levels of organic matter removal (stem only, whole tree, and whole tree plus forest floor) were applied in a factorial design at each site, and half of each treatment plot was kept free from interspecies competition with herbicides. Soil compaction had no negative impacts on tree growth at ten years; most sites responded positively to compaction due to the reduction of shrub understory competition. Removing more organic matter than the stems reduced stand volume on eight of the ten sites by more than 15 percent. This study indicates that harvesting operations that remove tree branches and foliage, and site preparation operations that remove the forest floor, such as site preparation burns, can have negative impacts on long-term soil productivity.

Keywords: *long-term productivity, soil compaction, nutrients, forest practices, guidelines for management, monitoring, vegetation management, loblolly pine,* Pinus taeda *L.*

Introduction

The North-American Long-Term Soil Productivity (LTSP) study began as a collaboration of the National Forest System and Forest Service Research in 1989. The study was founded to answer fundamental questions regarding the long-term consequences of soil disturbance on forest productivity, through carefully designed trials throughout the nation. The originality, scope, and careful design encouraged other partnerships to form among the Forest Service, forest industry, and academia. Fifteen years later, the comprehensive program has over 100 installations in the U.S. and Canada that comprise the world's largest coordinated research network addressing basic and applied science issues of forest management and sustained productivity.

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The LTSP program was founded in response to the National Forest Management Act of 1976 (NFMA). The NFMA states that the Secretary of Agriculture must ensure, through research and monitoring, that forest practices do not cause a lasting reduction of the productivity of the land. This mandate was clarified somewhat by the report of a committee of independent scientists (Code of Federal Regulations 1985) that, in part, stated that the Forest Service must monitor the effects of forest prescriptions on "significant changes in land productivity". The Forest Service recognized that clear, scientifically-based definitions of "significant changes in land productivity" and monitoring criteria would be needed to avoid dispute. The term "land productivity" is quite subjective, and can refer to any number of forest attributes and functions. However, at its most fundamental nature, land productivity can be considered a site's capacity to capture carbon in growing plants, i.e., net primary productivity (NPP). Because NPP, the sum of all dry matter produced per unit area per unit time, fluctuates greatly due to climate, stand development, and other factors not related to the

land, it was also decided that a 15 percent departure from a baseline would be deemed "significant" (USDA Forest Service 1987).

The Forest Service needed some metric other than NPP to monitor, however, because the intensity of effort required to measure NPP makes it impractical under operational monitoring conditions. Tracking stand growth through time, while operationally possible, does not assess soil productivity per se; differences in climate, stocking, genetics, vegetation management, and other practices affect forest productivity without affecting soil productivity (Burger 1996; Powers 2001). An alternative is to relate land productivity to measurable soil processes (Burger and Kelting 1999). The Forest Service adopted this approach, which is based on the following rationale (Powers and Avers 1995):

1. Forest management practices disturb soils
2. Soil disturbances affect soil properties and processes
3. Soil properties and processes determine site productivity

The approach has been used to develop preliminary monitoring protocols (Powers and Avers 1995; Powers et al. 1998; Page-Dumroese et al. 2000) based on the best scientific data available and personal experience. It has also been verified in research settings (Kelting et al. 1999).

Unfortunately, it is impossible to directly measure all soil properties and processes. Therefore, careful experimentation was needed to determine, for each region, what soil properties and processes were most indicative of productivity. Thus, the National Forest System asked Forest Service Research to develop a coordinated study to address these issues. A detailed review of the literature regarding forest management and site productivity determined that the two most fundamental causes of productivity loss following forest management activities were organic matter removal and soil porosity loss (Powers et al. 1990). The review also concluded that scant direct evidence of productivity loss was available, largely because previous studies were not designed well enough to clearly determine cause and effect. Previous studies of soil physical disturbance were confounded by different levels of organic matter removal and weed control, and studies of harvest intensity have been confounded by soil physical disturbance. Many of these studies were further complicated by uncontrolled differences in climate, stocking, and weed competition (Morris and Miller 1994).

Therefore, the founding principles of the LTSP study were that (1) soil is the key factor controlling site productivity that is affected by management, (2) the fundamental measure of productivity is vegetative carrying capacity, expressed as dry biomass accumulation, and (3) removal of site organic matter (slash and/or forest floor) and soil compaction are the most common causes of long-term productivity loss. The LTSP design was chosen to specifically address these problems and focus on the long-term cause and effect relationships between organic matter, soil compaction, and site productivity. The specific hypotheses LTSP was designed to test are shown in Table 1.

Powers et al. (2004) reported on the 10-year findings from selected installations on the southern Atlantic and Gulf coastal plains and in the Sierra Nevada Mountains in California, highlighting major trends. They found that little evidence existed for universal impacts of either soil compaction or organic matter removal, but the presence of understory vegetation caused a clear and widespread reduction in planted tree growth. Within a given region, however, generalized findings may not apply. Scott et al. (2004) reported on the 5-year results from 13 loblolly pine (*Pinus taeda*) sites across the soutern US, and found that results from one site were not necessarily indicative

Table 1. Hypotheses of the Long-Term Soil Productivity Study.

Hypothesis	H_0	H_a
1	Pulse changes in site organic matter and/or soil porosity do not affect the sustained productive potential of a site.	Critical changes in site organic matter and/or soil porosity have a lasting effect on potential productivity by altering soil stability, root penetration, soil air, water and nutrient balances, and energy flow.
2	If impacts on productivity occur from changes in organic matter and porosity, they are universal.	The biological significance of a change in organic matter or porosity varies by climate and soil type.
3	If impacts do occur, they are irreversible.	Negative impacts dissipate with time, or can be mitigated by management practices.
4	Plant diversity has no impact on the productive potential of a site.	Diverse communities affect site potential by using resources more fully or through nutrient cycling changes that affect the soil.

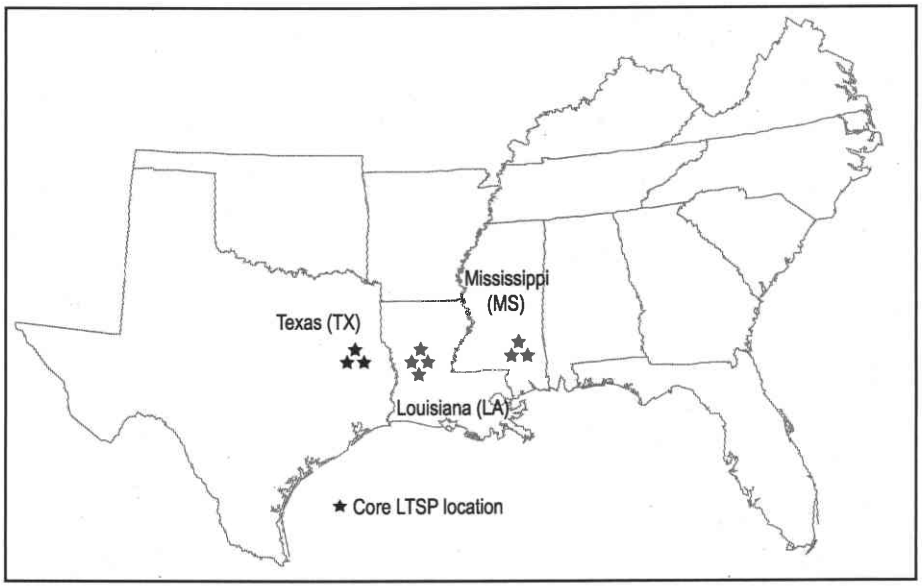


Figure 1. Ten locations of the North American Long-Term Soil Productivity study in the western Gulf Coastal Plain.

of other sites in the same area. Accordingly, the objectives of this paper are to: (1) determine how soil compaction and organic matter removal at harvest and stand diversity after harvest affected the site productivity of loblolly pine at age 10 years in the western Gulf Coastal Plain; and (2) determine soil or site indicators of productivity response to soil compaction and organic matter removal.

Materials and Methods

Study Sites

Ten locations of the LTSP study were installed in the southern United States Gulf Coastal Plain from 1990 to 1995 (Figure 1). All sites are located in the humid-temperate-subtropical Southern Mixed Forest or Outer Coastal Mixed Forest Province (Bailey 1995). Four sites were installed in the Kisatchie National Forest in Louisiana, while three sites each were installed in the DeSoto National Forest in Mississippi and the Davy Crockett National Forest in Texas, respectively. The soils were common Ultisols and Alfisols found on coastal plain uplands and terraces, and were formed from marine and alluvial sediments (Table 2). The surface soils ranged in texture from fine sandy loam to silt loam and overlaid heavier textured subsoils. The understory on the Louisiana and Texas plots was characterized by shrubs and small trees common across much of the southern coastal plain, including sweetgum (*Liquidambar styraciflua*), wax myrtle (*Morella cerifera*), yaupon (*Ilex vomitoria*), and assorted oaks (*Quercus* spp.). The understory in Mississippi was dominated by inkberry (*Ilex glabra*).

Treatments

Nine treatments were imposed in a 3 by 3 factorial design following a clearcut harvest of the existing stand, with organic matter removal and compaction as the main treatment factors and vegetative diversity as a split-plot factor (Figure 2). The three organic matter removal treatments were stem-only harvest, whole-tree harvest, and whole-tree harvest plus forest floor removal. The three levels of compaction were no compaction (no mechanical equipment was allowed on plots during harvesting), moderate compaction, and severe compaction. Severe compaction was defined as 80% of the root-growth limiting

Table 2. General site data for the ten locations of the Long-term Soil Productivity study in the Gulf coastal plain region.

Location	National Forest	Soil Series	Year Established	Previous Stand	Understory
LA 1	Calcasieu RD, Kisatchie NF	Malbis	1990	Loblolly	Grass
LA 2	Catahoula RD, Kisatchie NF	Glenmora	1992	Loblolly	Shrub
LA 3	Catahoula RD, Kisatchie NF	Metcalf	1993	Loblolly	Hardwood
LA 4	Catahoula RD, Kisatchie NF	Mayhew	1993	Loblolly	Hardwood
MS 1-3	Chicksawhay RD, Desoto NF	Freest	1994	Slash plantation	Shrub
TX 1-3	Davy Crockett NF	Kurth	1997	Loblolly/shortleaf	Shrub

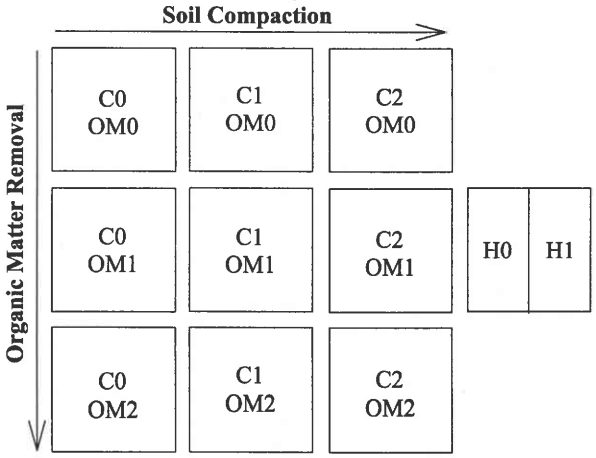


Figure 2. Treatment design and plot layout of the North American Long-Term Soil Productivity study sites in the western Gulf Coastal Plain.

bulk density, as determined from soil texture (Daddow and Warrington 1983). A field-based Proctor test was used to determine load and compaction level relationships at each site. Moderate compaction was defined as the geometric mean bulk density between the no compaction and severe compaction levels. The two experimental compaction levels were induced by pulling a multi-tire road compactor with two levels of ballast across the plots six times (Figure 3). After treatment installation, container loblolly pine seedlings from ten known half-sib families were planted at a 2.5-by-2.5-m spacing. Each 0.4-ha treatment plot was split into two 0.2-ha subplots (Figure 2). One of the subplots was kept clear of competing vegetation by manual removal and directed-spray herbicide applications (primarily glyphosate). Competing vegetation was allowed to grow freely on the paired subplot. Volunteer pines were controlled manually on all plots. Measurement plots were the interior 0.1 ha of each subplot.

Measurements

At age 10 years (age 5 in Texas), we measured tree height and diameter at breast height (dbh) of all pine trees in the 0.1-ha measurement plot with height poles and calipers. Pine volume was estimated using equations from Baldwin and Feduccia (1987). Prior to treatment, five soil samples were collected to 15 cm with a push probe sampler on each of three transect lines across each measurement plot and bulked by transect line. Mehlich III available soil P (phosphorus) (Mehlich 1984) and exchangeable Ca, Mg, and K (calcium, magnesium, and potassium) (Gillman 1979) were determined for each sample on a Hewlett-Packard 8453 colorimetric spectrophotometer[1] and a Perkin-Elmer 2100 atomic absorption spectrophotometer, respectively. Soil carbon was determined on a LECO CNS analyzer and converted to soil organic matter. Soil bulk density samples were collected prior to treatment, at age

Figure 3. Wobble-wheel road compactor and dozer used to compact soils in the western Gulf Coastal Plain Long-Term Soil Productivity sites. Photo by Allan Tiarks.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

5 years and at age 10 years, with a custom core extractor from ten random locations throughout each measurement plot in the four Louisiana sites. 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. The soils were dried at 105°C to a constant weight, and bulk density was recorded.

Data Analysis

The main effects of soil compaction, organic matter removal, and stand diversity (competition control) on loblolly pine growth were compared using analysis of variance (ANOVA), and the means were separated using a Duncan's Multiple Range Test at P = 0.10 (SAS Institute 2000). The relationship between soil P and relative productivity was determined with least-squares regression. The influence of compaction level and stand age on bulk density was determined with a mixed-model analysis of variance.

RESULTS AND DISCUSSION

Main Treatment Effects on Loblolly Pine Growth

Early stand volume production was generally increased by soil compaction, decreased by whole-tree harvesting, and increased by chemical weed control. Soil compaction increased volume growth in Louisiana and Mississippi by 16 and 24%, respectively (Table 3). It had no impact on volume growth of the pine trees in Texas at age 5. Compaction intensity had no effect. The moderate and severe compaction treatments had the same influence on stand growth in each state.

Organic matter removal had no significant effect on stand volume across the four blocks in Louisiana, but intensive organic matter removal clearly decreased productivity in Mississippi and Texas (Table 3). In Mississippi, the whole-tree harvest and whole-tree+forest floor harvest treatments reduced volume production by an average of 24% relative to the stem-only harvested treatment. In Texas, the whole-tree harvest treatment reduced productivity at age 5 by 26% compared to the stem-only treatment, and removing the forest floor increased this reduction to 65%.

The plantations with simple vegetative communities produced much more timber than the diverse communities. Across the Louisiana and Mississippi sites, chemical control of competing vegetation increased pine productivity by almost 50% compared to the plantations with no chemical weed control (Table 3).

Site-Treatment Interactions and Response to Compaction

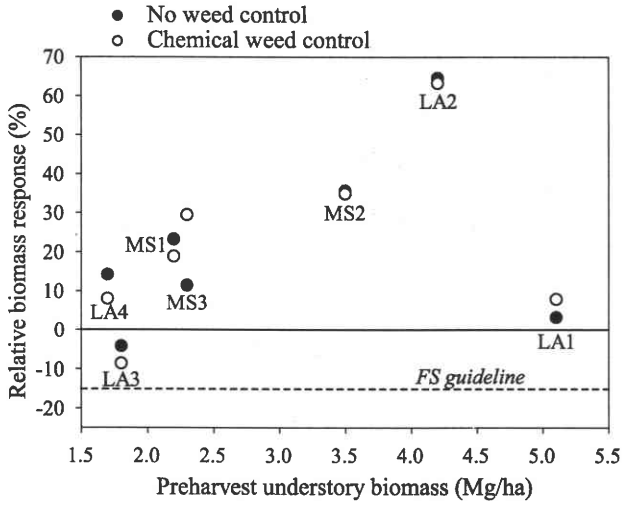
Compaction had the greatest positive impact on the relative volume of loblolly pine on the LA2, MS2, MS3, and MS1 sites (Figure 4), and the positive impact of compaction was related to the quantity and type of preharvest understory (less than 7.6 cm dbh). The LA2, MS2, MS3, and MS1 sites all had a heavy understory of shrub species and small hardwood trees (Table 2). The LA2 site was dominated by wax myrtle, yaupon, and sweetgum. The Mississippi sites were dominated by inkberry. The LA1 site, which had the most understory biomass before harvest, showed no positive response to compaction. The understory at LA1 was almost exclusively grass, due to frequent cattle grazing and prescribed fires. LA1 was also compacted before treatments due to the history of cattle grazing, and the experimental compaction was less effective at changing bulk density at this site (Tiarks et al. 1991). The LA3 and LA4 sites had little understory biomass and showed little response to compaction. These sites, however, had the greatest hardwood biomass (greater than 7.6 cm dbh) of all the sites (data not shown). The LA3 site was the only site to exhibit a negative response to the compaction. The Metcalf soil on LA3 was originally classified as an

Table 3. Stand volume response at age 10 to soil compaction, harvest intensity, and chemical weed control in three replicated LTSP study sites in the western Gulf coastal plain.

Treatment	Stand Volume (cubic meters per hectare)		
	Louisiana	Mississippi	Texas[2]
No Compaction	96b[1]	64b	4.8a
Moderate compaction	115a	79a	5.1a
Severe Compaction	107a	80a	5.1a
Stem-only harvest	111a	89a	6.9a
Whole-tree harvest	102a	66b	5.1b
Whole-tree+forest floor harvest	105a	70b	2.4c
No weed control	83b	62b	4.7a
Chemical weed control	129a	87a	5.3a

[1]Means within a column followed by the same letter are not significantly different at P < 0.10.
[2]Texas data were from age 5.

Figure 4. Average loblolly pine volume response at age 10 on compacted soils relative to the uncompacted soils as a function of the preharvest understory biomass on across the Louisiana and Mississippi Long-Term Soil Productivity study sites.



Alfisol when the study was installed, but was reclassified as a Vertisol. The soil texture at LA3 and LA4 averaged 29% clay in the upper 30 cm, whereas the average clay content of the LA1, LA2, and the MS sites was only 19% in the upper 30 cm.

The positive response of the planted pines to compaction on the sites with heavy shrub-based understories indicates that the understory plants were negatively impacted by compaction. The compaction probably did not have a direct effect on the plants; breaking stems and exposing roots would likely increase sprouting and dominance of these species. Compaction did not have an additive effect with the herbicide treatments. While the herbicide treatments were quite effective on relative loblolly pine productivity on all plots (Table 3), the herbicide application on the compacted plots had no additional impact compared to the uncompacted plots (Figure 4). Therefore, it is likely that the compaction had an indirect impact on the understory plants by increasing soil strength and reducing aeration. The planted pine probably responded because this indirect impact on the soil was not as important as the reduction of competition for resources.

In the early stages of the LTSP study, many foresters and scientists expected the soil compaction treatment to have the greatest negative impact on productivity. Soil physical disturbances are visually unappealing, and evidence of compaction-induced productivity losses in southern pine stands is abundant (Hatchell et al. 1970; Tiarks 1990; Aust et al. 1995; Miwa et al. 2004). One explanation of the lack of negative response may be that we did not achieve enough soil disturbance or the right form of disturbance to have a biological impact on the planted pines. This was definitely the case at the 20-30 cm depth, where the compaction treatments had no impact on bulk density in Louisiana (Table 4). The form of physical disturbance we created (compaction) is only one form of disturbance caused during forest management activities such as logging. Rutting and churning, unlike simple compaction, disturb not only the soil porosity, but they also disturb soil structure and may have a greater impact than simple compaction (Tiarks 1990). While compaction is usually the dominant forest management-induced soil disturbance, these results can not be applied to rutted or churned sites and may explain discrepancies between these data and previous studies.

Another explanation is that these trees are still quite young and only recently attained full canopy closure. Short-term results are not always indicative of long-term results, especially when multiple processes are functioning. For example, while the early productivity of the planted pines was improved by the compaction, it appears this increase was caused by a reduction in understory plants that were more susceptible to changes in soil properties. After canopy closure, when intraspecific competition for site resources will be greater than interspecific competition, soil properties will likely have a greater relative impact on pine productivity than before canopy closure. Essentially, as the stand matures, understory competition will be less important to pine productivity relative to near-surface soil

Table 4. Compaction effect on bulk density at three depths across four LTSP sites in Louisiana immediately after treatment and ten years after treatment.

		Bulk Density (megagrams per cubic meter)		
Depth	Compaction	Age 0	Age 10	Change[2]
0-10	Uncompacted	1.32b[1]	1.26b	-0.07b
	Moderate	1.41a	1.27b	-0.14a
	Severe	1.43a	1.30a	-0.13a
10-20	Uncompacted	1.48b	1.39c	-0.08a
	Moderate	1.54a	1.46b	-0.07a
	Severe	1.56a	1.48a	-0.07a
20-30	Uncompacted	1.51b	1.45c	-0.06a
	Moderate	1.52ab	1.47b	-0.05a
	Severe	1.53a	1.49a	-0.03a

[1]Means within a column and soil depth followed by the same letter are not significantly different at P = 0.10.
[2]Discrepancies between the difference of the Age 0 and Age 10 data and the change in bulk density data were due to rounding. All changes in bulk density from age 0 to age 10 were significantly different at P = 0.05.

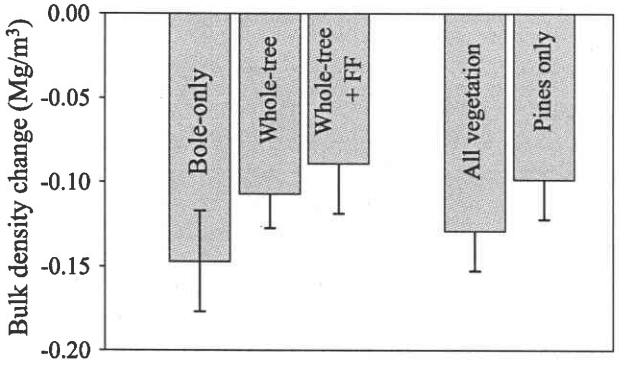
properties. Because of this, we also wanted to assess how well the soil has recovered from compaction to indicate whether long-term responses to compaction would be similar to or different from short-term responses.

Soil Recovery from Compaction

Bulk density in the surface soil at the four Louisiana sites was significantly increased by compaction at all three depths. The degree of compaction had no relative impact; the moderate and severe treatments resulted in similar bulk densities immediately post-treatment at all depths (Table 4). The bulk density of the compacted soils remained elevated over that of the uncompacted soils 10 years after treatment. The recovery of the bulk density was greatest in the surface 10 cm, but was significant at all depths (Table 4). Although recovery was significant at the lower two depths, it did not differ based on compaction intensity (Table 4), organic matter removal, or herbicide application. The surface 10 cm recovered differently depending on the treatment. Whole-tree and whole-tree+forest floor harvesting reduced the bulk density recovery from almost 0.15 Mg/m^3 to about 0.10 Mg/m^3 (Figure 5). Chemical weed control also reduced the recovery by about 0.03 Mg/m^3.

Natural recovery of soils from compaction occurs primarily through three mechanisms (Miwa et al. 2004). The first and generally most important process is shrinking and swelling of 2:1 expanding clays. The second, much less common in the southern coastal plain, is freezing and thawing. The third process is through biological disturbance; root penetration and biopedoturbation. The recovery of the deeper surface layers was unaffected by organic matter removal and chemical weed control. In the surface 10 cm, however, the recovery was reduced by removing tops and forest floor and by controlling the non-pine vegetation chemically. Removal of the forest floor and weeds may have altered the soil warming and cooling cycles and changed the freeze-thaw dynamics, but these treatments more likely altered bulk density recovery by affecting biopedoturbation. Coarse woody debris serves as a host for many insects and other ground-dwelling organisms (Harmon et al. 1986). Termites decompose the coarse woody debris and transport soil into the decomposing material (Tiarks et al. 1999). This soil juxtaposition caused by organisms is a natural amelioration for soil physical disturbances. The understory control probably lowered the bulk density recovery by reducing the number of fine roots exploiting the surface soil. Prior to canopy closure, the fine roots from the understory were probably much more numerous than the fine roots from the developing pine stand, and therefore had the most direct impact on soil compaction amelioration.

Figure 5. Change in bulk density of the surface 10 cm over ten years on the Louisiana LTSP sites as a function of organic matter removal and chemical weed control. Error bars represent one standard error.



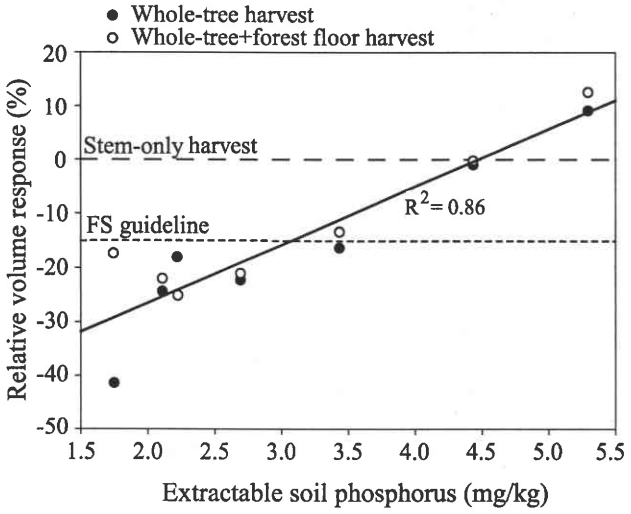
Site-Treatment Interactions and Response to Organic Matter Removal

At age 5 years, productivity loss due to whole-tree harvesting and whole-tree+forest floor harvesting was clearly related to site productivity as measured by the stem-only biomass growth at that time; productivity loss was greatest on sites with the lowest productivity (Scott et al. 2004). However, this measure would not be useful in assessing stands prior to harvest for potential declines.

We studied the relationship between surface soil nutrients and productivity loss. The soils were essentially either fertile or very infertile with respect to calcium, magnesium, and potassium (data not shown), which provided little insight regarding whether or not the harvesting reduced productivity. Soil phosphorus (P) was clearly related to the harvest intensity impact. The linear relationship between preharvest soil P concentrations and the relative biomass response was highly significant ($p < 0.0001$) and explained 86% of the variation (Figure 6). Whole-tree harvesting reduced productivity by 15% or more on the sites with less than 3.1 mg/kg of Mehlich III available P. This is very similar to the 3 mg/kg soil critical level reported for determining sites responsive to P fertilizer (Wells et al. 1973), and may be a good monitoring criterion for determining sites susceptible to productivity loss caused by organic matter removal.

Coastal plain soils, while ranging in texture from coarse sands to heavy clays, have widespread nutrient limitations. While soil N deficiencies are more widespread and have been more of a concern with respect to harvesting intensity, phosphorus deficiencies are common as well across the

Figure 6. Loblolly pine response at age 10 on the whole-tree and whole-tree+forest floor harvested plots relative to the stem-only harvested plots as a function of preharvest available soil phosphorus across the Louisiana and Mississippi Long-Term Soil Productivity sites.



southeastern United States (Allen 1987). Organic matter decomposition and nutrient release is of even greater importance to nutrient availability on weathered soils with infertile parent material. Research from Australia (Farrell 1984) and New Zealand (Smith et al. 2000) has indicated that harvest residues should be maintained on sandy sites to ensure productivity, largely due to reductions in N availability. Soil texture has been considered a primary variable in the role of organic matter and sustained forest productivity (Vance 2000), but data from these loamy Gulf coast LTSP sites show that soil texture is not exclusively indicative of low fertility in this region.

In many commercial harvesting operations in the southern pine region, whole-tree harvesting occurs by default since much of the tree crown biomass and slash is often concentrated near landings, even when efforts are made to redistribute the material through the stand. Therefore, additional care should be taken on soils with low available P to redistribute the slash evenly or consider P fertilization.

CONCLUSIONS

The LTSP study is the single largest study of forest management practices and soil productivity in the world. It was designed to help national forest planners meet the letter and spirit of several pieces of legislation by ensuring that forest management practices do not degrade soil productivity. It was also designed to develop and validate monitoring criteria that could be used in planning and monitoring protocols. The national forests and ranger districts in the Gulf Coastal Plain with LTSP installations benefit by having the sites in the planning and monitoring phases. They help in the National Environmental Planning Act (NEPA) process by providing research data on long-term effects. Referencing the LTSP study results adds to the credibility of their NEPA evaluations. The Forests also benefit from the close relationship to Forest Service Research, and vice versa. Several other studies on soil productivity and management have been implemented in the region based on this mutual interaction.

Soil compaction, organic matter removal, and stand diversity all had substantial impacts on the growth of planted loblolly pine across 10 sites in the western Gulf Coastal Plain. Soil compaction had a positive impact on loblolly pine growth at 9 of the 10 sites, but was clearly related to the preharvest understory type and biomass. Sites with shrubby species such as yaupon, wax myrtle, and inkberry benefited from compaction by reducing the understory growth. While we cannot forecast whether the remaining elevation in bulk density on the compacted plots will have a negative effect on overall soil productivity in the future, the 10-year improvements in soil properties suggest that these sites are recovering well from the experimental compaction. Harvesting practices that leave coarse woody debris on site and allow herbaceous and woody plants to grow will generally increase this natural amelioration. Removing tree tops, with or without removing the forest floor, reduced productivity by more than the allowable 15% on 8 of 10 sites. The degree of productivity loss was clearly related to available soil P; sites with less than 3.1 mg/kg of available P lost more than 15% productivity by whole-tree harvesting. Care should be taken on these sites to ensure that logging slash is redistributed evenly across the stand to return the nutrients to the whole stand or fertilization should be considered.

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