The North American Long-Term Soil Productivity Experiment: Coast-to-Coast Findings From the First Decade

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Abstract—*The National Forest Management Act of 1976 mandates that a site's productive capacity must be protected on federally managed lands. Monitoring the effects of management on a site's productive capacity is not easy, and in 1989 a national program of Long-Term Soil Productivity (LTSP) research was established to assist National Forests toward this end. The LTSP program focuses on disturbances associated with timber harvest, but findings apply to any activities altering vegetation or soil. LTSP centers on core experiments that manipulate site organic matter, soil porosity, and the complexity of the plant community. Results from a dozen decade-old LTSP installations in the Sierra Nevada and the Southern Coastal Plain do not indicate that site productivity has been impaired despite substantive soil compaction and massive removals of surface organic matter. The strongest effect of treatment on planted tree growth on sites governed by temperate and subtropical climates was the control of competing vegetation. With only one-fifth of the LTSP installations reporting, findings should not be generalized to other sites and climates.*

Introduction

The Long-Term Soil Productivity (LTSP) study began in 1989 as a "grass roots" proposal that grew to a national program of the USDA Forest Service. LTSP was founded to examine the long-term consequences of soil disturbance on fundamental forest productivity through a network of designed experiments. The concept caught the imagination of other resource managers and scientists, and partnerships and affiliations soon were forged among public and private sectors in the United States and Canada. Today, more than 100 LTSP and affiliated sites comprise the world's largest coordinated research network addressing basic and applied science issues of forest management and sustained productivity.

Background

Historical Basis

The LTSP program began in response to the National Forest Management Act of 1976 (NFMA) and related legislation (USDA Forest Service 1983). NFMA requires the U.S. Secretary of Agriculture to ensure, through research and monitoring, that forest management practices do not permanently impair the productivity of the land. This requirement seems superfluous because sustaining productivity is an obvious aim of modern forest management and has been a Forest Service goal since the agency was founded. It is remarkable only in that NFMA may be the world's first modern mandate for a forest land ethic that carries the weight of law.

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Responding to NFMA, an independent committee of scientists was appointed to form a framework for implementing the law. Their recommendations led in 1985 to a statement of responsibilities surrounding federal land management activities (Code of Federal Regulations 1985). One notable element was that the Forest Service must monitor the effects of forest management prescriptions, including "significant changes in land productivity." This monitoring requirement was developed more than a decade in advance of The Montreal Process (Canadian Forest Service 1995) and the environmental surge toward "green certification" (Anonymous 1995).

The Forest Service knew that clear and objective definitions were key to addressing its monitoring charge. "Land productivity" was a central issue. Broadly, it could be defined as a site's capacity to produce a cornucopia of timber, wildlife, watershed, fishery, and aesthetic values. All these values are legitimate expressions of land productivity, but some are less tangible, more subjective, and more variable temporally than others. Instead, and with guidance from the U.S. Office of General Council, a fundamental definition was forged. Land productivity was defined as the carrying capacity of a site for vegetative growth. This was useful, because the capacity of a site to capture carbon (C) and grow vegetation is central to its potential for producing all other values. Given the vagaries of annual fluctuations in dry matter production, consensus held that a departure from baseline would have to exceed 15 percent to be deemed significant (USDA Forest Service 1987). But what variables should be monitored?

The National Forest Approach

Trying to measure the productive potential of a site directly by assaying trends in tree or stand growth is fraught with frustrations and uncertainty because trends vary with stand age, structure, stocking, treatment history, and the lack of reference controls (Powers 2001). Consequently, soil-based indices have been proposed as more objective measures of a site's productive potential (Burger 1996, Powers and others 1990). The USDA Forest Service also saw the value in soil properties as an independent basis for monitoring potential productivity. In 1987 the Watershed and Air Management division of National Forest Systems adopted a program of soil quality monitoring that was based on the following rationale (Powers and Avers 1995):

- Management practices create soil disturbances.
- Soil disturbances affect soil and site processes.
- Soil and site processes control site productivity.

Monitoring soil and site processes directly is not feasible. Instead, the Forest Service proposed a monitoring strategy based on measurable soil variables that either reflect, or are correlated with, important site processes. Accordingly, each Forest Service Region has developed threshold monitoring standards for soil quality reflecting state-of-the-art knowledge and professional judgment (Page-Dumroese and others 2000; Powers and Avers 1995; Powers and others 1998). Threshold standards are meant to detect when significant changes have occurred in potential productivity at a statistical confidence of ± 15 percent of the true site mean. These standards await validation and are updated as findings accrue from research. Unfortunately, correlations between soil monitoring variables and potential productivity are mainly conceptual. Because they are conceptual and somewhat subjective, they can be challenged.

Research Coordination

Recognizing the difficulty inherent in developing soil quality monitoring standards based partly on professional judgment, the National Forest System (NFS) of the Forest Service asked Forest Service Research for assistance. A small but seasoned team of scientists and practitioners assembled informally in 1988 to address the problem. Extensive review of world literature revealed that two ecosystem properties most likely to impact long-term productivity were site organic matter and soil porosity. While these site and soil properties were seen clearly as of paramount importance, we concluded that existing information was sparse, site specific, often contradictory, and too anecdotal to be broadly useful. More fundamental work was needed, and we proposed a nationally coordinated field experiment to address the issue directly and unambiguously. The proposal was reviewed internally by leading Forest Service scientists and professionals, and both nationally and internationally by research scientists outside the agency. We believe that this was the most widely reviewed research study plan ever produced by the Forest Service. A final study plan was prepared (Powers and others 1989). The plan was approved as a national effort in 1989 by the Deputy Chiefs for Research and National Forest Systems in Washington, D.C., and 10-year funding was secured for implementing the study on public lands. The overview was published and circulated widely (Powers and others 1990, 1996; Powers and Avers 1995).

Partnerships

The first LTSP installation was established in 1990 on the Palustris Experimental Forest in the loblolly pine (*Pinus taeda*) forest type of the Louisiana Coastal Plain. The following year saw units established in the mixed conifer (*Abies/Pinus/Pseudotsuga*) forest of California's Sierra Nevada and in the glacial till landscape of Minnesota's aspen (*Populus deltoides/ tremuloides*) forest. The experiment then expanded to other sites and Life Zones. As the LTSP program gained momentum it drew widening attention. British Columbia's Ministry of Forests adopted the LTSP concept in 1990 as a high priority program for Interior British Columbia (Hope and others 1992). Two installations were established by 1994 and several more followed (Holcomb 1996). Independently, the Canadian Forest Service began experiments in Ontario that closely paralleled the LTSP design, and the two programs merged in 1996 to expand the network. Today, the total number of installations with the core design stands at 62 (figure 1).

In the United States, forest industry voiced concern that the experiment highlighted only "negative" impacts of management and that LTSP lacked treatments aimed at enhancing site productivity. Accordingly, we invited leaders from private and public forest management groups to a 1995 working session in St. Louis, Missouri, to air concerns and to find ways of improving the study and strengthening the network. This led to an expanded affiliation that included studies on industrial lands and elsewhere. Conditions for affiliation are that (1) studies have certain elements in common with the LTSP experimental design (at least the minimal potential impact treatment), (2) treatment plots be large enough to have minimal edge effect once plots attain leaf area carrying capacity, and (3) members agree to share findings and provide mutual support (Powers and others 1996). These affiliate sites have brought the LTSP network to more than 100 installations (figure 1), making it the world's largest coordinated effort aimed at understanding how pulse disturbances affect sustained forest productivity.

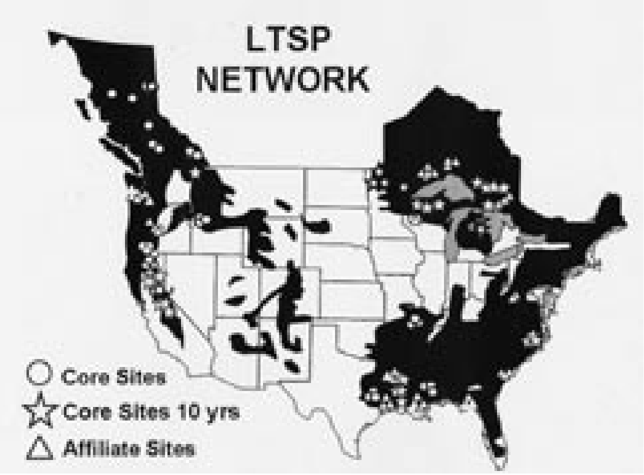

Figure 1—Location of core LTSP and affiliate installations on the approximate range of the commercial forest in the United States and two Canadian provinces. Stars indicate installations achieving at least 10 years of growth.

The Study

A Conceptual Model

The LTSP program is predicated on the principle that within the constraints of climate, a site's potential net primary productivity is strongly regulated by physical, chemical, and biotic soil processes affected readily by management. The key properties directly affected by management are soil porosity and site organic matter (OM). These two properties regulate critical site processes through their roles in microbial activity, soil aggregate stability, water and gas exchange, physical restrictions on rooting, and resource availability (figure 2).

Regardless of silvicultural strategy or harvest intensity, site organic matter and soil porosity are impacted directly by forest management operations. Therefore, they were targeted for specific manipulation in large-scale, long-term experiments meant to encompass the range of possibilities occurring under management. The experiments were designed to address these four hypotheses:

Null hypothesis	Alternative hypothesis
1. Pulse changes in site organic matter and/or soil porosity do not affect the sustained productive potential of a site (sustained capacity to capture carbon and produce phytomass).	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.

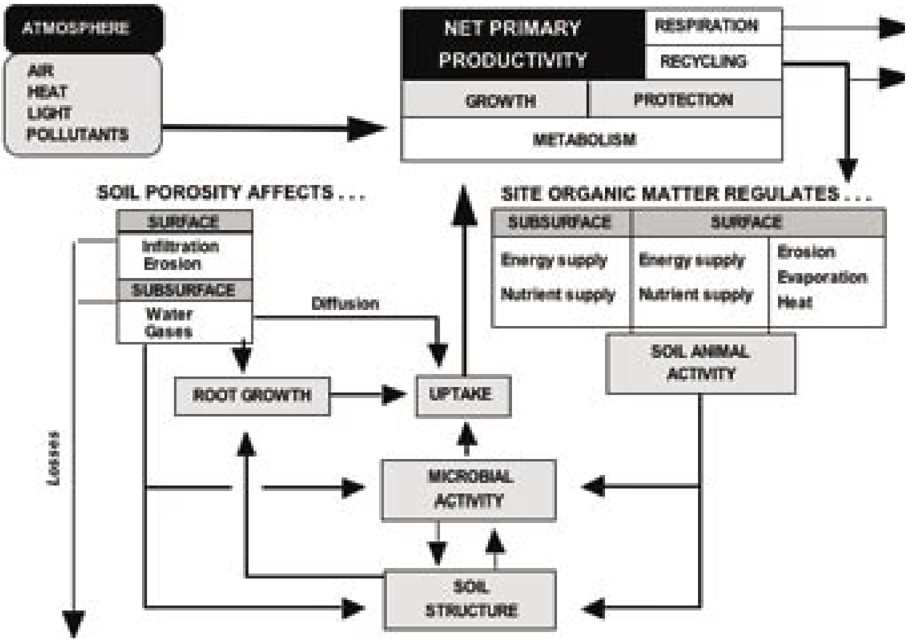

Figure 2—Conceptual model of the influence of site organic matter and soil porosity on fundamental site processes that regulate primary productivity.

Selecting Sites and Applying Treatments

The study was targeted at forest types, age classes, and soil conditions apt to fall under active forest management involving harvesting, thinning, or fuel modification. These were fully stocked, young-growth, even-aged stands—i.e., not "ancient forests" or non-forested openings. Preliminary plots of 0.2 or 0.4 ha were identified and surveyed for variability in soil and stand conditions. Those with comparable variability at a given location (similar soil type, stand density, and amounts of disturbance) were chosen for the experiment. Pretreatment samples were taken to quantify standing biomass and nutrient capital in the overstory, understory, and forest floor. Stands were then harvested under close supervision and treatments were imposed randomly. The main effect treatments were as follows:

Main effect	Symbol	Description of treatment
Modify site organic matter	OM_0	Tree boles removed. Retain crowns, felled understory, and forest floor.
	OM_1	All aboveground living vegetation removed. Forest floor retained.
	OM_2	All surface organic matter removed. Bare soil exposed.
Modify soil porosity	C_0	No soil compaction.
	C_1	Compact to an intermediate bulk density.
	C_2	Compact to a severe bulk density.

We had two reasons for choosing these levels of organic matter manipulation. First, they encompass the extremes in organic matter removal likely under any silvicultural system short of removing surface soil or extracting roots. Second, they produce a step series of nutrient removal that is disproportionate to biomass loss. Table 1 illustrates these points using six typical LTSP sites arrayed along a climatic gradient. It shows that overstory trees contain roughly 80 percent of site aboveground organic matter with about

Table 1—Absolute and proportional amounts of biomass and nitrogen removed by the three organic matter treatments on representative LTSP sites (OM_0 = bole only removed, OM_1 = whole tree removed, OM_2 = whole tree + understory and forest floor removed). Life zone codes after Holdridge (Lugo and others 1999); *BM* = boreal moist, *CTM* = cool temperate moist, *WTD* = warm temperate dry, *WTM* = warm temperate, moist, *STM* = subtopical moist.

			Biomass removed (Mg/ha) (% of above ground total)			Nitrogen removed (kg/ha) (% of above ground total)		
Location	**Life zone**	**Forest type**	**OM_0**	**OM_1**	**OM_2**	**OM_0**	**OM_1**	**OM_2**
British Columbia	*BM*	Subboreal spruce	126 *(56)*	158 *(71)*	223 *(100)*	195 *(18)*	253 *(24)*	1,068 *(100)*
Minnesota	*CTM*	Trembling aspen	175 *(61)*	214 *(75)*	286 *(100)*	194 *(30)*	316 *(48)*	653 *(100)*
Idaho	*CTM*	Mixed conifer	160 *(61)*	191 *(73)*	261 *(100)*	190 *(22)*	410 *(48)*	846 *(100)*
California	*WTD*	Mixed conifer	252 *(47)*	473 *(89)*	532 *(100)*	218 *(20)*	609 *(57)*	1,064 *(100)*
Missouri	*WTM*	Central hardwood	96 *(42)*	175 *(77)*	228 *(100)*	195 *(24)*	540 *(67)*	811 *(100)*
Louisiana	*STM*	Loblolly pine	133 *(77)*	153 *(88)*	173 *(100)*	134 *(38)*	229 *(65)*	352 *(100)*

two-thirds occurring in boles. At best, the forest floor accounts for only one-fourth of aboveground organic matter.

Nitrogen (N) shows a different trend. Although half or more of aboveground organic matter may be in tree boles, this accounts for only one-fifth to one-third of the aboveground N capital. On average (and in the absence of frequent disturbance), the forest floor of mature stands contains as much N as boles and crowns, combined. However, the actual proportion of aboveground N in the forest floor varies with climate (table 1). In moist boreal forests of British Columbia where decomposition is slowed by cool temperature and perhaps by partial anaerobia, the forest floor accumulates far more N than is contained in the vegetation. Under warm, humid conditions, the forest floor decomposes rapidly and is a relatively low reservoir of N. Regardless of Life Zone, the understory in mature forests is only a minor component of site organic matter or N (only a few percentage points of the aboveground total after canopies have closed).

Compaction was accomplished through multiple passes of heavy machinery to achieve target levels of soil bulk density varying by soil texture (Daddow and Warrington 1983). Organic removal was accomplished by full suspension of boles or crowns, or by manually raking the forest floor from the plot to expose mineral soil. Experimental treatments were not meant to mimic operational practices, but rather to bracket the extremes in disturbance likely to occur under present or future management. Generally, all factorial combinations of main effect treatments were applied, producing nine core combinations of organic matter removal and soil compaction. Treatment plots (0.4 ha) were separated from residual stands by a distance at least equivalent to the height of bordering trees. This plot size and separation avoided competitive edge effects that could mask the true impact of the treatments, a confounding factor that affects small plot studies and many historical investigations (Powers and others 1990, 1994). Only rarely were treatments replicated at a given location. High establishment costs (about $60 thousand per set of 9 treatments) and the need to generalize findings across a broad ranges of sites convinced us that the better approach was to replicate the experiment within particular soil types (soil Series of Families) but at geographically separated locations. Soil types were chosen based on their regional prevalence and on their position along a continuum of site productivity within a regional forest type. In California for example, three installations occur on each of three soil types representing low, medium and high levels of productivity (nine in all), and another three installations occur on unreplicated soil types representing levels of productivity between the extremes. Only a few installations were established in a given year and replicates in a given soil type sometimes were established in different years. In California, three installations (Central, Owl, and Vista) are replicates of a particular soil Series or Family, but Challenge and Wallace are not (table 2). The LTSP study is planned to extend several decades to at least the culmination of mean annual volume increment. Only those achieving 10 years from treatment are reported here.

Plots were regenerated with the tree species indigenous to the site and measurement trees were separated from outer plot boundaries by several rows of buffer trees. Except for aspen (*Populus*) forests and the mixed conifer sites of interior British Columbia where policy precluded herbicides, all main effect treatment plots were split. One half of each plot was kept weed-free by regular applications of herbicides, and the other half was allowed to develop naturally (thereby producing side-by-side subplots with simple and diverse forest communities). Where possible, the more severe treatments were applied and followed by mitigative measures, such as fertilization to replace nutrients and subsoiling to alleviate compaction. Each field installation was equipped with an automated climatological monitoring station, thereby linking all sites in a network characterized by precipitation, temperature, solar radiation, and relative humidity.

Post Treatment Measurements

Although many measurements could be taken, principal investigators agreed that a reduced set of eight core measurements were critical to the success of the LTSP program. Beyond treatment establishment, funds were extremely limited. Therefore, minimum measurement intervals were identified for each variable:

Measurement variable	Minimum measurement interval
Climatological data	Continuous.
Soil moisture and temperature	Monthly.
Soil bulk density	Each 5 years.
Soil strength	Seasonally each 5 years.
Soil organic matter content and chemical composition	Each 5 years.
Water infiltration and saturated hydraulic conductivity	Each 5 years.
Plant survival, growth, damage from pests, NPP	Each 5 years.
Foliar chemistry and standing nutrient capital	Each 5 years.

Methods for estimating growth and net primary productivity (NPP) were left to the discretion of each principal investigator, but generally they involved periodic destructive sampling within the treated buffer. While early findings have been reported for individual sites (Alban and others 1994; Amaranthus and others 1996; Tiarks and others 1998; Powers and Fiddler 1997; Stone and Elioff 1998), most have dealt with stand conditions short of crown closure and may not be indicative of long-term trends when sites are stocked at carrying capacity. This paper constitutes the first effort at summarizing findings from installations that have reached 10 growing seasons. It highlights installations in two geomorphic provinces with differing climates: the Sierra Nevada of California, and the Southern Coastal Plain (table 2). Analyses are principally of two types: analysis of variance and least squares regression via standard procedures.

Table 2—Site and pretreatment stand characteristics of LTSP installations achieving 10 years of growth. Life zone codes after Holdridge (Lugo and others 1999); *BM* = boreal moist, *CTM* = cool temperate moist, *WTD* = warm temperate, dry, *WTM* = warm temperate, moist; *STD* = subtropical dry, *STM* = subtopical moist. Nd = information not determined or not available.

Location	Installation name	Life zone	Forest type	Elev (m)	ppt. (cm)	Soil origin	Stand age (yr)	Preharvest biomass (kg/ha)		
								Overstory	Understory	FF
California	Central	*WTD*	Mixed conifer	1685	114	Granodiorite	117	422,111	94	80,455
California	Challenge	*WTD*	Mixed conifer	790	173	Metabasalt	108	473,348	576	60,926
California	Owl	*WTD*	Mixed conifer	1805	114	Granodiorite	115	576,071	34	72,233
California	Vista	*WTD*	Mixed conifer	1560	76	Granodiorite	132	373,609	43	72,567
California	Wallace	*WTD*	Mixed conifer	1575	178	Volcanic ash	230	450,193	83	115,757
Idaho	Priest River	*CTM*	Mixed conifer	900	85	Volcanic ash	120	191,250	1,750	68,000
Louisiana	Glenmora	*STD*	Pine-hardwoods	61	147	Marine sediments	52	153,000	4,200	15,900
Louisiana	Malbis	*STD*	Pine-hardwoods	52	150	Marine sediments	45	91,000	5,100	Nd
Louisiana	Mayhew	*STD*	Pine-hardwoods	61	147	Marine sediments	55	236,200	1,700	15,400
Louisiana	Metcalf	*STD*	Pine-hardwoods	61	147	Marine sediments	55	203,200	1,800	20,500
North Carolina	Croatan	*WTM*	Pine-hardwoods	7	136	Marine sediments	65	167,800	3,190	52,410

Findings to Date

Findings reported too hastily can be misleading. While a decade may seem a long observational period for many studies, we have resisted making a hasty synopsis of cross-site comparisons. Even at 10 years, crown canopies have not closed on many treatment plots. However, we believe that oscillations from initial perturbations have dampened enough to give us an early glimpse of longer-term trends. We confine our analyses to simple responses of soil and vegetation to the main effect treatments on our oldest installations for which data are available, those from the Southern Coastal Plain and Sierra Nevada—two regions contrasting greatly in climate and geology. Our analyses carry the caveat that trends may change when data are available from all LTSP installations.

Organic Matter

Productivity

We tested the hypothesis that site organic matter removal affects forest productivity by comparing total standing biomass at 10 years for 12 sites, five from the Sierra Nevada and seven from the Southern Coastal Plain. Planting through logging slash sometimes reduces tree survival. Therefore, we based our analyses on total standing biomass (planted trees plus understory vegetation) on non-herbicide plots. Total vegetative production reflects site potential more fully, particularly where tree stocking has not reached site carrying capacity.

Removing all surface organic matter prior to planting had no general impact on total vegetative production at 10 years, regardless of geographic province (figure 3). The linear trend determined by regression suggests that removing surface organic matter reduces productivity more on poorer sites than on better, but the intercept is not significantly different from zero ($p = 0.33$) and the slope trend is not significantly different from 1.0 ($p = 0.62$).

Soil Chemistry

Data from the seven Coastal Plain sites indicate that organic matter removal had negligible impact on the concentration of organic C in the

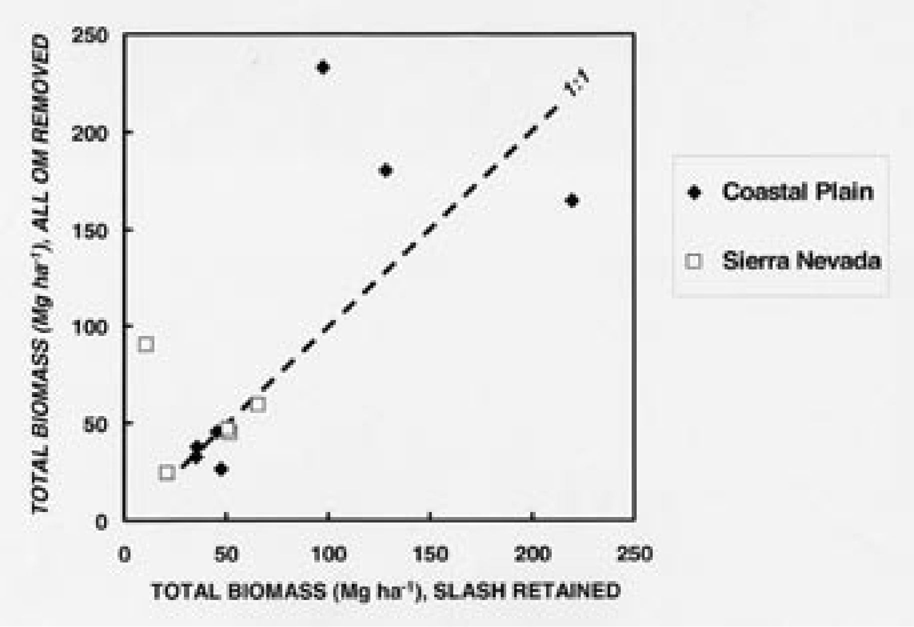

Figure 3—Standing biomass of trees and understory vegetation at 10 years as influenced by the retention or removal of organic surface residues (no soil compaction). Dashed line indicates 1:1 parity between treatments. Basis: 12 sites in California and the Southern Coastal Plain. (OM = organic matter.)

upper soil profile (figure 4). Nor did removing surface organic matter have any apparent effect on the mass of C or N in the upper soil profile at 10 years. Analysis of variance for soil C and N content on the three North Carolina installations replicated on the Croatan National Forest detected no significant effect among organic matter removal treatments (table 3). Yet, when the same soils were analyzed for organic C concentrations before treatment and at time intervals thereafter, post-treatment concentrations were greater at all depths than initial values (figure 5). This was true at all depths, even where all surface organic matter had been removed.

This presents a curious and seemingly contradictory point. On one hand, surface organic matter removal seemed to have no obvious effect on soil C storage at 10 years. On the other hand, soil carbon concentrations significantly increased following harvest. The explanation for this lies in the primary source of soil organic C. Apparently, soil inputs following disturbance depend less on decomposition of surface residues and more on the decay of fine roots that remained from the previously harvested stand. This conclusion is supported by work elsewhere. In a Tennessee study more than a decade after harvesting a mixed-hardwood forest, Johnson and Todd

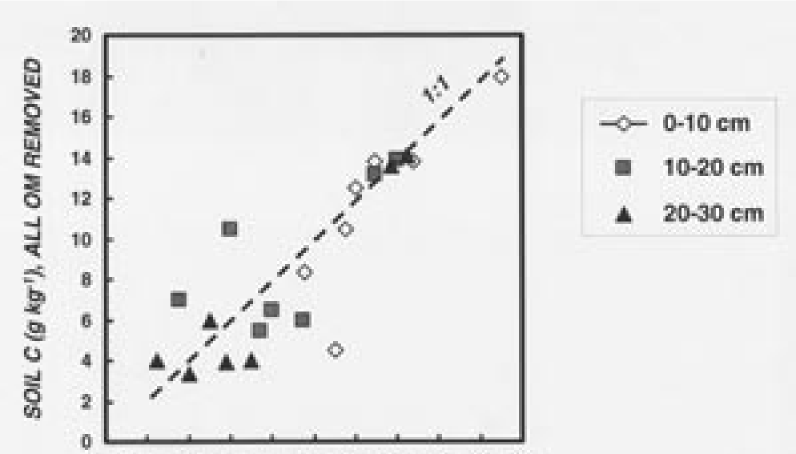

Figure 4—Concentration of organic soil carbon at 10 years for three soil depths as influenced by the retention or removal of organic surface residues. Dashed line indicates 1:1 parity between treatments. Basis: seven sites in the Southern Coastal Plain.

Table 3—Influence of organic matter removal on soil organic carbon (C) and nitrogen (N) 10 years after treatment at the North Carolina LTSP sites. Statistical significance of differences among treatments indicated by *p > F*.

	Organic matter removal			
Soil depth (cm)	**OM$_0$**	**OM$_1$**	**OM$_2$**	**p > F**
	Organic C (Mg ha^{-1})			
0-10	28.4	33.3	33.8	*0.21*
10-20	21.4	23.5	25.1	*0.61*
20-30	14.0	25.1	16.5	*0.69*
	Total N (kg ha^{-1})			
0-10	807	905	882	*0.85*
10-20	542	524	540	*0.99*
20-30	352	385	368	*0.94*

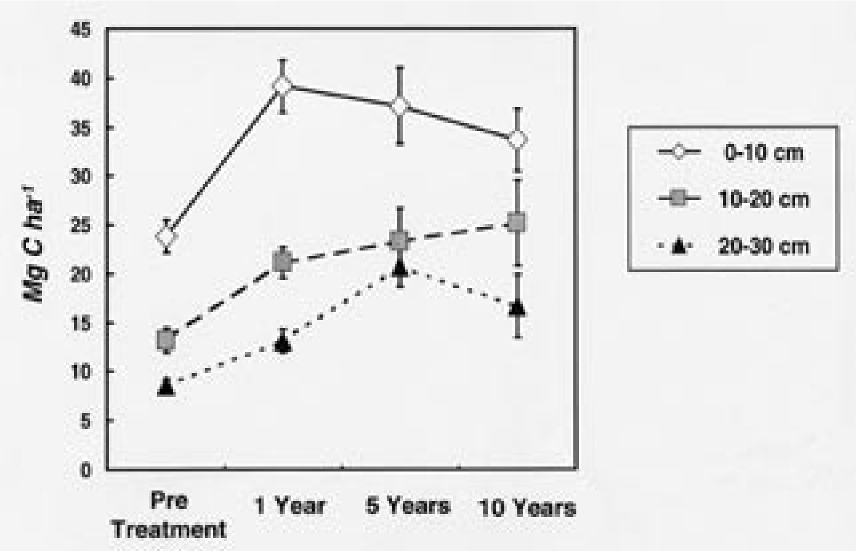

Figure 5—Quantity of fine fraction organic soil carbon stored at three soil depths before and after the OM$_1$ treatment on the Croatan LTSP site in North Carolina. Vertical bars indicate one standard error of the mean. Trends were similar among all OM treatments.

(1992) found no differences in soil organic matter beneath previous piles of logging slash and units free of slash. Evidently, under moderate and warmer climates, C is respired as CO_2 as surface residues decompose, and very little C is incorporated into the soil beyond. In their work on California soils similar to our California LTSP sites, McColl and others (1990) showed that dissolved organic C from mature forests contributed less than 1 Mg C ha^{-1} yr^{-1} to the mineral soil—only a fraction of the increases we found (figure 5).

On the other hand, fine roots decaying from harvested stands provide sizable C inputs in fractions small enough to pass a conventional 2 mm sieve. Van Lear and others (2000) found that soil C concentrations were more than an order of magnitude greater in the vicinity of roots remaining from a stand harvested 16 years earlier than in the general soil. The effect was evident to as much as a meter depth. Root decay apparently follows a simple Q_{10} model of rate increasing with temperature (Chen and others 2000), and should be quite rapid in soils of the warm, humid Southern Coastal Plain and in those dominated by a Mediterranean climate. We conclude that organic C from surface residues (logging slash, understory vegetation, and forest floor) most likely is respired as CO_2 during decomposition and contributes relatively little to soil C. And while organic N mineralized to ammonium during decomposition presumably is released to the soil, either it is immobilized quickly, nitrified and leached, or is too miniscule relative to organic N to be detected through conventional analysis (table 3).

Soil Compaction

Soil compaction effects on productivity through the first 10 years were assayed by comparing total standing biomass (trees plus understory vegetation) on C_0 (not compacted) and C_2 (severely compacted) treatments (figure 6). Organic matter treatment was held constant at OM_2 (complete removal) to eliminate the possibility of compaction x organic matter interactions. The regression trend suggests that in general, soil compaction leads to slightly greater productivity, but the slope of the linear trend is not significantly different from 1.0 ($p = 0.22$) and the intercept is not significantly different from zero ($p = 0.82$). We conclude that soil compaction in our most extreme treatments did not significantly or universally affect total vegetative productivity on sites in the Sierra Nevada and Southern Coastal Plain.

But findings may be biased if trees on compacted soils have lower understory competition, or if soil texture is such that both understory and overstory growth are increased by compaction as was reported by Powers and Fiddler (1997). We found that understory biomass was 55 percent greater on plots not compacted ($p = 0.08$), although this was not so on soils with a sandy texture where biomass tended to be greater on compacted soil. To reduce possible confounding, comparisons also were made of tree biomass for C_0 and C_2 treatments on plots kept free of understory vegetation. Even so, 10-year tree biomass on C_0 and C_2 plots were identical ($Y = 1.94 + 1.00X$, $adj.\ r^2 = 0.78$). Data for plots free of understory competition (open squares) are superimposed on figure 6. We found no evidence that 10-year productivity was universally impacted by soil compaction, regardless of the presence or absence of understory vegetation.

Given that soil compaction generally is believed to reduce tree growth, this result is surprising. One explanation for the lack of an overall soil compaction effect might be that our treatments did not reach compaction levels considered to be severe. To examine this, we calculated soil bulk density immediately following severe compaction as a function of bulk

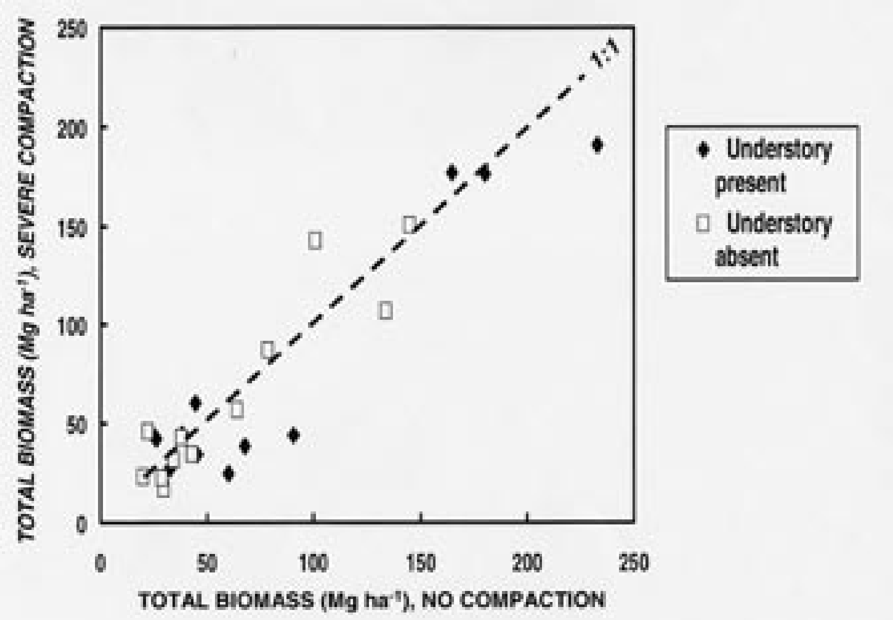

Figure 6—Effect of severe soil compaction on total standing biomass at 10 years (OM_2 treatment). Filled diamonds indicate the biomass of trees + understory vegetation where understory vegetation was present. Open squares indicate tree biomass where understory vegetation was absent. Neither trend differs significantly from a 1:1 relationship, indicating that severe soil compaction had no general effect on productivity.

density immediately before compaction for the 10-20 cm depth zone over a broad range of sites in the LTSP network. The trend was strongly linear of the form:

$$Y = 0.426 + 0.788X \qquad \text{[Eq. 1]}$$
$$r^2 = 0.95$$

Where:

X = soil bulk density in Mg m^{-3} at 10-20 cm before soil compaction

Y = soil bulk density at 10-20 cm in the first year following severe compaction.

r^2 = the proportion of variation in Y explained by the linear relationship.

This indicates that the degree to which soil bulk density was increased by compaction depends strongly on the initial bulk density. That is, soils with low initial bulk densities were compacted more than soils where bulk densities already were high. It also suggests that soil with an initial bulk density of 1.99 Mg m^{-3} can not be compacted further through the procedures we employed.

Soil compaction occurs at the expense of larger pores, resulting in the loss of aeration porosity (Siegel-Issem and others, in press). This means that soils compacted further from a very high initial bulk density may lose air-filled pore space and the soil may become waterlogged or suffer from the buildup of respiratory gases. Grable and Siemer (1968) suggest that an aeration porosity of 10 percent is a critical limit for root respiration and growth. Although we did not measure pore size distribution on most of our soils, we can solve for approximate total porosity by assuming a soil particle density of 2.65 Mg m^{-3}. Using Eq. 1 above, and solving for the bulk density at which no further compaction is possible by the means we used, we can infer that the "uncompactable porosity" remaining at a bulk density of 1.99 is 24 percent, and that this essentially defines the micropores remaining after practically all air-filled porosity has been depleted.

The highest bulk densities we achieved on any depth for any of the sites in figure 6 were in the range of 1.65 to 1.71 Mg m^{-3} (Louisiana). Based on the simple approximations above, this translates to a total porosity between 38 and 35 percent immediately following compaction, for an estimated aeration porosity of between 14 and 11 percent once microporosity is subtracted. This suggests that aeration porosity following severe compaction on the Louisiana sites remained just above the 10 percent threshold proposed by Grable and Siemer (1968). Greenhouse studies have shown that loblolly pine can grow reasonably well even under waterlogged conditions (Siegel-Issem and others, in press). This is probably because of the presence of aerenchyma cells allowing gas exchange between roots and the aboveground atmosphere.

Another possibility explaining the absence of a clear impact of soil compaction on productivity is that soils may have recovered quickly from the initial effects of compaction. We tested for recovery by comparing soil bulk densities at 10-20 cm in the first year after severe compaction treatment with those on the same plots after 10 years. Figure 7 indicates that recovery in that period has been negligible at soil depths below 10 cm.

We conclude that despite appreciable increases in soil bulk density, particularly on lower density soils, compaction has not affected productivity in a general sense over the first 10 years. In our view, the most likely explanations concern the facts that (1) soil compaction may improve soil water availability on droughty sites (Gomez and others 2002); (2) the highest soil bulk densities were associated with loblolly pine sites, a species that tolerates high bulk densities and poorly drained conditions (Siegel-Issem and others, in press);

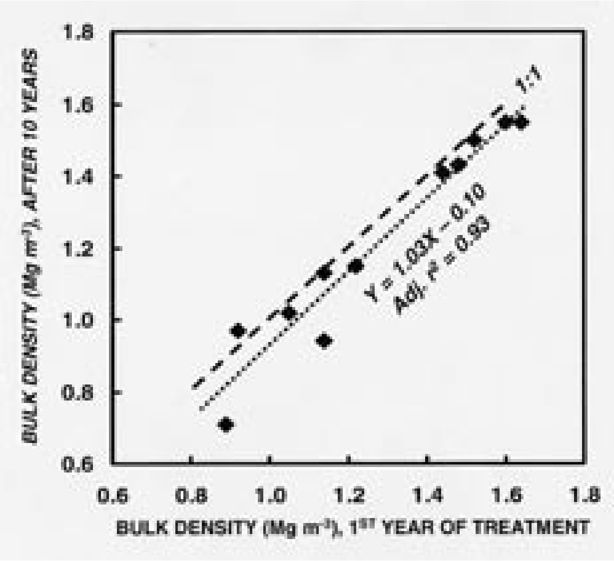

Figure 7—Soil bulk density recovery from severe compaction between the first and 10th year in the 10-20 cm depth zone on 11 LTSP installations. Understory excluded. No recovery indicated by the 1:1 line of parity. Regression line indicates that the higher the initial bulk density, the lower the rate of recovery.

and (3) soils are not compacted readily around stumps left from the previous stand (large surficial roots buffer against compaction). Friable soil bordering roots of remnant stumps maintains a favorable balance of moisture and aeration and becomes the locus for increased rooting activity and superior growth in the new stand (Van Lear and others 2000).

Evidence abounds that soil compaction reduces tree growth (Greacen and Sands 1980, Powers and others 1990) and models for estimating tree growth reduction with increasing compaction have been developed (Froehlich and McNabb 1984). But more recent findings indicate that the impacts of compaction are not universal. Instead, impacts depend largely on site conditions affecting air and water balance in the rooting zone (Gomez and others 2002; Heninger and others 2002; Miller and others 1996; Siegel-Issem and others, in press).

The Presence of Understory Vegetation

Over the first 10 years of the LTSP experiment, the single strongest factor affecting planted tree growth was the competitive effect of understory vegetation. Whether in the Sierra Nevada or the Southern Coastal Plain, tree biomass averaged about one-fifth greater where understory vegetation was excluded (figure 8). In the Sierra Nevada, where summer drought is common, planted tree productivity averaged more than three times higher in the absence of understory vegetation.

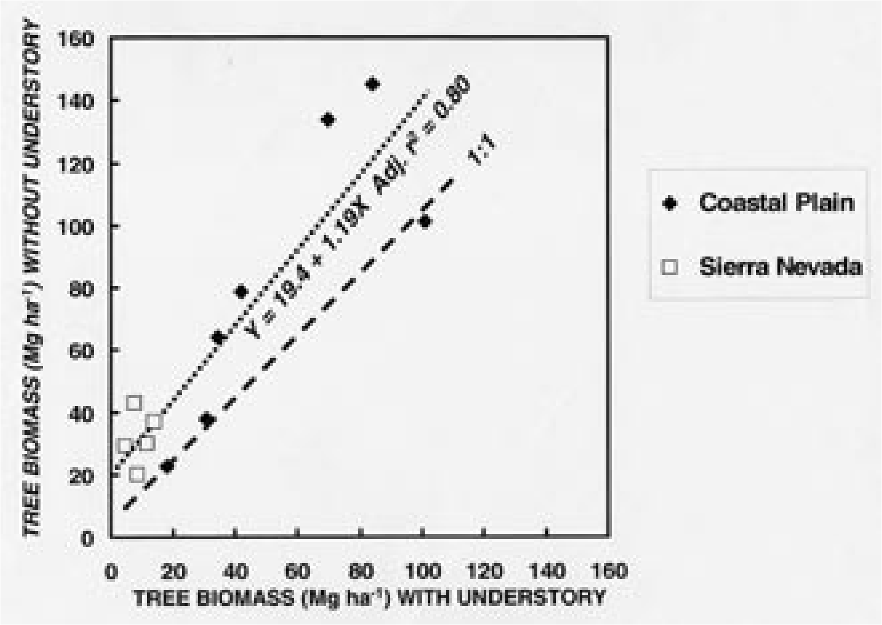

Figure 8—Effect of understory vegetation on the biomass of planted trees at 10 years for OM_2C_0 treatments on 12 LTSP installations. Regression line indicates that growth response to vegetation control is proportionally greater on lower productivity sites, but absolutely greater at higher levels of productivity. Dashed line indicates 1:1 parity between treatments.

Conclusions

The LTSP experiment is still in its infancy. Installations were established over several years, and only the oldest and most productive are approaching site carrying capacity. The findings reported here may provide the earliest glimpse into general longer-term trends. Or they may be seen as aberrations once a more complete data set emerges and vegetation more fully occupies our sites. What we can conclude for the Sierra Nevada and the Southern Coastal Plain is that there is no evidence that soil productivity has been seriously impaired in the first 10 years despite massive removals of surface organic matter and substantial soil compaction.

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