North American Long-Term Soil Productivity Research Program

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Abstract.—The National Long-term Soil Productivity research program was chartered to address National Forest Management Act concerns over possible losses in soil productivity on National Forest lands. The program supports validation of soil quality monitoring standards and process-level productivity research. Summarized results are supplied to Forests as collected. National Forest managers use them in developing forest plans and modifying management practices. Results are treated as the best available evidence and are used within the adaptive management process.

INTRODUCTION

Origins of the Long Term Soil Productivity (LTSP) program can be traced from informal discussions in 1986 between National Forest System (NFS) managers and Forest Service Research (FSR) scientists. NFS managers needed valid soil quality monitoring standards as a consequence of the National Forest Management Act of 1976 (NFMA), and sought help from Forest Service Research. Researchers needed a more fundamental understanding of site productivity and the processes controlling it to develop and evaluate alternative silvicultural systems. Open and active communication between researchers and managers led to a major review paper on the world' s experience concerning declines in fundamental productivity (Powers and others 1990) and a template for what was to become the LTSP program. Further technical discussion between Forest Service scientists, international scientists, and researchers from several U. S. universities and forest industry resulted in a generic study plan which was drafted and circulated for national review. In 1989, following national review, the LTSP plan became an official Forest Service cooperative program with the signing of the national study plan by the Deputy Chiefs for National Forest Systems and Research[2].

DESIGN AND IMPLEMENTATION

Background

Soil was selected as an indicator of site productivity potential because it is a fundamental resource that controls the quantity and quality of such renewable forest resources as timber, wildlife habitat, forage, and water yield, and because it is a non-renewable resource directly affected by forest management practices. The USDA Office of General Council interprets land productivity to mean the inherent capacity or potential of a soil to produce vegetation[2]. The LTSP program centers on two concepts:

1. the soil is the key site factor controlling productivity that is affected by management, and
2. the fundamental measure of productivity is the site's carrying capacity for plant growth.

Research has shown that productivity declines on non-wetland sites are related principally to site organic matter losses and soil porosity reductions (Powers and others 1990). Although concepts are well established, there is little specific understanding of how site organic matter and soil porosity are linked to control fundamental processes governing productivity or what threshold levels of organic matter and soil porosity are needed to maintain site productivity.

The national study has three main objectives:

1. Validating regional soil quality monitoring standards against soil productivity potential;
2. Determining the productive potential of the land for vegetative growth; and
3. Understanding how soil porosity and site organic matter interact to regulate long-term site productivity.

These objectives are best addressed by a designed experiment with treatments effecting large, systematic changes in fundamental soil properties. A controlled experiment is preferable to quantifying operational practices which are difficult to control, generally confound several variables, vary from region to region, and are likely to become obsolete.

Experimental Design and Treatments

Each installation of the study (Figure 1) consists of a core set of nine plots which represent all possible combinations of three levels of compaction (none, moderate, and severe) and three levels of organic matter removal (bole only, bole + crown, and total above-ground organic matter). The 1-acre plots are regenerated with the species or species group appropriate to each region. Each plot is split into two equal parts with one half receiving total competition control, focusing site resources only on the subject trees. The other half receives no competition control and the plant community is allowed to develop. Along with the core experiment, plots of ameliorative treatments and best

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[2]USDA Forest Service. 1989. Evaluating timber management impacts on long-term soil productivity: a Research and National Forest System cooperative study. Study Plan. 32 p.

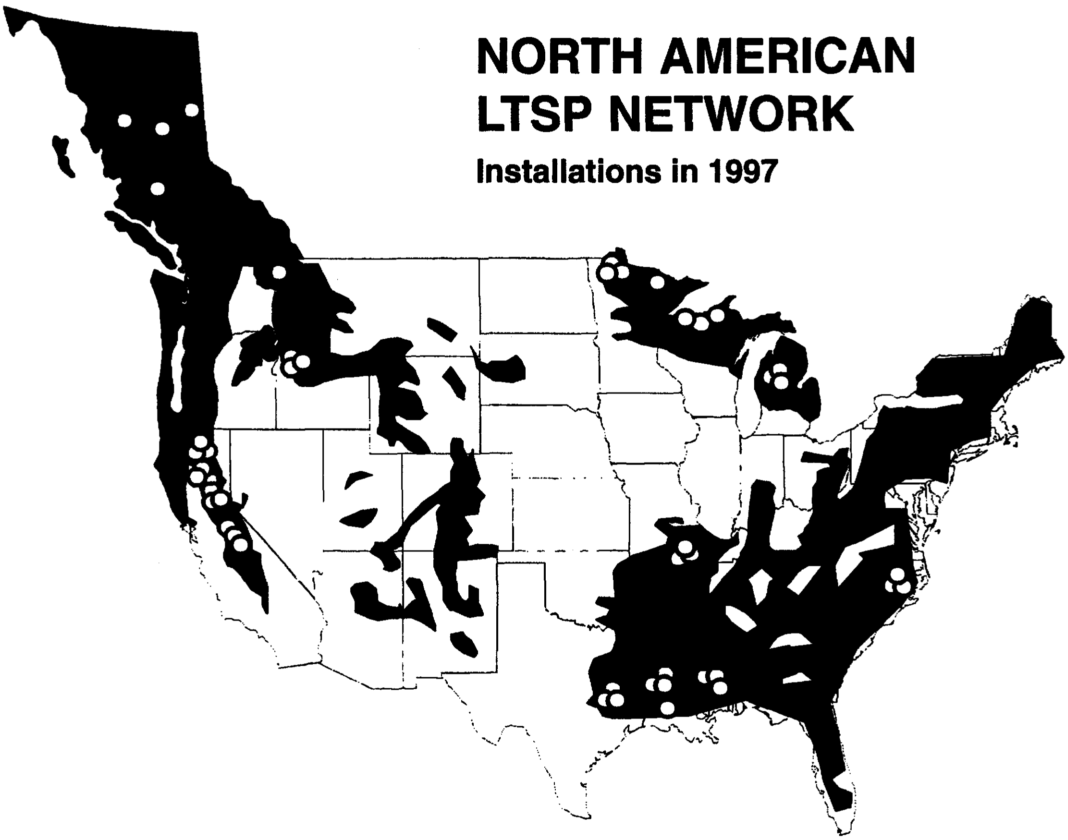

Figure 1.—Locations of current LTSP installations in North America.

management practices are added at many LTSP sites to see how soil productivity can be restored or improved. The standardized experimental design is shown in Figure 2. Most sites are on National Forests, but in Missouri the plots are located on state lands as is one installation in California. Researchers in the British Columbia Ministry of Forests, Canada, adopted the LTSP design and have installations at four locations with more planned. Locations of the current LTSP study installations are shown in Figure 1 and Table 1 summarizes the forests and species. Our discussion centers on the U.S. Forest Service phase of LTSP.

Candidate sites are arrayed along a gradient in soil properties believed to be directly linked to potential productivity, recognizing that the importance of any suite of properties varies by region. Study sites are selected from the candidates to cover the range of soil-site conditions found within a timber type.

Implementation

The design, installation, development of research of soil processes, maintenance and protection of this network was accomplished by direct communication between NFS managers

Table 1—Location and species of current LTSP study installations.

Region/ Station	National Forest/ Experimental Forest	Number of Installations	Species
1/RM	Priest River	1	Hemlock
4/RM	Boise	3	Mixed Conifer
5/PSW	Blodgett (Univ. CA)	1	Mixed Conifer
5/PSW	Eldorado	1	Mixed Conifer
5/PSW	Lassen/Black's Mountain	3	Mixed Conifer
5/PSW	Plumas	2	Mixed Conifer
5/PSW	Sierra	3	Mixed Conifer
5/PSW	Tahoe	2	Mixed Conifer
8/SRS	Davy Crocket	3	Loblolly Pine
8/SRS	DeSoto	3	Loblolly Pine
8/SRS	Croatan	3	Loblolly Pine
8/SRS	Kisatchie	1	Loblolly Pine
8/SRS	Kisatchie	3	Loblolly Pine
9/NC	Chippewa/Marcell	1	Aspen
9/NC	Chippewa	3	Aspen
9/NC	Huron	3	Aspen
9/NC	Ottawa	3	Aspen
9/NC	MO Dept. of Conservation	3	Oak-Hickory
BC[a]	Prince George	3	Lodgepole Pine/White Spruce
BC	Prince George	1	Aspen

[a] Plots in Prince George Province, Canada were installed following the specifications of the USDA Forest Service study and are considered part of the LTSP network for data analysis.

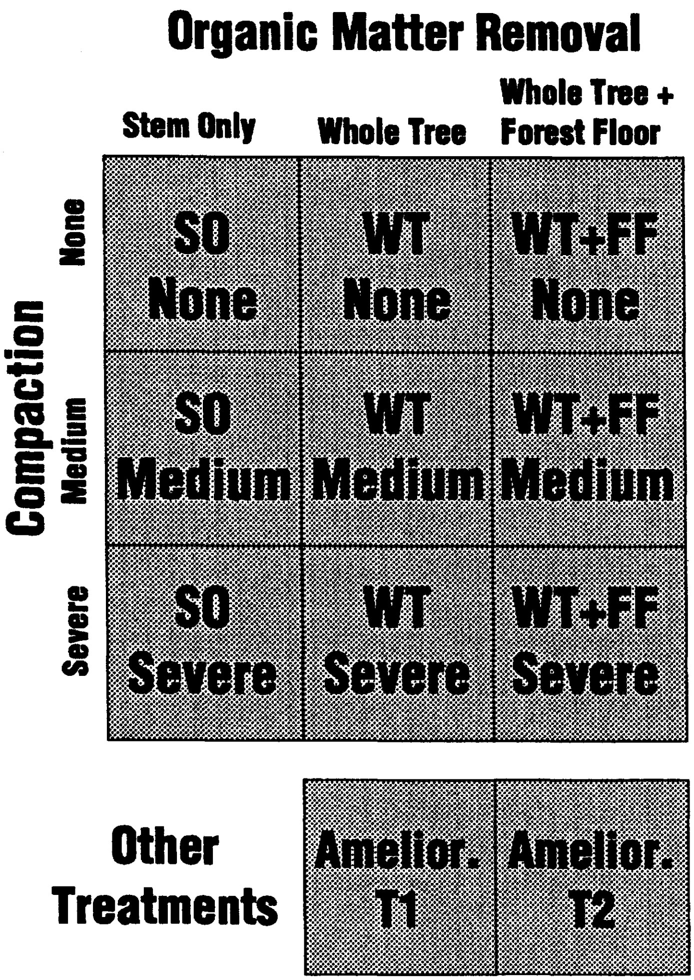

Figure 2.—Standardized experimental design for LTSP treatments. Each whole-plot treatment has competing vegetation controlled on one of the plot and the other half receives no competition control. Treatments to enhance productivity (amelioration) may be added.

and FSR scientists. Through times of tight budgets and shrinking resources, LTSP completed the demanding installation phase. The LTSP network exists because the right people in critical management positions were willing to take a substantial risk, key scientists agreed that the issues warranted a large research effort crossing Station boundaries, and through the willingness of Forest Service leadership to commit special funding.

An effort such as this can succeed only with continual commitment and regular feedback. In planning the study network, the founders included a communication plan within the generic study plan. This communication plan defines three committees and their roles in maintaining the LTSP effort.

National Oversight Committee. This committee is chaired by the Associate Deputy Chief for NFS. The National Oversight Committee consists of the appointed Chair of the National Technical Committee and at least one representative from each of the Washington Office staffs of Vegetation Management and Protection Research; Forest Management; Wildlife, Fish, Water and Air Research; and Watershed and Air Management. The primary duties of this group are to: 1) ensure that work is focused on the areas of highest national priority; 2) inform the Chief and Congress of progress and needs; 3) coordinate activities and seek and direct funding for the effort; 4) provide for a review of study proposals; and 5) review, evaluate and incorporate modifications to the proposals.

National Technical Committee. The National Technical Committee members are the Principal Investigators and Regional Soil Scientists involved in the study installation and maintenance and interpretation of study results. This includes members representing the British of Columbia Ministry of Forests and scientists managing other long-term productivity plots with designs and objectives similar to LTSP. This committee is chaired by a Forest Service Principal Investigator appointed by the National Oversight Committee. The primary responsibilities of this group are to: 1) assure that scientific methods are consistent and appropriate to meet program objectives; 2) provide for the establishment of a national database of research results; 3) communicate progress, needs, opportunities, and substantive findings to the Oversight Committee; and 4) coordinate and prepare results for publication. This group meets once per year near one of the field installations (Table 1.) to review progress.

Regional Steering Committee. The Regional Steering Committee (RSC) is composed of the Research Station Principal Investigator(s), Regional Soil Scientist and Regional Silviculturist. This group is charged with identifying study sites, developing collaboration with National Forests, Ranger Districts, and other researchers, preparing specific study plans, and implementation of studies. This committee shares the responsibility of ensuring public awareness of the program with National Forests and Ranger Districts.

For example, in Texas there was public concern about using clearcutting to harvest the timber required to implement the study. The Southern RSC worked with the National Forests & Grasslands in Texas and the public to develop the following alternatives: 1) No Action, as required by NEPA, 1969; 2) harvest 14 patch clearcuts 1.5-2.5 acres in size, with 30-foot borders around plots, and 100-foot borders thinned to a basal area of 30 square feet per acre outside the 30-foot borders; and the competition control portion of the study would not be installed; 3) clearcut approximately 90 acres to allow for the full study installation; and 4) clearcut approximately 40 contiguous acres to allow for half of the study to be installed (no competition control plots). The RSC made several presentations to interested groups about the study and the proposed alternatives. The presentations focused on management needs for the information; the value of the information that would be generated; and that the study was not a study of clearcutting, but used clearcutting as a means of creating needed conditions. Upon evaluation of the alternatives and

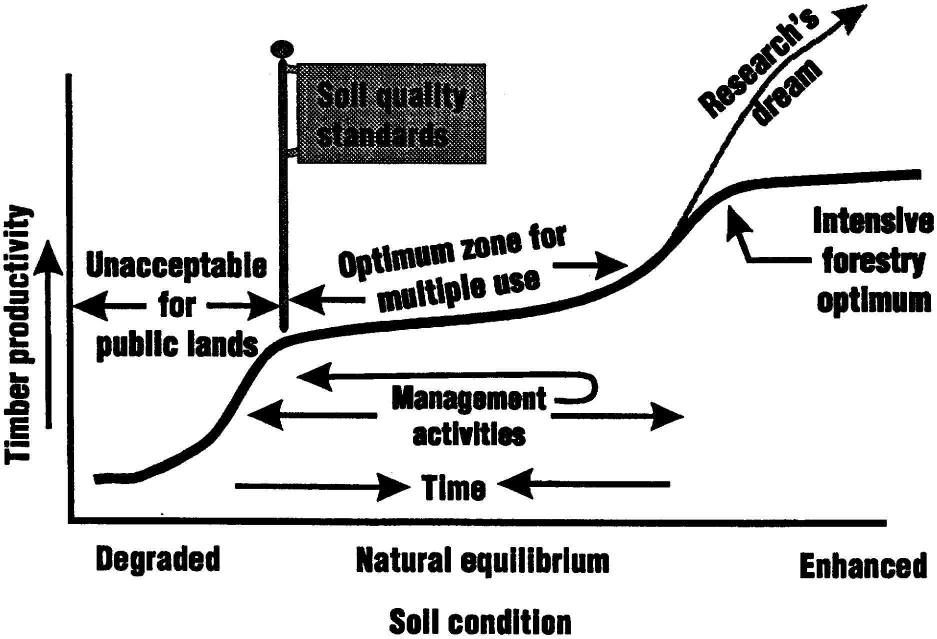

Figure 3.—Idealized relation ship of soil condition quality to productivity of a site. Soil quality standards are established to prevent degradation on the site which would lead to losses of productivity that have been define by law as unacceptable on public lands.

the knowledge value and tradeoffs associated with each, the decision was to adopt Alternative 3 and fully install the study because group selection (Alternative 2) affected management of twice the area and neither Alternatives 1 or 4 met the objectives of the study.

INTERPRETING AND USING RESULTS

Conceptual Framework

As in the inception and installation phases of the long-term soil productivity study, the communication of the results requires NFS managers and research scientists to remain focused on the common goal of validating soil quality monitoring on public lands. This is especially important for LTSP which crosses several administrative layers, is long-term and is producing volumes of useful results. Researchers, silviculturists, soil scientists, and administrators must understand how the results lead to interpretations related to policies and management of public land. The relationship between soil quality and vegetative productivity is the common focal point for LTSP.

In an idealized relationship between soil condition and timber productivity (Figure 3), soil condition is represented by a continuum broken into three zones of soil quality; natural equilibrium, degraded, and enhanced. Unmanaged forest soils reach a natural , dynamic state of equilibrium in physical, chemical, and biological characteristics. In a zone near this equilibrium, timber productivity is not maximized, but other organisms make significant contributions to the ecosystem. This is probably the zone that is optimum for multiple use as defined by Forest Service management policies. In this zone, low intensity management impacts shift the soil condition from the natural state. Without further inputs, the soil condition moves back to equilibrium. Thus, productivity changes associated with the changes in soil condition from normal management activities such as harvesting are small. With increased management intensity, timber production can be increased to a higher level, but possibly at the expense of other uses or resources. Usually this requires the application of several treatments such as tillage and fertilization simultaneously. These may be combined with other practices such as weed control and genetic selection that concentrate the productivity onto a target species. Unfortunately productivity also can be significantly reduced if the soil condition deteriorates beyond a threshold. If management activities degrade the soil below some threshold, productivity can collapse to a new lower level.

The concerns over productivity loss are expressed in legislation such in the National Forest Management Act (USDA Forest Service 1983) and Forest Service policies (U.S. Code of Federal Regulations 1985). These laws and regulations specify research and continuous monitoring to safeguard the land's productivity. As part of the effort to comply with this law, each Region has established soil quality standards meant to detect losses in productivity greater than 15 percent. Thus the soil quality standards, along with other policies, have established thresholds or red flags to prevent the soil from being degraded. These standards are designed to keep productivity from moving into the degraded zone.

Changes to Soil Quality and Productivity

Effects of Management. Preliminary results from the LTSP study illustrate our concepts. In Figure 4, the heights of the loblolly pines, *Pinus taeda* L., planted on the first LTSP site were compared with the heights of the harvested stand for the first 7 years. When low intensity harvesting was

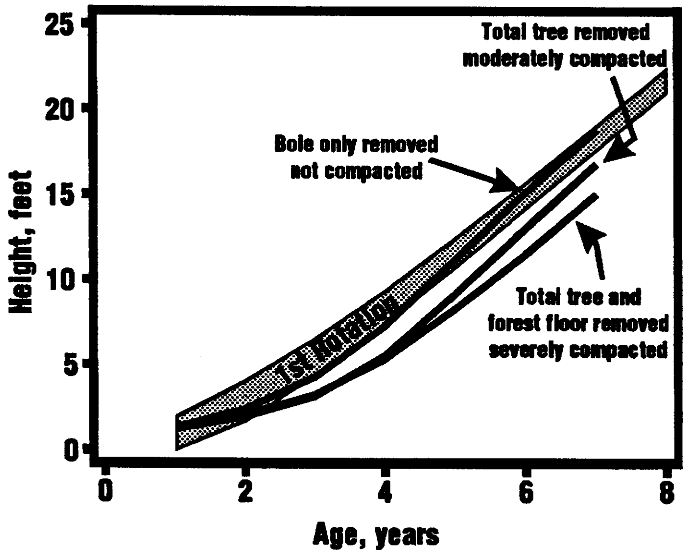

Figure 4.—Height growth over time of loblolly pine on plots treated with three levels of organic matter removal and soil compaction and the estimated height of the previous stand at the same ages. Plots are on the Kisatchie National Forest in central Louisiana.

employed, productivity was maintained at the same level as the original stand. At an intermediate level of harvesting impact, productivity was reduced, but the magnitude of the reduction appears to be getting smaller as the stand ages. Thus, with time, soil condition moves back to its equilibrium. The high impact harvesting treatment reduced height by about 20 percent compared to either the original stand or the low impact harvesting treatment and there does not appear to be recovery at this time. Thus, removal of all above ground biomass followed by severe compaction has degraded the site below acceptable productivity levels. On an operational basis, Region 8's soil quality standards should (and do) prevent harvesting impacts that are greater than the intermediate level. These results are confirmed by studies nearby which show even greater losses in pine productivity in the second rotation following disking or bedding during site preparation (Haywood and Tiarks 1995, Tiarks and Haywood 1996). Soil phosphorus is inherently low on both of these sites so the small amount of phosphorus removed in logging residues appears to have induced deficiencies. The loss in productivity and soil quality can be corrected with phosphorus fertilizer applications.

Losses in productivity are not limited to the timber species, and measurements of other stand components are included as well. On the Croatan National Forest, the number of species and biomass production was quantified by stem form class at 2 years (Table 2.) The number of species was significantly greater on the severely compacted plots where all above ground tree and forest floor biomass was removed compared to the plots not compacted and only the stems were removed at harvest. The greatest increase in number of species and in biomass occurred in the grasses and herb classes. However, the overall biomass on the highly impacted plots decreased by 43 percent compared to the low impact treatments. Increasing numbers of species in the grass and herbaceous classes may be a desirable outcome of management. However, because of the overall loss in productivity, compacting the soil or removing all of the logging residues is not an acceptable management tool and other alternatives should be used.

Results showing these declines are very effective in communicating the importance of soil quality standards to National Forest partners. Large and small private land owners also are concerned about such reductions in productivity as well as the increased productivity from amelioration of timber and other species in these systems. This led to the development of two important ongoing research partnerships with southern industries and universities which are closely linked to LTSP. The VPI/ Westvaco Sustainable Management Study was established with objectives similar to LTSP but with the additional

Table 2.—Number of species and biomass production in understory of stand at 2 years on Croatan National Forest without vegetation control after stem only removal and no compaction or total organic matter residue removal and severe compaction. (From Mellin 1995)

	Number of species		Biomass	
Stem form	Stem only not compacted	Total tree+ forest floor severely compacted	Stem only not compacted	Total tree+ forest floor severely compacted
	-------- number species/plot---------		--------------lbs/acre-------------	
Trees	18	12	974	409
Shrubs	20	20	2872	674
Grasses	7	16	147	1113
Herbs	8	15	12	71
Total	53	63	4005	2267

Table 3.— Ameliorative effect of bedding plus fertilizer with and without herbicide on loblolly pines at age 5 on the Croatan National Forest.

Treatment	height	d.b.h.	volume
	feet	inches	cu ft/ac
Stem only removal not compacted not herbicided	11.4	1.7	29
Stem only removal not compacted herbicided	17.3	3.7	193
Bedded and fertilized not herbicided	19.4	3.3	187
Bedded and fertilized herbicided	21.2	4.5	385

objective of determining if intensive forest management enhances productivity above natural levels (Powers and others 1996) in a sustainable way. Another study (Monitoring Productivity and Environmental Quality in Southern Pine Plantations) involving three forest industries, two universities and Forest Service Research was established to provide linkage between intensive plantation management and LTSP (Powers and others 1996). One of the first products of this LTSP-MPEQ linkage is a data base of biomass and nutrient contents of all the components of stands representative of the loblolly pine range and management intensities.

When possible, ameliorative treatments have been included as part of the LTSP installations. On the Croatan National Forest in North Carolina, herbicide, and bedding combined with fertilization both increased loblolly pine growth compared to the lowest impact treatment in the core LTSP design (Table 3). As the stands further develop, the long-term economic and biological impacts can be assessed. The dramatic differences in tree size and stand structure do demonstrate the impact management can have if rapid development of a stand is desired for species restoration, visual effects and even timber production.

Not all management practices or amelioration treatments have the beneficial effect that is desired and expected when applied. While the intent is to improve soil quality, in practice the operation can reduce soil quality and productivity shown as U-shaped arrow on Figure 3. Stump pulling was included as an ameliorative treatment in some of the LTSP plots in Idaho, but the negative effects on Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, seedlings was greater than the severe compaction treatment (Table 4). Many ameliorative treatments have the potential to impact soil properties in ways that are not initially apparent. Through monitoring, the real effects on these activities can be understood and the practices abandoned when results are not consistently positive. Subsequent research studies can be used to investigate soil processes involved and develop desired alternatives.

Effects of time. Time will push the productivity back to equilibrium for both the positive and negative effects of management, assuming the activity has not caused a permanent change to the site, such as slope failure. The amount of time for full recovery depends on the degree of degradation, soil and site properties, presence of weatherable minerals in the soil, clay type, and tree species. For example, compacted soils will eventually return to their natural state, but the length of time required depends on the depth of compaction, presence and depth of freezing and thawing cycles, and presence of expanding clays. In Mississippi, the upper 5 cm of soil in skid trails would be expected to return to the uncompacted level after about 12 years (Dickerson 1976). However, in Minnesota, where recovery should be faster that in Mississippi because of more freezing and thawing and higher levels of organic matter, soils showed little signs of recovery after 9 years at depths greater than 20 cm. Thus, the depth of compaction is much more important than soil properties, and recovery will be much slower in soils compacted deeper than 30 cm. The relative increase in bulk densities at planting and after a recovery period (Table 4) show some recovery in Minnesota and Louisiana but none on the compacted plots in Idaho. On the Louisiana site, the dominant understory was grasses which should speed recovery compared to the herbicided treatments. The lack of recovery after compaction in the Idaho soils, especially compared to the effects of stump pulling is unexpected. Compaction, as

Table 4.—Relative increase in bulk density at 0-10 cm and tree heights compared to uncompacted plots at three locations

Location	Treatment	Relative bulk density		Relative
		At planting	Post planting[a]	tree height[b]
		------------ percent of uncompacted------------		
ID	Severely compacted	23	26	-1
ID	Stumps pulled	25	-9	-18
MN	Severely compacted	19	15	-20
LA	Severely compacted not herbicided	9	2	-12
LA	Severely compacted herbicided	9	6	-16

[a]Post planting measurements were made 3 years after planting in ID and 5 years after planting in MN and LA.
[b]Tree species are Douglas-fir in ID, aspen, *Populus tremuloides* Michx. and *P. grandidentata* Michx., in MN and loblolly pine in LA.

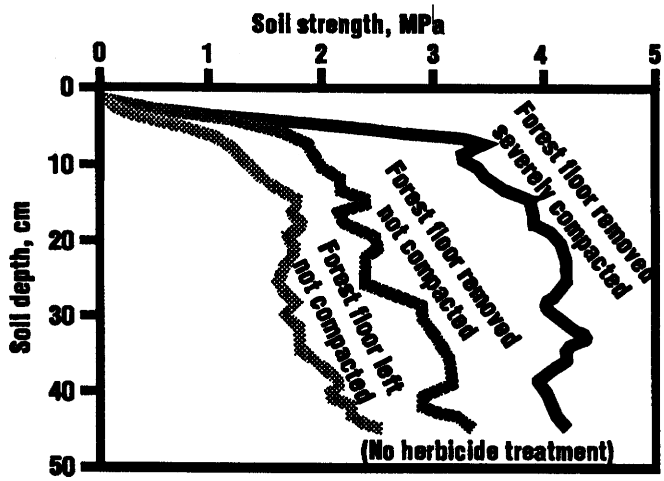

Figure 5.—Differences in soil strength with depth for three LTSP treatments at Challenge Experimental Forest measured in July.

measured by bulk density, also had mixed effects on the heights of Douglas-fir seedlings. These inconclusive results indicate that bulk density may not be the best indicator for monitoring soil properties changed by compaction.

Soil strength measured by a recording penetrometer is a faster way of assessing compaction and is sensitive to changes in bulk density and other soil properties such as water content that affect root growth. For many plants, root growth slows when soil strength exceeds 2 MPa and stops at strengths greater than 3 MPa (Whalley and others 1995). In California, soil strength was increased by removal of the forest floor sufficiently to reduce root growth even when the soil was not compacted (Figure 5). Removal of the forest floor allowed greater evaporation from the soil, raising soil strength as the soil dried. The effects of organic matter levels and soil compaction on other soil and biological process are being measured on various LTSP sites. At each location, ecosystem components related to soil quality at that site are being measured to increase the understanding of the processes involved. Examples of measurements being made at one or more sites include soil arthropod diversity, earthworm populations, types and numbers of ectomycorrhizal roots, soil organic matter quality, water regimes, and soil erosion.

Communicating Results. The committees that were established to plan and implement the study are being maintained and expanded to communicate not only the results of the study, but to aid in the adoption of management strategies. Each year the National Technical Committee meets at one of the LTSP sites along with representatives of one or more of the Regional Steering Committees, the National Oversight Committee, and investigators of studies that have been linked to LTSP. Status of the plots, growth measurements and successes and failures in monitoring efforts are shared and plans for more integrated measurements are finalized. This meeting is informal and facilitates open discussion of all aspects of LTSP.

In all Regions, LTSP results are communicated through the usual technology transfer process of workshops, conferences and publications. The RSC and the Forest Soil Scientist where the plots are located use preliminary findings in revising Forest Plans, to develop better monitoring methods and in ongoing operations. As an example, in the Kings River Ecological Management Area, monitoring forest soil impacts on growth in small openings proved to be very difficult. Instead, the findings on key soil variables from LTSP are used to develop methods of monitoring the soil to estimate effects on growth. In Mississippi, soil redox recording methods developed on the LTSP plots in Louisiana are being used to monitor the recovery of soil disturbed from salvage logging after a tornado. Easy access is being maintained to the sites so they can be used as demonstration areas to test soil quality standards and in the development of monitoring approaches for other resources.

To date, the LTSP study is a superb example on the national scale of the beneficial working relationship that exists at the local level. By networking, the local efforts have been leveraged, providing greater returns that the individual efforts would have. Now the challenge is in maintaining the study, both on the ground and in the Forest Service's thinking. Long-term experiments are like good wines in that they appreciate with age. As of this writing, the plots range in age from 0 to 7 years with the study designed to run 60 to 120 years. Thus, while the results may be tasted at these young ages, they must be treated as peeks at the more full-bodied rewards to come. It is imperative that any interpretations made using early results be treated as tentative and subject to change. Through these and similar efforts at all locations of the LTSP study, results are being applied to "Caring for the Land".

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