Effects of Soil Disturbance on the Fundamental, Sustainable Productivity of Managed Forests[1]

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Abstract

Environmental policies in the United States and abroad are reducing timber harvests while wood demand is mounting. Reduced harvesting on public lands means that privately owned lands will be managed with greater intensity in the United States and that wood will be imported from other nations lacking strong environmental safeguards. It is imperative, therefore, that both public and private forest lands be managed to sustain their productivity, and many nations are seeking effective monitoring methods. Central to this is our ability to estimate a site's fundamental capacity for growing vegetation, and to detect changes in this capacity caused by management. Because soil is the factor of a site modified most easily and profoundly by management, and because soil largely is independent of the current condition of vegetation, soil-based variables offer our most effective and practicable indices of sustainable productivity. The North American Long-Term Soil Productivity cooperative research program (LTSP) is the world's most extensive coordinated effort to address questions of sustainable productivity in managed forests. Early findings from the 12 LTSP sites in California illustrate the physical importance of organic soil cover in reducing soil erosion and maintaining favorable soil temperature and moisture relations during summer drought. Findings also show that the biological significance of soil compaction depends on soil texture. Moderate compaction degrades vegetative growth on fine-textured soils but can enhance growth on coarse-textured soils where drought is a factor. Impacts of soil compaction on tree growth often are masked by effects of competing vegetation. Measurements taken under operational conditions show that compaction associated with mechanized thinning can reduce soil rooting volume by as much as one-half. Subsoiling seems to mitigate the effect. Root damage caused by subsoiling did not adversely affect the growth of residual trees. Results are providing practicable field methods for monitoring management impacts on sustainable productivity.

Forests offer many values and commodities beyond wood production. Concerned that forests have suffered from overemphasis on timber, environmentalists call for more conservative forest management practices that reduce wood harvest and preserve or restore other ecological values (Drengson and Taylor 1997). On many public lands of the western United States—historically a major source of domestic timber—harvesting continues, but at a rate less than one-third that of the last decade (USDA Committee of Scientists 1999). Pressure to de-emphasize wood production here and abroad comes while the land area formerly available for production forestry is shrinking at an annual rate of 0.4 percent (FAO 1997).

Paralleling the trend on public lands of the United States, a "green advocacy" has gained momentum and has spawned an expansive international industry to certify what is, and is not, "sustainable forestry" (Hammond and Hammond 1997, Journal of Forestry 1995). In general, leading forest scientists

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agree that timber harvesting, if conducted so as to preserve potential site productivity, need not compromise other ecosystem values (Attiwill 1994, Kimmins 1996). Many in North America's private forestry sector are skeptical of third-party "green certification" where criteria may be based more on speculation than on science (Berg and Olszewski 1995). Yet, ignoring green certification could limit markets for industrial wood.

Progress has been made toward developing more uniform and objective standards for green certification. The central international body is the Forest Stewardship Council with two affiliates in the United States—SmartWood and Scientific Certification Systems (Mater and others 1999). Green certification aims at protecting multiple forest values and long-term site productivity, but advocates often seem naïve and myopic. If all the world's forests were managed under green certification standards of the Forest Stewardship Council, harvests would average 0.7 m^3 ha^{-1} annually (Binkley 1997). Unfortunately, this average would require a one-third increase (1.1 billion ha) in global forest area just to meet the current wood demand of the world's population. Kimmins (1996) points out that popular standards for green certification often are so stringent that harvested yields are lowered by more than if the sites had been severely degraded by exploitative management. Implications of mandating unnecessarily low harvests are serious. World population and demand for wood products are rising at similar rates (FAO 1997). This demand permeates all societies (FAO 1997) and increases by 70 to 80 million m^3 annually—a volume equivalent to British Columbia's entire allowable cut in 1993 (Kimmins 1996).

Reduced wood production from green-certified nations creates a strong incentive for other countries to accelerate forest harvesting beyond sustainable levels to reap the rewards of global demand (Kimmins 1996). A scarcity in domestic wood supply will raise wood prices, stimulating consumer preference for nonrenewable substitutes. Recent studies show that with each 1 percent rise in the price of softwood lumber, the use of cement rises by 0.15 percent, structural steel by 0.3 percent, and brick by 0.65 percent (Binkley 1997). Sustaining the productivity of United States forests, regardless of ownership, is in our national interest.

Currently, a simple definition of "sustainable forestry" lacks international consensus (Nambiar and Brown 1997, Sullivan 1994). No one in good conscience can support management practices that degrade forest productivity. The problem is how to produce more wood from less area without impairing the land's potential to provide other social benefits now or in the future. Clearly, the need for a closer linkage between management and research in the forest planning process has never been stronger (USDA Committee of Scientists 1999).

This paper describes the genesis of the North American Long-Term Soil Productivity (LTSP) cooperative research program and summarizes results from the various component studies done to date in the Sierra Nevada and Cascades of California.

Developing Indices of Sustainable Forestry

An International Movement

The United Nations Conference on Environment and Development of 1992 ("The Earth Summit") led to a nonbinding agreement to establish principles for sustainable forest management (United Nations 1992). As a result, international committees have formed to develop criteria and indicators for the conservation and sustainable management of forests of the world. One such committee met informally in Montreal, Canada, in 1993. Deliberations of what has come to be called "The Montreal Process" culminated in a 1995 meeting in Santiago, Chile. There, in the "Santiago Declaration," representatives from Argentina, Australia, Canada, Chile, China, Japan, Republic of Korea, Mexico, New Zealand, Russian Federation, Uruguay, and the United States agreed to develop, implement, and continually update nonbinding criteria and indicators for the sustainable management of temperate and boreal forests (Canadian Forest Service 1995). A first step is to find an unambiguous, effective, and objective way to monitor the land's health that covers all levels of management intensity.

Monitoring Productivity Directly

The fundamental indicator of a forest's well-being is the rate at which atmospheric carbon is captured photosynthetically and accumulated as organic matter. This rate is termed "net primary productivity" (NPP). In turn, NPP is the common basis for most fundamental ecosystem processes that produce the characteristics of forests valued by society. Accordingly, degrading a site's NPP potential also degrades its potential for producing flora, fauna, habitat, clean and abundant water, and recovery from disturbance. Monitoring the departures in NPP from baseline conditions would give us a sensitive measure of the health of a forest ecosystem and whether it is agrading, degrading, or stable. Unfortunately, NPP is extremely difficult to measure. Current rates are affected not only by site quality, but also by the present age, stocking, and structure of the forest. Therefore, they may not indicate the site's true potential at full stocking, or "leaf area carrying capacity" (Grier and others 1989, Powers 1999b, Waring and Running 1998). And even at full stocking, it is almost impossible to measure NPP accurately in forests of irregular structure. An unbiased surrogate for NPP is needed that is independent of the current condition of the vegetation.

The Soil Quality Approach

Soil can be a strong and independent surrogate for measures of potential NPP. Together with climate and biotic potential of vegetation, soil forms the foundation for forest production. As recognized in the Montreal Process and Santiago Agreement, soil-based indicators of sustainable forestry must include measures of erosion, organic matter, compaction, nutrient cycling, and pollution (Ramakrishna and Davidson 1999). The USDA Forest Service recognized this requirement well in advance of the Montreal Process. The National Forest Management Act of 1976 mandates that the USDA Forest Service must manage public forest lands without impairing their permanent productivity. Accordingly, and in consultation with Forest Service Research, the Watershed and Air Management Staff of the USDA Forest Service adopted a program for monitoring the effects of management practices that is based on the following logic: management practices create soil disturbances; soil disturbances affect soil and site processes; and soil and site processes control forest productivity.

Monitoring soil and site processes is not feasible at an operational scale. Therefore, USDA Forest Service monitoring strategy centers on measurable soil variables, which, if altered beyond a threshold, indicate that potential productivity has been degraded. These thresholds of soil quality are based partly on research, but largely on professional judgment. Threshold standards for the USDA Forest Service Regions of the United States have been summarized by Powers and others (1998). Current standards for the Pacific Southwest Region are shown in *table 1*. Although these standards represent a progressive step, they are not universally accepted.

The LTSP Program

Guidelines suggested by the Montreal Process are vague and too general to be useful in operational monitoring. The USDA Forest Service's standards for monitoring soil quality (*table 1)* are much more specific but still based on conclusions drawn largely from scattered, anecdotal—and sometimes contradictory—research. This creates problems. Because the standards have not

Table 1—*Current standards of soil quality adopted by the Pacific Southwest Region, USDA Forest Service (Powers and others 1999b). Standards indicate thresholds for significant soil degradation.*

Variable	Quality standard
Operational area	Standards extend to all land capable of growing vegetation
Erosion	Not to exceed rate of soil formation, or about 2 Mg ha^{-1} yr^{-1}.
Soil cover	Forest floor covers less than 50 percent of area.
Organic matter	Litter and duff cover less than 50 percent of area. Fewer than 12 decomposing logs ha^{-1} at least 30 cm in diameter and 3 m in length.
Infiltration	Reduced to ratings of 6 or 8, as defined by Regional Erosion Hazard ratings. Extent depends on cumulative watershed effects analysis.
Compaction	Total soil porosity reduced more than 10 percent, depending on soil type, over an area large enough to reduce productive potential.
Displacement	Soil organic matter in upper 30 cm reduced more than 15 percent from natural conditions. Affects enough area that productive potential is reduced.

been calibrated against true measures of potential productivity, they may be too restrictive in some cases and too lenient in others. Without convincing evidence that such standards are accurate, forest managers in the private sector are not apt to take them seriously.

In the late 1980s, I arranged a series of small group meetings among key USDA Forest Service scientists and leaders in National Forest System to explore prospects for a definitive study national in scope. We agreed that guidelines for detecting changes in fundamental productivity were cumbersome and inconclusive. After an exhaustive review of the world's literature, our core group agreed on the following principles for guiding such a study. (1) Within the constraints set by climate and relief, the productive potential of a site depends on soil resources. (2) Management practices cause soil disturbances that affect soil properties and processes. In turn, these processes govern potential productivity. (3) The main soil processes controlling potential productivity involve physical, chemical, and biological interactions between soil porosity and site organic matter.

The third principle provides a framework for research. Recognizing that it is unlikely that any simple response would apply to all climates, soils, and forest types, our core group agreed on a common experimental design that would be applied consistently to a spectrum of benchmark sites across the United States. Following discussion among international scientific peers, a study plan was drafted and reviewed nationally by silviculturists and soil scientists in both research and management arms of the USDA Forest Service. In 1989, the final plan for a Long-Term Soil Productivity (LTSP) cooperative study was approved by the Deputy Chiefs for Forest Service Research and National Forest System. Simultaneously, our rationale and proposal were presented at a major international conference, reviewed technically, and published in the proceedings (Powers and others 1990). Along with their counterparts from the National Forest System, principal investigators from USDA Forest Service Research began implementing the LTSP experiment in 1989. Funding for the installation phase came from the Washington Office through excess timber sale receipts (approximately $9 million between 1989 and 1998).

The four main objectives of the LTSP program are to: (1) determine how site carrying capacity for NPP is affected by pulse changes in soil porosity and site organic matter; (2) develop a fundamental understanding of the controlling processes; (3) produce practicable, soil-based indicators for monitoring changes in site carrying capacity; and (4) develop generalized estimation models for site carrying capacity, as conditioned by soil and climatic variables.

The effort is hypothesis driven and involves manipulation designed to stress the soil's capacity for NPP. It focuses on major forest types of the United States within the component classified as commercial forest land. LTSP centers on closed-canopy, young-mature forests growing near the culmination of mean annual increment. It is chartered to run to at least the culmination of mean annual increment on each site (a rotation, or planning horizon). Details of this remarkably successful, North American-wide program are described by Powers (1999a).

Within a climatic region and forest type, National Forests are solicited for sites that represent an array of the major soil types along a productivity gradient. Candidate sites are examined carefully for variation in soil and stocking. If satisfactory, and with concurrence of National Forest and Ranger District personnel, each forest stand is inventoried and at least 30 trees are felled and sampled to estimate the biomass and nutrient contents of their boles and crowns (Powers and Fiddler 1997). The understory, forest floor (all organic detritus above the mineral soil), and mineral soil to 100 cm in depth also are sampled for mass and nutrient content. Regression methods are used to expand sample data to an areal basis. This process characterizes the mass and chemical state of the forest immediately prior to treatment (*table 2*).

Once sites have been characterized, all trees are felled and nine core treatments are assigned randomly to 0.4-ha plots. These treatments consist of three levels of organic matter removal/retention (commercial bole removed/

Table 2—*Approximate biomass and nitrogen (N) content of ecosystem before and after removing various components at the Challenge LTSP site (Powers and Fiddler 1997)*

Ecosystem component	Biomass in component	N content of component	Cumulative ecosystem N content	Cumulative-proportion of ecosystem N	Ecosystem N remaining after removal
	$Mg\ ha^{-1}$	$kg\ ha^{-1}$	$kg\ ha^{-1}$	percent	percent
Tree layer					
Boles	425.3	440.3	440.3	5.1	94.9
Crowns	48.0	164.6	604.9	7.0	93.0
Understory layer					
Shrubs	0.4	3.1	608.0	7.0	93.0
Herbs	0.2	1.4	609.4	7.1	92.9
Forest floor layer					
Woody debris	9.6	29.7	639.1	7.5	92.5
Litter	49.0	425.4	1,064.5	12.3	87.7
Mineral soil (1 m)	—	7,630.0	8,694.5	100.0	00.0

crown, understory and forest floor retained; all living vegetation removed/forest floor retained; all vegetation and the forest floor removed/mineral soil exposed), crossed factorially with three levels of soil compaction (nil, intermediate, extreme) (*fig. 1*). Additional plots representing best management practices, as well as mitigation treatments (subsoiling, fertilization), are included if space is available. Plots are reforested with tree species native to the site.

Following the reforestation phase, treatment plots are divided into two 0.2-ha subplots. Native understory flora is allowed to develop naturally on one subplot. The other is kept only in trees by applied herbicides. These treatments of site organic matter and soil porosity produce a factorial, split-plot matrix encompassing the soil disturbances common to almost any operational harvesting practice. The vegetation control treatments permit complex and simple plant communities to develop side-by-side. With time, each plot and subplot provides a distinct measure of NPP as affected by pulse disturbance. Plots are sufficiently large that vegetative performance will not be confounded by edge effects from the surrounding forest. Measurement protocols have been standardized throughout the country (Powers and Fiddler 1997, Powers and others 1990).

The first LTSP installation was completed on the Palustris Experimental Forest in Louisiana in 1990. The second was at Challenge Experimental Forest in California in 1991. By 1996, the LTSP concept had spread to the Canadian Provinces of British Columbia and Ontario. Soon the program expanded to complementary studies by collaborators in academia and the forest industry. Today, the network includes 62 core LTSP installations and 40 affiliated installations, making it the world's largest and best-coordinated network of studies examining how soil disturbance impacts potential site productivity (*fig. 2*). Of the 62 core installations, 12 are in the mixed-conifer forest type of the western Sierra Nevada of California (*table 3*).

The oldest California installations have completed only twelve growing seasons, and the youngest only six. Intensive measurements are taken at 5-year intervals, partly because of restricted research funds, and partly because initial perturbations are not likely to indicate long-term trends. LTSP scientists agree that the first reliable indicators of long-term trends are not apt to appear until crowns have closed on all treatments at a site. All of the California installations have achieved their 5-year measurements, but none has reached crown closure on all treatments.

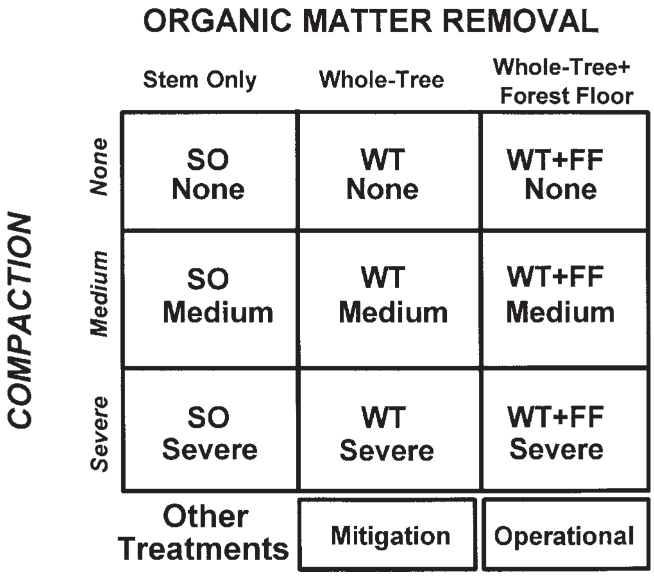

Figure 1—Standardized field design of the factorial core treatments in the LTSP experiment. Each treatment cell measures 0.4 ha and is regenerated to the principal forest trees of the region. Regional vegetation is excluded on one half of each cell and allowed to develop on the other.

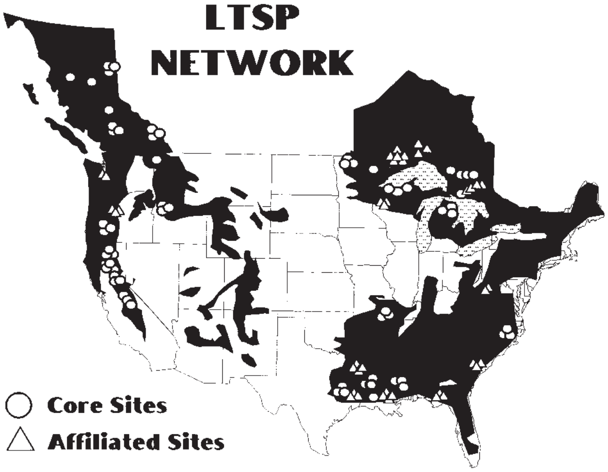

Figure 2—Distribution of core and affiliated experiments of the North American Long-Term Soil Productivity cooperative research program. Commercial forest area is shaded.

Early findings have been presented at conferences as progress reports and are summarized in the following section, along with my interpretations. Most of the NPP data are still being analyzed, and growth data reported here reflect volume measures, not NPP, although trends between volume increment and NPP will track closely. Until all installations reach crown closure, these findings are simply a nest of case studies that should not (and generally *cannot*) be examined by inferential statistics. Early trends are not offered as long-term projections. Collectively, however, they show progress and provide important preliminary findings.

Table 3—*General characteristics of 12 LTSP sites in California (Powers and Fiddler 1997)*

Place name	Year established	Parent material	Relative drought	Site quality	Forest	Ranger District or other
Challenge	1991	Metabasalt	Low	High	Plumas	Feather River
Wallace	1993	Volcanic ash	Low	Mod.	Eldorado	Georgetown
Central Camp	1993	Granodiorite	High	Mod.	Sierra	Minarets
Owl	1993	Granodiorite	High	Mod.	Sierra	Minarets
Vista	1993	Granodiorite	High	Mod.	Sierra	Mariposa
Blodgett	1994	Basalt	Low	High	Blodgett	U. of Calif.
Brady City	1995	Basalt	Low	High	Tahoe	Downieville
Lowell Hill	1995	Basalt	Low	High	Tahoe	Navada City
Rogers	1996	Granodiorite	Mod.	High	Plumas	Feather River
Aspen	1997	Volcanic ash	Mod.	Low	Lassen	Eagle Lake
Bunchgrass	1997	Volcanic ash	Mod.	Low	Lassen	Hat Creek
Cone	1997	Volcanic ash	Mod.	Low	Lassen	Eagle Lake

Early Results from LTSP

Infiltration and Erosion

Several important findings—albeit preliminary—have emerged from the California LTSP study. Troncoso (1997), working with granitic soils from the three Sierra National Forest sites, found that severe compaction reduced water infiltation by 72 percent in surface soils. Lessened infiltration can lead to surface runoff during intensive rainfall and to reduced soil water recharge. Although soil water recharge may not be a problem if precipitation occurs as low intensity rain or snow, soil erosion is another matter. Surface erosion occurs when hydraulic forces exceed the binding strengths of soil aggregates, a relatively stable assemblage of organic material and mineral particles. Materials such as organic detritus on the soil surface will break the impact of raindrops. Therefore, erosion rates will be high if the soil surface lacks cover by organic matter and if the stability of soil aggregates is low. A simple way to measure soil erosion is to drive thin pins deeply into the soil, leaving a portion exposed above the soil line. Monitoring changes in soil elevation on the pins over time provides an index of the rate soil erosion.

Sandy Inceptisols with low organic matter content, such as the Dome soil series on the three Sierra National Forest sites, lack much profile development, and soil aggregate stability is very low. Therefore, soil particles are easily detached by raindrop impact and surface water flow if infiltration rate is too low. Although erosion pins were installed at the Sierra LTSP sites, funding limitations have precluded any measurements. Casual observations, however, indicate that erosion rates there are relatively high where soil surfaces were bared and severely compacted.

Only at the Challenge site, the first California installation, have we taken measurements on erosion pins. There, soil elevations were measured after 3 years on all plots. Using changes on the Control plot as a standard, relative erosion rates increased as much as sevenfold (*table 4*). Slope variation among plots precluded a smooth response surface across treatments, but some points do seem clear. First, soil compaction *per se* had no obvious influence on relative erosion rate. In fact, in three of four cases where soil was protected with slash or forest floor, relative erosion rates on compacted plots were lower than for the control plot. Second, the soil cover effect was profound. Regardless of compaction level, erosion always was much greater where the surface organic layer was gone. Soil aggregation is much stronger on the clay-textured soil at Challenge than on the sandy textures of the Sierra National Forest sites. Presumably, if rainfall intensity were as great at the Sierra sites as at Challenge, soil erosion rates would be far greater than noted. A solid conclusion is that surface organic cover comprises the first line of defense against the erosion of surface soil.

Table 4—*Relative rate of soil loss over 3 years at the Challenge LTSP site (control = 100, Powers and Fiddler 1997)*

Compaction level	Relative rate of erosion when residual ground cover was:		
	Logging slash	Forest floor	Bare soil
	----------	percent	----------
None	100	187	416
Moderate	66	270	812
Severe	84	43	330

Table 5—*Effects of presence or absence of forest floor on mean monthly temperature and moisture at 20-cm depth of noncompacted soil, Challenge LTSP site (Powers 1999b)*

Month	Soil temperature (°C)			Percent soil moisture		
	Present	Absent	Difference	Present	Absent	Difference
April	12.8	13.3	0.5	34	34	0
May	17.8	21.5	3.7	26	14	-12
June	19.0	22.8	3.8	21	13	-8
July	20.2	24.6	4.4	25	18	-7
August	18.5	23.7	5.2	20	13	-7
September	17.5	21.0	3.5	15	12	-3

Significance of Surface Organic Residues

Organic residues that protect the soil surface from raindrop impact and runoff also insulate against high summer temperatures and evaporative moisture loss. From June through August at Challenge, bare soils averaged 23.7°C at 15 cm in depth—4.5°C warmer than soils covered by forest floor (*table 5*). Also, bare soils were essentially dry by May, whereas presence of a forest floor kept soils relatively moist into August. On the sandy soils of the Sierra National Forest sites, Troncoso (1997) found that surface soils were depleted of plant-available moisture by August, but moisture was available throughout the dry summer where logging slash had been retained (*fig. 3*). Studies a year later on these same soils (Swearingen 1999) showed that the mulching effect extends deep into the soil profile. Where logging slash had been retained, soil moisture at a depth of 75 cm remained well above the wilting coefficient (about 8 percent moisture content) throughout the summer, but soils were dry by mid-July where surfaces were bare. Obviously, a condition that extends the period of plant-available moisture favors plant growth under the conditions of a Mediterranean climate. Surface organic residues do that by acting as mulch against solar heat and evaporative losses.

As soils dry, strength mounts between soil particles, regardless of the level of compaction. Increased soil strength means increased resistance to root elongation. Root stress increases greatly above 2 MPa (1 MPa = 10 atmospheres of pressure, or 10.3 kg cm^{-2}) and growth essentially ceases at 3 MPa (Sands and others 1979). At Challenge, soil strength measurements taken in July of the third year showed that strengths averaged 2 MPa or less throughout the upper 40 cm where a forest floor was present but a full MPa greater where it was absent (Powers and Fiddler 1997). Thus, surface organic residues affect root behavior in dimensions beyond simple water availability.

A progressive view of the worth of surface residues is that their direct effect on soil moisture is important but ephemeral. The mulch value of a forest floor should dissipate as canopies close and transpiration dominates evaporation. However, organic residues are a major component of the carbon cycle that supplies an energy substrate to soil organisms that dominate soil processes. In turn, these processes control the storage and biological availability of soil water and nutrients. The nutritional significance of the forest floor is far greater than indicated by its biomass. For example, the mass of the forest floor before harvest at the Challenge LTSP site was only 11 percent of the total biomass above ground (*table 2*), but the forest floor contained 43 percent of above-ground nitrogen—nearly three times that in the tree crowns that either are exported or retained as logging slash. Therefore, loss of the forest floor may

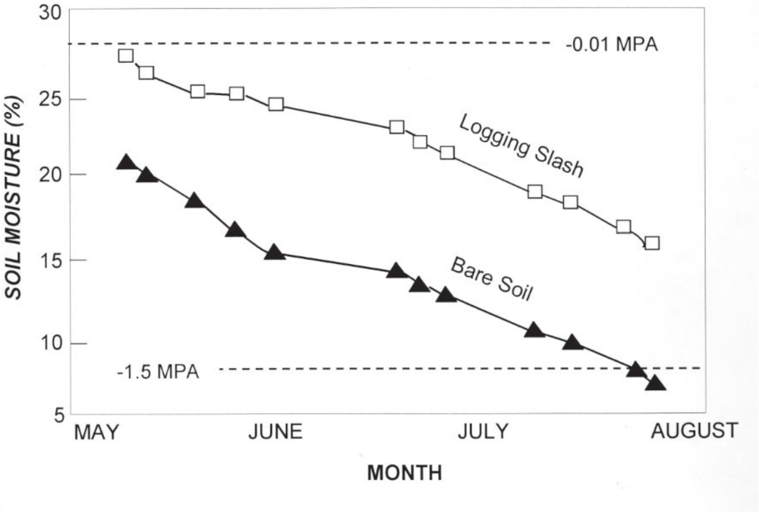

Figure 3—Soil moisture trends at a depth of 15 cm as affected by presence or absence of surface organic residues. Sierra National Forest LTSP sites, third year. Dashed lines indicate moisture content at field capacity (upper) and at wilting coefficient (lower) (Troncoso 1997).

eventually have a profound effect on soil fertility on sites less fertile than at Challenge. Its importance probably exceeds that of the crown material in logging slash.

The physical value of surface residues is conditioned by climate. At higher latitudes or at elevations where soil temperatures approach the cryic temperature regime, anything reducing soil temperature reduces primary productivity. In the frigid and cryic temperature zones, surface residues accumulate and insulate the soil, lowering soil temperature and diurnal flux (Fleming and others 1994). Moist sites remain wet and aeration may be impaired. On better-drained sites, water stress can develop because water viscosity increases rapidly as temperatures approach freezing (viscosity is 16 percent greater at 5°C than at 10°C). The same insulating properties of surface residues that reduce primary productivity in cold forests become beneficial in warm, dry regions such as found in the mixed-conifer and pine forests of California (*table 5, fig. 3*).

Significance of Compaction

Effects of soil compaction on soil moisture go beyond simple infiltration, but certain principles must be understood to interpret LTSP findings that, at first glance, may seem contradictory. Compaction alters soil pore size and volume—variables that influence the availability of soil water to plants. Soil pores are divided by convention into two size classes, based on water-retention properties (Childs and others 1989, Taylor and Ashcroft 1972). "Micropores" are voids so small that they remain filled with capillary water when gravitational water has drained and the soil is at field capacity. Much of this micropore water is held at tensions between 0.01 and 3.1 MPa (the lowest tension of hygroscopic water), meaning that not all of the water in micropores (that held at tensions > 1.5 MPa) is available to plant roots. "Macropores" are soil voids sufficiently large (> 14 μm radius) that capillary water will not bridge their diameters following gravitational drainage. Loosely held water (0.01 to 1.5 MPa tension) is retained as a cohesive film on the surfaces of particles bordering macropores, and the remaining void is filled with air. This low-tension film is the principal source of water for plant uptake and accounts for roughly half of the total water-holding capacity of an uncompacted soil (a higher proportion for sands, a lower proportion for clays). As low-tension water is depleted from macropores by transpiration or evaporation, films become thinner. As films thin, a tension gradient develops and macropores are recharged partially by water held in micropores. Eventually, water films in all soil pores thin to such high tension (by convention, >1.5 MPa) that the soil is said to have dried to "wilting coefficient." When soil pore radii are less that 0.1 μm, the affinity between water molecules

Table 6—*Effects of soil compaction (NC = not compacted, C = compacted) and understory vegetation on plant and soil properties for soils of contrasting textures (severe compaction on the clay, moderate compaction on the sand) (Powers 1999b)*

Variable	**Understory vegetation absent**				**Understory vegetation present**			
	Clay		**Sand**		**Clay**		**Sand**	
	NC	C	NC	C	NC	C	NC	C
Relative growth (pct)								
Abies concolor	100	56	100	167	22	33	67	100
Pinus ponderosa	100	60	100	169	33	47	94	125
Vegetative cover (pct)	Trace	Trace	Trace	Trace	91	56	55	68
Soil bulk density (Mg m^{-3})	0.88	1.13	1.06	1.14	0.88	1.13	1.06	1.14
Total soil porosity (pct)	67	57	60	57	67	57	60	57
Change in AWC (pct)	0	-24	0	+65	0	-24	0	+65
Predawn$_{\psi_p}$ (MPa)								
Abies concolor	-0.54	-0.63	-1.13	-0.93	-1.74	-1.15	-2.37	-3.47
Pinus ponderosa	-0.60	-0.66	-1.05	-1.14	-0.88	-0.87	-1.61	-2.05

and pore surfaces is so great that water is said to be unavailable to plants.

Soil macropores also are essential to infiltration of precipitation and exchange of oxygen and respiratory gases between the atmosphere and the root. A macropore volume of at least 10 percent of total soil volume is needed for proper root respiration by terrestrial plants (Grable and Siemer 1968, Vomocil and Flocker 1961). Soils with too few macropores may become anaerobic; those with too many may be excessively drained and droughty. Unfortunately, the distribution of soil pore sizes is difficult to measure and essentially impossible to measure in the field.

Working with sandy soils on the Sierra National Forest LTSP sites, Swearingen (1999) showed that, at a depth of 15 cm, compacted soils retained plant-available water through late June, but noncompacted soils were depleted by mid-May. At a depth of 75 cm, the wilting coefficient was reached by late June on noncompacted soils and mid-July on compacted soils. Thus, a certain amount of compaction seemed to favor the storage of low-tension soil water. But is this effect universal? And how does it affect vegetative growth?

To study these questions, the Challenge and Vista LTSP sites were chosen for more intensive study because they represent extremes in soil texture. Work centered on plots with complete organic matter removal and either no or severe compaction. As might be expected for a fine-textured soil, both tree growth and vegetative cover were suppressed (about 40 percent) by compacting the clayey soil at Challenge (*table 6*). Soil bulk density increased by 28 percent, equating to a reduction in total porosity of 15 percent. Such a reduction seems small, except that it comes at the expense of aeration porosity (macropores are the first to be deformed by compaction). Clay micelles (flat particles less than 0.002 mm in size) compact into a hard, platy structure. Although particle surface area is high, macroporosity is relatively low in clays. Measurements made in the laboratory with intact soil columns from treated plots at Challenge show a loss in plant-available water (AWC) of 24 percent. Therefore, compaction reduced both the soil's aeration and its capacity to store available water. Lowered soil AWC measured in the laboratory is not simply academic. It is reflected by field measurements of predawn xylem water potentials (ψ_p) taken in August at the peak of drought. Predawn water potentials were 17 percent lower in white fir and 10 percent lower in ponderosa pine following compaction (*table 6*), meaning that trees on compacted plots were not rehydrating fully at night when stomata were closed. Lowered AWC translates to plant drought under Mediterranean climatic conditions, helping explain why both tree growth and ground cover were suppressed by compaction on the clayey soil.

Different results were found on the sandy soil at Vista, where both trees and understory vegetation grew appreciably better on moderately compacted plots (*table 6*). Soil bulk density also was increased by moderate compaction, but only by 8 percent. Because sand grains are large, angular particles (0.05 to 2.0 mm), they have less surface area per unit volume than clay particles. Total soil porosity generally is lower in sands than in clays and is weighted heavily to macropores. Consequently, sandy soils drain quickly and, because their microporosity and specific surface area are low, retain little water. Compacting the sandy soil moderately at Vista increased AWC by 65 percent (*table 6*). Apparently, this difference reflects a rearrangement of sand grains and a reduction of pore sizes. As a consequence, white fir ψ_p in August improved an average of 18 percent. Xylem water potentials were lower (trees were drier) after compaction in ponderosa pine—possibly because the pines were about five times larger than the firs. Larger trees mean greater crown surface area and greater transpiration rates. Presumably, larger trees on compacted soil depleted soil water more rapidly throughout the summer. From this I conclude that compaction effects on plant growth depend upon soil texture, the degree of compaction, and whether or not AWC is a limiting factor.

Improved growth from compaction also occurred for aspen on droughty sands in Michigan (Stone and others 1999) and for ponderosa pine on the sandy soil at Rogers (Gomez and others 2002). Recent measurements at Central Camp and Owl LTSP sites on the Sierra National Forest show that growth was reduced by more severe compaction. Differing responses to compaction among sandy-textured soils on sites classified as the same soil series probably trace to subtle differences in distributions of pore size and/or particle size, which is fertile ground for further investigation. A contract was completed recently for detailed classification and textural analyses of the soils at all LTSP installations.

Other recent LTSP measurements of ponderosa pine growth illustrate how this concept might extend to a variety of soil textures. Severely compacting a clay-textured soil (Challenge) can lower tree growth by nearly half (*fig. 4*). The effect was much less on a loam (Blodgett) or sandy loam (volcanic ash at Wallace) and even promoted growth on a moderately compacted sand (Vista). Work underway by University of California graduate students is quantifying how compaction affects pore size distribution, water availability, and tree growth on these and other LTSP soils.

Confounding from Competing Vegetation

Compacting the clayey soil at Challenge clearly reduced AWC and conifer growth rates (*table 6*). It also increased soil strength by about 1.5 MPa throughout the upper 40 cm (Powers and Fiddler 1997). In all, the soil's productive potential was reduced substantially by compaction. Yet, this effect was apparent only when trees were free of competition from understory vegetation. Where vegetation was *not* controlled, trees were appreciably larger and their ψ_p equal or greater on *compacted* plots (*table 6*), although their absolute growth was 40 to 67 percent less than on noncompacted plots where vegetation had been controlled (Powers and Fiddler 1997). This is because the density of understory vegetation was nearly twice as great on noncompacted plots (91 percent cover vs. 56 percent cover). Understory seedlings germinating from seed could recolonize noncompacted, clayey soil much more easily than compacted soil. Less

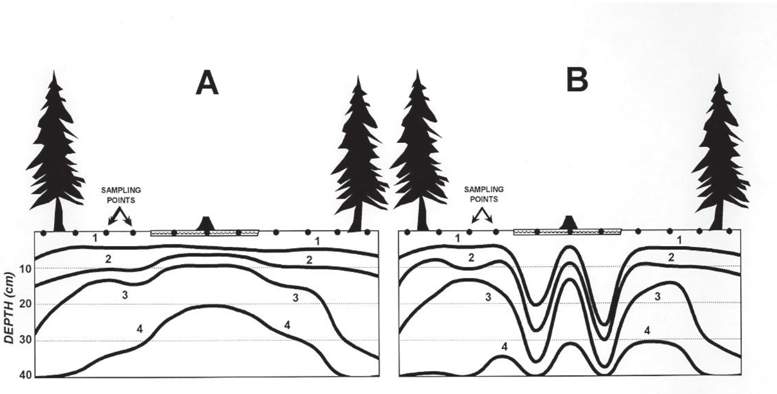

Figure 6—Soil strength MPa isolines at Pondosa in fall 1998 following mechanized thinning of every third row (Powers and others 1999). (A) Thinned only. Friable rooting zone was reduced by half beneath traffic lanes. (B) Thinned and tilled along harvester tracks. Tilth returned to prethinning levels.

I conclude from this that techniques for measuring soil strength, developed from LTSP studies, can be used to distinguish physical changes in the soil that are caused by field operations. Therefore, soil strength should have a prominent place in the operational methods for monitoring soil quality by the USDA Forest Service's Pacific Southwest Region (*table 1*).

The Roseburg Study

To further extend LTSP principles of physical soil mitigation to an operational setting, we began a second experiment in fall 1998 with cooperation from Roseburg Resources Co. in the Pondosa Burn north of Burney, California. The test forest is a 15-year-old plantation of ponderosa pine established after salvage logging in the aftermath of a 1977 wildfire. Although soils were compacted somewhat by salvage logging, tree survival was excellent. Canopies have closed, and the plantation is being thinned by whole-tree harvesting to maintain high rates of tree growth and to reduce fuel buildup. Four primary treatments have been established on 0.4-ha plots in a randomized design of four blocks: (1) unthinned control, (2) thin and remove every third row of trees, (3) thin and remove every third row, subsoil the traffic lanes, and (4) thin and remove every third row, fertilize and subsoil the traffic lanes.

Thinning was done with a three-wheeled Morbark Wolverine shear and grapple skidder. Whole trees were skidded to a landing, where they were chipped. Traffic lanes within thinned strips were tilled to a depth of about 0.5 m along wheel tracks, using two passes of a winged subsoiler drawn by crawler tractor. Fertilization involved granular urea and ammonium triple phosphate applied at 224 kg N ha^{-1} and 336 kg P ha^{-1} in the tilled tracks. Tillage provided an opportunity to work N and P into the rooting zone of residual trees. Penetrometer readings taken shortly after treatment in fall 1998 showed that mechanized thinning led to soil compaction and reduced the friable rooting depth by half (*fig. 6A*). In contrast, subsoiling the compacted traffic lanes lowered soil strength to prethinning levels (*fig. 6B*). This treatment should create a furrow effect that collects and retains soil moisture and extends tree growth into the summer.

Early results from this LTSP-related study reinforce the significance of soil strength for detecting treatment differences on soil's physical properties. They also indicate that: mechanical row thinning compacted the soil beneath the traffic lanes; compaction extended to at least 40 cm; and subsoiling seems to have mitigated the effect. How this translates to soil moisture availability, understory diversity, root growth, and tree growth will be determined in the coming years.

Organic Residues

Principles learned from LTSP indicate that replenishment of organic matter is critical to sustained productivity of forested ecosystems. Organic carbon in forest detritus is the substrate energizing most soil biotic processes that control nutrient and water availability, aeration, and soil structure. Detritus can create a fuel bed that increases the risk of forest destruction by fire, however, particularly in our summer-dry climate. The problem facing management is how to reduce fire risk without depleting organic matter on and within the surface soil.

Conventional methods of managing residues include low-intensity burns or mechanical removal of some of the fuel load through whole-tree harvesting. Both methods remove organic carbon from the site. While solving the immediate fuel problem, they offer nothing for long-term carbon storage or improvement of soil quality. On more mesic to xeric sites with less fertile soils, losses of surface residues likely will lead to deficiencies of N and P when the stand is at leaf-area carrying capacity, and nutrient uptake peaks (Powers 1999). Two experiments are underway and a third is planned to test effective alternatives to burning or removal of organic residues. Each involves retention of residues in chips.

The Sierra Pacific Study

The first experiment in the Sierra Pacific study began in 1993 with commercial harvesting of a 90-year-old mixed-conifer stand on what is now Sierra Pacific Industries land near Blodgett Forest in Eldorado County. Logging slash (about 50 Mg ha^{-1} containing about 640 kg N ha^{-1}) was treated in three ways: residues were scattered and broadcast burned; residues were piled by tractor into windrows and the windrows were burned; and residues were chipped on the site and returned to the ground as linear, 30-m rows of wood and foliage shredded to sizes averaging between 2 and 5 cm in length. The first two treatments are conventional, but the third is an innovative means of retaining organic matter while reducing its flammability and concentrating it to create a critical mass that retains water and perhaps creates an ideal medium for nonsymbiotic nitrogen fixation. Rows of chips resemble large, fallen, decomposing trees spaced about 20 m apart. Treatment plots, 0.2 ha each, were replicated four times and planted with mixed species of conifers in spring 1994.

Concentrating chips into piles offers several benefits. First, it reduces the fuel profile throughout the unit to a compact, localized condition. Second, it avoids high temperature effects in broadcast chip applications that may heat-girdle some conifer seedlings. Third, chip piles dry from the surface inward, creating cool, moist conditions in their interiors and in the soil beneath them. Finally, once chip piles have decomposed, conditions may be ideal for free-living, nitrogen-fixing bacteria. Nitrogen fixation rates have been shown to be much higher in chip piles (because of the organic carbon source and anaerobic conditions) than in any other field medium (Jurgensen and others 1980). The trick is to reduce chips as quickly as possible from large, flat objects with low specific surface area to small, amorphous bodies with great surface area for retaining moisture. This reduction occurs in natural decomposition by the removal by fungi of linear molecular chains of cellulose to leave a residuum of lignin (Blanchette and Shaw 1978). Cooperating with scientists in the USDA Forest Service's Rocky Mountain Research Station, we are attempting to speed this process by inoculating some chip piles with pure strains of *Postia placenta*—an aggressive brown rot fungus particularly adept at consuming cellulosic sugars.

The Roseburg Study

Along with the main-effect treatments with thinning and tillage described previously, four secondary treatments, each occupying 0.1-ha subplots, were added to each block of the Roseburg study at Pondosa as supplements to Treatment 3 described earlier. They involved retention of woody residues as chips to reduce fuel volumes while retaining site organic matter. They were: (3a) all thinnings chipped, returned to traffic lanes, subsoiled, and rototilled; (3b) traffic lanes subsoiled, thinning chips added to the surface; (3c) thinnings chipped and returned, fertilized with N and P, subsoiled, and rototilled; and (3d) traffic lanes subsoiled, thinning chips added to the surface, fertilized with N and P.

Chips were returned to the site to see if residue retention would improve soil water storage capacity, soil fertility, and carbon sequestration. The purpose of chip fertilization was to lower the C:N ratio to favor microbial decomposition (chemical analyses are not available at this time). Chips either were retained on the surface to act as mulch or tilled into the soil to increase decomposition.

The Kings River Study

A third residue modification study is planned for the Kings River Administrative Unit of the Sierra National Forest. The study area is characterized as the drier end of the westside Sierra Nevada mixed-conifer and ponderosa pine forest types. Soil AWCs are moderate to low. Fire suppression has led to heavy fuel accumulations in the understory. The challenge is to manage the Unit for a variety of resources while lowering fire risk. The common strategy when creating fuel breaks or site preparation following timber harvest is to remove whole trees during the harvest and to pile and burn remaining residues. Unfortunately, such treatments deplete the site of organic materials, potentially affecting soil fertility, AWC, and erodibility.

Recent mechanical innovations provide another choice. Preliminary tests of an innovative rotary mulcher in the southern pine region of the eastern United States show a high potential for reducing fuels, retaining site organic matter, and improving physical soil properties important to plant growth. Attached to a crawler tractor, the rotary mulcher grinds stumps, shrubs and logging slash into fine residues. These residues may be left on the soil surface to serve as an evaporative mulch or mixed into the surface soil in a single operation. Grinding residues into a fine particle size not only reduces the fuel profile, but it also increases the specific surface area of the biomass. Higher specific area spells greater rates of microbial decomposition. Incorporating these fine materials into mineral soil offers a huge bonus of increasing AWC, soil aggregate stability, nutrient retention, and carbon sequestration. A small grant was obtained for testing this technique in the fall of 1999. Work will center on shaded fuel breaks and on group selection openings. Rotary mulching will be compared against conventional best-management practices in its effect on seedling survival, growth, and vigor, and on soil AWC, nutrient storage, and aggregate stability.

Emerging Indicators of Sustainability

A major objective of the LTSP effort is to develop effective and practicable methods for monitoring changes in a site's carrying capacity for NPP. Although LTSP is in its infancy, soil strength as measured with a recording cone penetrometer (*figs. 5, and 6*) has emerged as a premier method for assessing soil physical properties. The sensitivity of penetrometer readings to soil moisture and hardness shows its capacity for integrating several soil physical changes that affect root behavior. Management practices that increase soil strength above 2 MPa during the potential growing season indicate that the site's capacity for plant growth has been diminished. Accordingly, and based solely on early findings from LTSP, soil strength has been proposed as the single most useful index of soil physical condition in operational monitoring for sustainable forest management (Powers and others 1998). Other recommendations include anaerobically mineralizable nitrogen as a single, integrative measure of nutrient supply, and the presence or absence of biopores and fecal aggregates as an index of soil invertebrate activity (Powers and others 1998). Declines in either of these properties with time suggest declines in soil biotic function and, most likely, a declining productive potential. The foundation for these biotic indices of sustainable forestry practices was developed in part by regional and national findings from LTSP.

Although the LTSP effort is young, findings are emerging rapidly. Already they are modifying standards for monitoring soil quality for National Forests of the United States, such as standards shown in *table 1*. As the concept of soil quality evolves, so will the effectiveness of soil-based standards. To be practicable, monitoring methods must focus on the simplest possible indices of key physical, nutritional, and biological properties and processes of the soil. Standards will be subject to continual refinement. When strong calibrations emerge between soil variables and NPP, as conditioned by climate and soil type, such indices will be universally accepted. Findings from LTSP research promise to be the primary means for achieving this acceptance.

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