Chapter 23
The Key Roles of Four Experimental Forests in the LTSP International Research Program

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Abstract Four Experimental Forests were pivotal in piloting the long-term soil productivity (LTSP) cooperative research program—one of the most successful and extensive collaborative science efforts yet undertaken by the USDA Forest Service. Launched on the Palustris, Challenge, Marcell, and Priest River Experimental Forests, LTSP traces to a seminal discussion during a field tour in central Louisiana in 1986. P. E. Avers, National Soils Program Leader in Washington DC, described to D. H. Alban and R. F. Powers a problem arising from the National Forest Management Act of 1976 (NFMA). That conversation sparked an idea that quickly caught fire. This chapter documents how LTSP came to be and why four Experimental Forests were central to its success. It began with a ripple effect of the NFMA.

Keywords Challenge Experimental Forest · Marcell Experimental Forest · Palustris Experimental Forest · Priest River Experimental Forest · Long-term research · Sustainable productivity

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23.1 Background

23.1.1 The Challenge of NFMA

In 1989, the annual meeting of the American Society of Agronomy (ASA) was held in New Orleans. One of ASA's tri-societies is the Soil Science Society of America, and its S-7 Division then was called "Forest and Range Soils." That Division's meeting included a field trip to tour sites of forest soils of interest in the region. Seated on a tour bus behind Forest Service researchers Robert Powers and David Alban was Peter Avers, National Soils Program Leader for the administrative arm of the Forest Service. At one point, Peter leaned forward and remarked that his national program needed help from Forest Service Research.

The problem that Avers described concerned language in National Forest Management Act (NFMA) that echoed earlier mandates in the Multiple-Use Sustained-Yield Act of 1960 and the Natural Resources Planning Act of 1974. Namely, that public resources should be managed *without impairment of the productivity of the land* (USDA Forest Service 1993). The essence of NFMA was that the Forest Service should conduct research, monitoring, and assessment to ensure sustained yield in perpetuity while protecting all resource values. This statement of public land ethic is remarkable in that it precedes by more than a decade the Dutch Soil Protection Act of 1987 and Australia's National Forest Policy Statement of 1992 (Nambiar 1996; Powers et al. 1998).

Provisions in NFMA called for the creation of a national committee to counsel and advise the Secretary of Agriculture during the development of National Forest planning regulations, and the Secretary asked the National Academy of Sciences for help. The eight-member Committee of Scientists, formed in 1977 and chaired by A. W. Cooper of North Carolina State University, forged a framework for implementing NFMA. Recommendations were finalized in 1979 and incorporated into the 1985 Code of Federal Regulations for Forest Planning. A notable

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section required the Forest Service to monitor the effects of forest management prescriptions, including "significant changes in land productivity" (USDA Forest Service 1985)—a requirement preceding by more than a decade the "Criteria and Indicators of Sustainable Forestry" of the Montreal Process (Canadian Forest Service 1995) and the environmental surge toward "green certification" (Anonymous 1995). Thus, it is landmark. It also was a tall order because it demanded of Forest Service managers a level of resource knowledge absent in any single individual.

23.1.2 Defining the Problem

The Forest Service knew that unambiguous definitions were central to carrying out its monitoring charge. At the fore was a clear and objective definition of "land productivity." In the broadest sense, land productivity might mean the capacity of a site to produce a sustainable flow of a myriad of forest and range values. However, many values are difficult to assess because they are subjective. Accordingly, and with guidance from the US Office of General Council (OGC), a working definition emerged. *Land productivity* was interpreted as the carrying capacity of a site for sustaining growth of native vegetation. In turn, *carrying capacity* was seen as the average periodic dry matter production when the site was fully stocked, and analogous to net primary productivity in a mature forest community. Finally, *significant change* was defined as a reduced level of carrying capacity induced by management that could be detected within practicable levels of operational monitoring (USDA Forest Service 1987). Given the vagaries of climatic flux in dry matter production and realistic operational limitations, discussions with Land Management Planning and OGC led to a decision that productivity declines of 15 % or greater would have to occur to be measurable under operational conditions. And this became the working threshold for "significant decline" (USDA Forest Service 1987).

23.1.3 Monitoring What?

The question facing the USDA Forest Service was how to monitor possible productivity change. Measuring vegetation directly seemed logical but beset with problems. What if vegetation was not at a stocking level that reflected stability? What if current productivity reflected unknown conditions in the past, such as unusual storm damage or pest outbreaks? Departures of any given forest stand from a productivity baseline required both a solid knowledge of the baseline and the passing of enough time to detect a substantive change. Taking the lead in this, the Watershed and Air Management division of National Forest Systems (NFS) adopted a monitoring philosophy based on the following principles:

1. Management practices create soil disturbances.
2. Soil disturbances affect soil and site processes.
3. Soil and site processes control fundamental forest productivity.

Soil and site processes clearly govern fundamental productivity within the limits of climate and biology. But monitoring soil and site processes directly simply was not feasible, nor was our knowledge of baselines and processes perfect. The questions confronting soil scientists were how to determine baseline "soil productivity," and how to monitor management-caused changes to it. This is the concept since recognized as "soil quality" (Doran et al. 1994; Karlen et al. 1997; National Research Council 1993). Broad definitions of soil quality existed, but they were too qualitative and conceptual to be useful. Consequently, the Watershed and Air Management division proposed that a national template be developed. The template would list measurable soil properties linked to potential productivity. These properties would be monitored and thresholds set to indicate significant risks to productivity. Based largely on professional judgment, threshold standards were set regionally to alert managers of serious, possibly irreversible problems stemming from management practices.

23.2 Birth of a Plan

23.2.1 Tackling the Problem

Standards based on professional judgment are a good first step. But subjective standards are controversial and readily challenged. To be convincing, standards needed to be anchored in objective science. Powers, following a recent research sabbatical to New Zealand, had been particularly impressed by a small-scale experiment aimed at solving a similar problem (Murphy et al. 2004). Recognizing that the New Zealand experiment was additive and not factorial, and that it had several drawbacks, Powers saw the NFS predicament as a unique opportunity for a new research thrust along the lines of the New Zealand experiment, and over several months, he, Avers, and Alban discussed this further. Avers had scheduled a field review of the California Region's soils and watershed programs in spring, 1987, and Powers invited key scientists from the several Research Stations to attend. Forged at this meeting was the nucleus for a possible cooperative program. Returning home, scientists discussed the concept for a national program with their Station administrators. Directors were supportive of the grassroots concept, but advised that coordination with the Washington Office (headquarters in Washington DC) was essential in launching a program of this scope. Subsequently, administrative leaders in Forest Management and Soil staffs, both in Research and Development (R&D) and the NFS, were briefed and a cadre of Avers, R. G. Cline, R. O. Fitzgerald, and N. S. Loftus Jr. from the Washington Office, plus Alban, Powers, R. E. Miller, A. E. Tiarks, and C. G. Wells from the North Central, Pacific Southwest, Pacific Northwest, Southern, and Southeastern Research Stations, respectively, assembled in St. Louis, MO, in 1988 to discuss an approach.

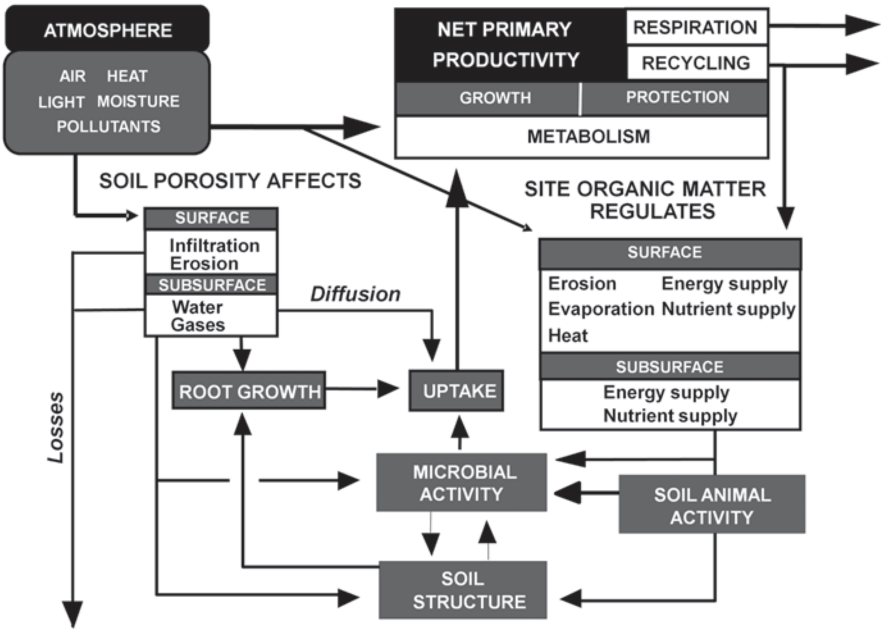

Fig. 23.1 Conceptual model of how soil porosity and site organic matter regulate net primary productivity within the framework of environmental controls. (from Powers et al. 1990)

The St. Louis meeting had several aims. We needed to clarify issues stemming from NFMA and to reach consensus on how to address the issues in a way that would further both the management and research arms of the Forest Service. We agreed that the scientific basis for soil quality monitoring was shaky. Some of what helped shape professional judgment was merely opinion and much of the remainder rested on anecdotal evidence. We agreed that another round of expert opinion might help in the short run. But what truly was needed was an objective and robust series of original experiments to provide the scientific foundation for sound policy. Thus, a second aim was to develop consensus on, and commitment for, an entirely new cooperative research approach.

Apportioning literature review among the researchers, several weeks were spent examining published evidence purporting to show productivity decline caused by management impacts on soil. We concluded that most claims could be attributed to other factors. However, two soil characteristics with promising linkages to lowered productive capacity were losses in soil organic matter and soil porosity—properties governing fundamental site processes that regulate net primary productivity within a climatic and genetic framework (Fig. 23.1).

Based on this conceptual model, we drafted an experimental design to test the following null hypotheses (Powers 2006):

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

2. If productivity changes do occur, they are universal.
3. Such changes are irreversible.
4. Plant diversity has no impact on the productive potential of a site.

23.2.2 Presenting the Concept

Our conclusions on purported productivity declines and our call for a new research approach were showcased at the 7th North American Forest Soils Conference held in Vancouver, British Columbia, in 1988. The paper received broad international attention and technical review, and it was published 2 years later in the conference proceedings (Powers et al. 1990).

Immediately following the 1988 conference, we prepared a plan for a nationally coordinated study to determine the long-term effects of soil disturbance on fundamental productivity. The Washington Office sent the plan for technical review to all Forest Service research silviculturists and soil scientists and their counterparts in Regional Offices, as well as individuals in other forestry research institutions both domestically and abroad. As such, it stands as the most widely reviewed research study plan in the history of the USDA Forest Service. Review comments were assembled in the Washington Office and final adjustments to the plan were made there by the authors. In 1989, the plan was presented to the Deputy Chiefs for R&D and the NFS and approved as a national study of long-term soil productivity (LTSP; Powers et al. 1989). Installation cost was to be covered from excess timber sale receipts administered from the Washington Office through the Forest Service Regional Offices.

23.3 The Hard Part Begins

23.3.1 Core Treatments

The LTSP study centered on commercial forest types on National Forests across the nation. Requirements were that sites must support young-mature forests typifying those under active timber management. Soils typical of each forest type and spanning a range of potential productivities would be identified, thus ensuring broad latitude in soil properties. Once sites were selected, treatments were to follow a standard template of three levels of site organic matter removal (commercial bole only, whole tree, and whole tree plus forest floor) crossed with three levels of soil compaction (none, moderate, and severe). Each treatment plot was to encompass at least 1 acre (0.4 ha) with an appropriate buffer that separated treatment plots from surrounding timber.

Plots were to be harvested by the most practicable means and regenerated with species characterizing the previous forest. Treatment plots were then to be split, one half receiving regular vegetation control (trees developing without competing vegetation), the other half allowed to regenerate to natural understory vegetation. In this simplicity, there is elegance, and a factorial matrix of 18 possible treatment combinations was created. Response was to be measured as dry matter production per unit area over time (net primary productivity). Split plot treatments afforded two measures of productivity: timber production free of competing vegetation and ecosystem production that included both trees and emerging understory. This twist allowed the testing of all hypotheses stated previously.

23.3.2 Just Enough Organization to Avoid Chaos

Participation in LTSP was voluntary, requiring only an agreement between a principle investigator from the Research Station and the chief soil scientist and silviculturist in the participating Forest Service Region. National oversight was provided by four members of the Washington Office representing timber and soils interests—two from R&D and two from the NFS. Technical guidance was provided by a national committee consisting of principal investigators from Research Stations and the chief regional soil scientists from participating Forest Service administrative Regions. The Technical Committee was chartered to have at least one formal meeting annually led by an appointed chair, with the meeting venue shifting about the country. Regional guidance was secured through steering committees consisting of the research principal investigators from the participating Experiment Stations, plus the lead soil scientist and silviculturist for each participating Forest Service administrative region (initially regions 4, 5, 8, and 9). The Regional Committees identified the soil and forest types for focusing the LTSP experiment, encouraged cooperation among National Forests and Ranger Districts, and met at least annually to review progress, set priorities, and find solutions to emerging problems. Financial backing was secure. With this tidy level of organization, all that remained was to choose sites and implement the study.

23.3.3 Overcoming Inertia

The problem was how to begin. Rounds of discussion were held among the Technical Committee on how to choose sites and apply treatments. All agreed that the forest cover types and field sites would be identified by the Regional Steering Committees to span a gradient of soils and that actual approach in installing treatments would be at the discretion of the principal investigators. Individual ingenuity was freed to achieve an end product, rather than a means of getting there. Since there was no historical guideline for any of this, all of us agreed that the pilot installations would be on Experimental Forests under the control of the Southern, Pacific Southwest, North Central, and Intermountain Research Stations. Experimental Forests had the advantage of being under the jurisdiction of the Research Stations and treatments could be applied under categorical exclusion, thereby avoiding administrative

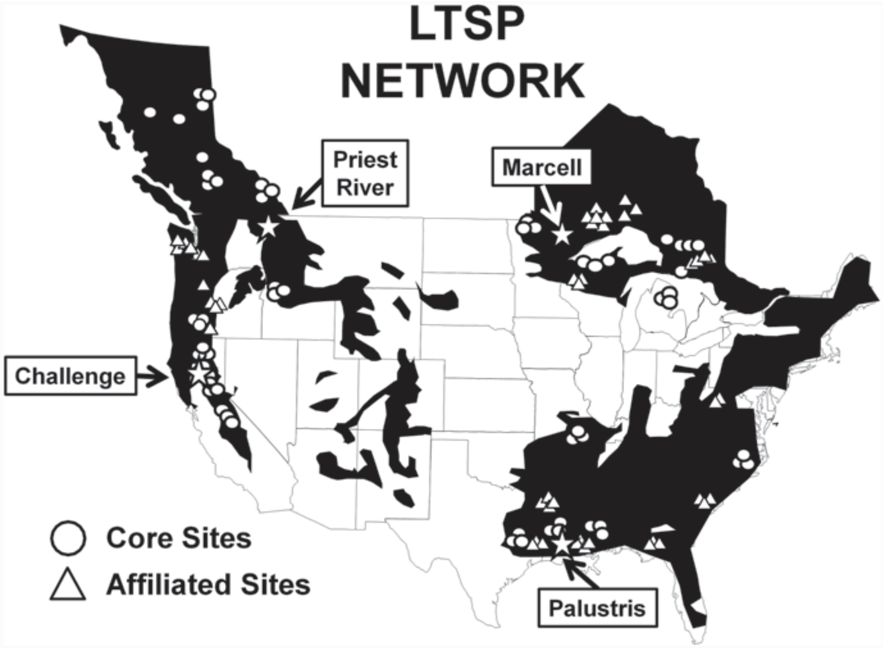

Fig. 23.2 Distribution of North American core and affiliate LTSP installations. Shading shows forest area capable of mean annual increments of 20 ft^3 $acre^{-1}$ of merchantable wood. The first four installations all were on USDA Forest Service Experimental Forests as indicated by stars

delays. They also had historically high visibility (making them useful for demonstration) and a close rapport with Ranger District and National Forest personnel. Finally, most Experimental Forests had lodging facilities that would reduce the cost of travel. Thus, they had tangible, practical advantages for piloting the program.

We discussed how best to get started, but we soon reached the point of diminishing returns on "what ifs." To break the gridlock, A. E. Tiarks boldly volunteered to be the guinea pig and establish the first installation on the Palustris Experimental Forest in Louisiana. The pioneering experiment was installed in 1990 under a memorandum of understanding among the Station Directors of the Southern and Southeastern Forest Experiment Stations (now combined into the Southern Research Station) and the Regional Forester of the Southern Region, USDA Forest Service. Challenge Experimental Forest in California was the second replication, and the Marcell in Minnesota and Priest River in Idaho soon followed. The Canadian government quickly became a partner, first through the British Columbia Ministry of Forests and then the Canadian Forest Service, each securing their own sources of funding. Affiliate installations also were recognized on public and private forest lands in Canada and the USA. In 2012, Mainland China's National Academy of Science also became an active partner following reciprocal visits. Today, more than 100 LTSP installations of core and affiliate sites have been established to create the world's largest network of studies aimed at understanding how management affects the fundamental productivity of forest land (Fig. 23.2). Most core installations are

Table 23.1 General characteristics of the first four Experimental Forests at the time of LTSP establishment. (Forest cover types follow Eyre (1980))

Experimental Forest (and State)	Palustris (Louisiana)	Challenge (California)	Marcell (Minnesota)	Priest River (Idaho)
Location	Kisatchie National Forest, Lat. 31.02 N, Long. 92.38 W	Plumas National Forest, Lat. 39.50 N, Long. 121.22 W	Chippewa National Forest, Lat. 47.30 N, Long. 90.30 W	Idaho Panhandle National Forest, Lat. 48° 21′ N, Long. 116° 41′ W
Elevation (feet)	150	2,765	1,411	2,040
Annual ppt. (inches)	46	67	30	33
Soil parent material	Coastal Plain sediments	Metamorphosed basalt	Des Moines lobe till	Lacustrine sediment overlain with volcanic ash
Soil family	Fine-loamy, siliceous, thermic Plinthic Paleudults	Mesic Typic Palexerults	Arenic Eutroboralf	Frigid, Andic Fragiudalf
Forest cover type	Loblolly pine (SAF Type 81)	Mixed-conifer (SAF Type 243)	Aspen (SAF Type 16)	Mixed-conifer (SAF Type 215)
Stand age (years)	37	108	70	90
Preharvest biomass (tons/acre)				
Trees	40.95	211.46	94.12	71.43
Understory	2.28	0.26	1.24	0.08
Forest floor	0.00	27.18	44.16	10.72
Year of establishment	1990	1991	1992	1992

on national and state forests, but expansion would have been doubtful had we not pioneered LTSP on four key Experimental Forests whose characteristics are shown in Table 23.1. Our trial and error experiences in establishing the experiment on these four forests provide insights into the best approaches for large-scale manipulative studies and demonstrate what is possible through a grassroots effort of determined scientists and administrators.

23.4 The First Installations

23.4.1 Palustris Experimental Forest

Managers from both the Southern Region and the Kisatchie National Forest agreed with Tiarks that the southern LTSP effort should center on the widespread loblolly pine (*Pinus taeda*) forest type and that the first site should be on Louisiana's Palustris Experimental Forest. Palustris was established in 1935 and draws its name from the virgin forests of *P. palustris* (longleaf pine) that once covered a vast area of the South. Climate is subtropical and typical of the Southern Coastal Plain, with rainfall spaced fairly evenly throughout the year. Like other Experimental Forests, the Palustris had long-term records, high visibility, and a good degree of protection. Furthermore, the Palustris had completed the National Environmental Policy Act (NEPA) public process for comment for harvesting. Because the installation required a uniform stand and soils of broad extent, site selection narrowed to one suitable stand recommended by Eugene Shoulders, a scientist familiar with its history. It was a good place to begin.

23.4.1.1 The Study Site

Shoulders recalled that the existing stand of loblolly pine had been established as a direct seeding demonstration area in 1953. Previously, the site supported old-growth longleaf pine, harvested in the 1930s with poor subsequent regeneration. It was burned regularly as prescribed in range management studies, so that there was little woody understory and negligible forest floor. Assisted by the National Forest soil scientist, a detailed soil survey was made in each 0.5- and 1-acre plot to ensure uniformity. The upper 12 in. of soil was sampled for bulk density and chemical properties at nine locations per plot. Diameters of all living pines were measured and three trees in each plot were selected for destructive biomass measurements. All the preharvest soil and vegetation samples had been collected by early fall 1989.

23.4.1.2 Administrative Hurdles

Discussions with the silviculture, sales, and purchasing personnel in the Kisatchie Forest Supervisor's office determined that the best logging approach was through two timber sales. The first sale of the surrounding buffer trees was straightforward, and in 30 days LTSP plots were isolated for further treatment (Fig. 23.3).

The second sale was tailored to plots with no compaction. By locating an access alley between the understory control and no understory control halves of the plots, logging equipment could lift trees from the uncompacted plots without disturbing the soil (Fig. 23.4). As the plots were logged, tops and limbs were removed or left on the plots depending on treatment. Close cooperation between sales administration and the logger ensured that the work was completed in late 1989 according to specifications. Remaining treatments were applied and the site was planted in February 1990.

23.4.1.3 Achieving Compaction

First attempts of soil compaction during the summer before harvest clearly showed the futility of compacting dry soils that have the property of "hard when dry." Thus, compaction began in early winter when logging was completed and soils were moist.

Fig. 23.3 Aerial view of the first LTSP site on the Palustris Experimental Forest showing logged buffers. This isolated individual plots for applying LTSP treatments. Note that the 1-acre units are divided, allowing equipment access

Fig. 23.4 Full-tree suspension of trees by a loader to avoid machine traffic and possible soil compaction at the Palustris Experimental Forest installation

Fig. 23.5 Tractor-drawn Wobble Wheel used in our first soil compaction effort. Note ballast for adjusting the Wobble Wheel load

A pneumatic tired compactor called a "Wobble Wheel" (Fig. 23.5) was adjusted to two different axle loads to achieve intermediate and severe levels of soil compaction. The axle loads were estimated from published literature and confirmed on small test areas in the buffer. The compactor, towed by a small crawler tractor, was chosen because its axles flexed to the uneven terrain, it allowed various loadings, and it was narrow enough to fit between tree stumps. It was towed across each plot three times in one direction and then three more passes perpendicularly. On plots where logging residues remained, limbs and tops were pulled aside to form a path during compaction and then replaced. Because the site had been burned regularly, there was no woody understory. The forest floor was thin enough that it did not interfere with the compaction which was completed before any forest floor removal.

The compaction treatment produced bulk densities averaging 1.47, 1.54, and 1.60 Mg m^{-3} in the surface 4 in. for the uncompacted, moderate, and severe treatments, respectively (Tiarks et al. 1991). Where logging slash was retained, materials were distributed evenly by hand. Where the thin forest floor was removed, hand equipment was used to mow and rake the grasses and herbs present. Materials were moved manually and stacked off the plot. Once the treatments were completed in February 1990, containerized loblolly seedlings were planted at 8 × 8-foot spacing. A weather station was erected on the site to collect temperature, rainfall, and several other parameters.

23.4.1.4 Findings

One striking early finding was that removing more than the main bole reduced new seedling growth substantially. This was attributed to the increased nutrient mass removed in tree foliage and understory and underscores the significance of surface residues to the nutrient cycle in humid climates and impoverished soils. These early results led both the National Forest and private land managers to limit whole tree harvesting whenever possible. None of the treatments reduced the soil organic carbon concentration within the top 180 cm after a full decade (Tiarks et al. 2004).

However, the porosity of the soil did increase as the soil carbon concentration increased, showing the importance of maintaining organic carbon within the soil profile in respect to soil physical properties.

As this was the first LTSP site, successful installation demonstrated to the cooperating scientists and National Forest managers that the study could be implemented as proposed to meet the criteria of the study plan. It also served to demonstrate the field design for LTSP to prospective cooperators in extending the experiment to other sites in the South. Visits to the Palustris pilot site by personnel from the forests in Mississippi and Texas overcame doubts about the potential returns from the long-term study.

23.4.2 Challenge Experimental Forest

We identified the Sierra Nevada mixed-conifer forest type as having the highest priority for soil disturbance research. Characterized by *Abies concolor, Calocedrus decurrens, Pinus lambertiana, P. ponderosa,* and *Pseudotsuga menziesii* in the north, this forest type is second only to *Sequoia sempervirens* in potential productivity in California, and ranks first in forest management issues. The first of our 12 replicate California installations would be at the Challenge Experimental Forest.

Located on the Plumas National Forest, Challenge was chartered in 1942 to tackle management questions concerning young-growth forests of the Sierra Nevada's west slope. Forests were even-aged, century-old stands that regenerated following clearcutting, railroad logging, and slash fires. Challenge was a prime candidate because it was managed by the Pacific Southwest Research Station's (PSW) unit with lead responsibility for LTSP and it typified low-elevation mixed-conifer forests of superior productivity, anchoring the upper end of the site quality spectrum. Challenge also is well-roaded, accessible year-round, and a convenient drive from our research offices in Redding. It attracts many tours that showcase silvicultural research.

23.4.2.1 Approach

PSW held an advantage. The California Region's Silvicultural Development Unit (SDU) was administratively assigned to PSW to assist with field operations and technology transfer. SDU personnel were experienced in inventory methods, timber sale contracts, and inspection of contracted operations. Temporary plots of 1 and 0.5 acres were established and sampled to describe spatial variability in edaphic and stand conditions, and those with similar spatial variation were accepted.

Experience at the Palustris Experimental Forest had little application here because Challenge vegetation and forest floor masses were greater by half an order of magnitude (Table 23.1). Therefore, we improvised new methods to meet our needs. Plot buffers needed to be as wide as the height of the bordering forest to minimize

Fig. 23.6 A half-acre treatment plot exposed by logging the surrounding buffer. Dominant tree heights approach 160 ft

edge effect, and these wide buffers more than doubled the area to be harvested (35 acres).Harvesting contracts for the buffer and main plots were advertised separately with the buffer contract awarded first. Special clauses required hand-felling and skidding to a landing without trafficking the treatment plots. In all, 1.125 million board feet were harvested in about 30 days, leaving treatment plots isolated for further work (Fig. 23.6).

We developed diameter-based biomass equations by sampling more than three dozen trees spanning the range of sizes and species (including understory hardwoods). Understory biomass and forest floor mass were measured by sampling randomized subplots of fixed area, and results appear in Table 23.1.

Harvesting operations were more complicated for the treatment plots. Large tree sizes, gentle slopes, and our ban on ground traffic posed a challenge that the logger met with ingenuity and improvisation. Trees were removed by full suspension, using a truck-mounted 60-ft tower and sufficient cable drums to serve as a live skyline yarder. Tail blocks were hung in large trees at the back of each plot and placed at least 90 ft high for adequate lift (Fig. 23.7). A practical advantage of having a single logger deal both with the buffers and the treatment plots was that potential tail block trees could be marked and left standing in the buffer to provide lift if no suitable trees were present at the back of the treatment plot. In all, 432 thousand board feet were removed from treatment plots in about 30 days.

Whole trees were removed by full suspension if plots were not to be compacted (Fig. 23.8). Slash was retained by delimbing the felled trees and removing boles. For compacted plots, slash was stored in the buffer until it could be returned following compaction. Through a separate service contract, hand crews raked forest floors onto tarps which were carried to the nearest buffer. A ten-person raking crew could complete 1 acre a day.

Compared with harvesting procedures, soil compaction operations were simple. The thick forest floor prevented appreciable compaction, so it had to be removed before compaction, then replaced and distributed uniformly. Compaction was applied

Fig. 23.7 To get adequate deflection for full suspension, tail blocks were set at least 90 ft above the ground

Fig. 23.8 Whole-tree removal was accomplished either by a shovel loader operating from the buffer as shown or by cable suspension. Both methods avoid vehicular traffic on the plots

with a Dynapac vibrating roller weighing 32,000 £ (Fig. 23.9). We established a test strip in one of the buffers to determine the number of roller passes needed to reach target bulk densities. Compaction proceeded in perpendicular passes on each plot at the rate of 1–2 acres per day, depending on the target density level. Forest floors and logging slash were respread at the rate of 2–3 acres per day through a special service contract.

Fig. 23.9 Achieving uniform soil compaction at Challenge through perpendicular passes of a vibrating roller

We planted species reflecting the composition of the dominant conifer overstory at the time of harvest. Given California's summer drought, we knew that survival hinged on first-year root growth. Accordingly, each planting spot was drilled to a depth of about 12 in. using a gasoline-powered auger. Bare root seedlings were planted at 8 × 8-foot spacing in an alternating arrangement of species (*Abies concolor, Pinus ponderosa, P. lambertiana, Pseudotsuga menziesii*). Survival is greater for *Pinus ponderosa* than for other species, so to ensure full stocking, each planting spot had two augered planting holes. One hole received the sequential species noted above, the other a *Pinus ponderosa*.

23.4.2.2 Subsequent Operations

Trees and emerging vegetation were left to develop for 3 years. Then, half of each 1-acre plot received glyphosate applied as a directed spray and *Pinus ponderosa,* the "insurance" species, was rogued if the other conifer from the mix of four seemed apt to survive. Otherwise, the pine was left. Plots have been remeasured every 5 years.

23.4.2.3 Important Findings

Challenge was not meant as a stand-alone experiment, but simply the first of a dozen California installations spanning the spectrum of soil types and site qualities in the mixed-conifer forest. Yet, several "firsts" emerged from this trial. Our pretreatment harvests at Challenge provided the first detailed assessment of mass and nutrient content of any California forest ecosystem (Powers 2002). Of the 6,807 lbs nitrogen contained per acre in vegetation and soil at Challenge, less than 8 % was in standing vegetation and only a small fraction of this (0.7 %) was in the understory. Although the forest floor mass was 12 % of the standing forest mass, it contained 43 % of aboveground nitrogen, illustrating its significance as a major nutrient reservoir and one that is affected readily by disturbances. We found that forest floor removal has a greater effect on reducing soil nitrogen availability than does whole-tree harvesting (Craigg 2006). Yet, productivity was not affected over the first decade on such fertile California soils (Powers et al. 2005), and we conclude that lesser biomass removals as in commercial thinning or whole-tree harvesting are not apt to affect the productive potential of a site as fertile as this.

Challenge showed us other positive benefits of the forest floor beyond its significance as a nitrogen reservoir. Average summer soil temperatures in the fine root zone were 8 °F cooler if a forest floor was present than if it was absent, and available soil moisture was extended 3 months longer—both critical factors affecting seedling survival and performance in a Mediterranean climate. Where soil cover was present, soil compaction had little effect on soil erosion rate measured over the first 3 years. But removing the forest floor accelerated soil erosion two- to eightfold (Powers 2002).

To our knowledge, the experiment at Challenge stands as the first rigorous testing of the modern recording soil penetrometer in North American forestry. Measurements taken in midsummer of the third year at Challenge showed that strengths in the fine root zone averaged 2 MPa or less where the forest floor was present, but a full MPa greater where it was absent, indicating how moisture evaporation from exposed soil increased the difficulty for root penetration (Powers and Fiddler 1997). Compaction increased soil strength by an average of 1.5 MPa during the growing season and conifer growth was reduced severely (Gomez et al. 2002a; Powers and Fiddler 1997). Experience gained at Challenge and expanded to other sites led us to recommend the recording penetrometer as an important tool for operational soil quality monitoring (Powers et al. 1998). Carbon research at Challenge and subsequent LTSP sites established that isotopic ratios of ^{13}C to ^{12}C were sensitive indicators of cumulative water stress from soil compaction (Gomez et al. 2002b).

The Challenge LTSP experiment was the first to demonstrate that competing vegetation can mask the fundamental effect of soil compaction. Because compaction can reduce the density and abundance of returning vegetation, auger-planted trees growing in compacted soils may find less competition for soil resources (Powers and Fiddler 1997). By eliminating competing vegetation, the detrimental effect of soil compaction on tree growth was apparent. Subsequent studies revealed that depending on soil texture and climate, moderate soil compaction may reduce, promote, or have little effect on tree growth because of changes in pore size and water retention (Gomez et al. 2002a; Powers et al. 2005)—possibly the first report of this in forestry, and one of international significance.

23.4.3 Marcell Experimental Forest

Established as a formal research site in 1962, the 898-acre Marcell Experimental Forest focused on both small-plot and watershed-scale research in several forest types of fire origin, including *Pinus banksiana* and *P. resinosa*, and mixed stands of *Picea mariana, Larix laricina, Betula* spp., and *Populus* spp. Granite and gneiss

Fig. 23.10 Litter removal "party" at Marcell Experimental Forest. *Left* to *right*: Peter Roussopoulos, David Lothner, and Donald Boelter, research administrators at the then North Central Research Station

underlay glacial tills of clay, sand, and gravel. Upland soils are sandy to clayey, and lowland soils are humic, including peatlands. Marcell is dominated by a continental climate with moist, warm summers and cold, dry winters with abundant sunlight. The site was adjacent to the first NADP site in the nation which had been operating since 1978. And, of course, the Experimental Forest had both the forest type (aspen) and soil type (moderate moisture holding capacity) we sought for beginning the study.

23.4.3.1 Approach

Because the study would require substantial commitment of personnel and capital for an extended period, we presented several seminars describing the proposal to all interested parties. Helpful in selling the program in the Lake States was that it was a nationwide effort and that all parties were interested in answering the basic questions of the impacts of soil changes on site productivity. We selected a unit of 70-year-old mixed hardwoods dominated equally by *Populus tremuloides* and *P. grandidentata*. Field treatments began in February 1991.

Our aspen site on the Marcell had several characteristics that simplified treatment operations. To minimize unwanted soil compaction, logging was done in winter when the soil was protected by 12 in. of frost capped with 17 in. of snow. Trees were leafless during harvest, so we were restricted to whole-tree removal and whole-tree plus forest floor removal. Reforestation was simplified because of the natural suckering of aspen, and it regenerates to such a high density that understory vegetation control was not considered. Spring was approaching, providing us a narrow window for installing treatments.

To consolidate support, we hosted a postharvest "litter removal party" on the Experimental Forest and our guests included several Station administrators (Fig. 23.10). Snow fell the night before litter raking began. It melted by midday, but the litter was left damp and heavy enough to tax office-softened muscles. Other attendees included representatives from the Forest Service Washington office, the Eastern Region office in Milwaukee, and others from the North Central Forest Experiment Station and all the forests on which future plots were to be established. The hard physical work and the evening discussions created enthusiasm for the study and helped establish "buy-in" and favor future cooperation and funding.

Soil compaction was accomplished using the "Wobble Wheel" method used at Palustris Experimental Forest, but breakdowns were frequent. The challenge faced at Marcell was keeping the Wobble Wheel working on our plots and out of the repair shop. Two unharvested plots were retained, and these are remeasured on the same schedule as our treated plots. Treatments were completed and the experiment was established on May 29, 1992.

The Marcell Experimental Forest was the pilot for techniques we applied over the next 3 years to replicated plots on other forests. At Marcell, we learned that compaction with a Wobble Wheel as used at Palustris was not very effective, and we shifted to a front-end loader at all other installations. Our Marcell experiment afforded good estimates of the effort needed to remove the forest floor from the other sites which previous to the Marcell experience was nearly impossible to estimate.

23.4.3.2 Important Findings

Our Marcell LTSP site was not meant as a stand-alone experiment, but merely the pilot in an extensive series throughout the aspen forest of the Lake States. Still, some results are notable. While compaction at Marcell significantly increased soil strength and soil bulk density, essentially no recovery was found in the first 5 years following treatment (Stone and Elioff 1998). By 15 years, some recovery had occurred, but soil strength and bulk density were still considerably greater than pretreatment levels. Total vegetation biomass 15 years after harvest showed that both forest floor removal and soil compaction had major effects, supporting those observed earlier (Alban et al. 1994). Plots with compaction or forest floor removal averaged 31 % less vegetation biomass than plots without these treatments.

23.4.4 Priest River Experimental Forest

Located on a western spur of Idaho's Selkirk Mountains, Priest River was established for research in 1911, placing it among the earliest Experimental Forests in the nation. Encompassing 2,400 acres, Priest River describes a cool, temperate forest with a modified maritime climate. Annual precipitation averages 32 in., falling mainly as winter snow. Soils include volcanic ash deposits over granitics and metamorphic Precambrian rocks of the Belt Series. We were presented a list of three candidate sites on the Experimental Forest that might meet our needs. All were even-aged, mixed stands of *Pinus monticola, Larix occidentalis,* and *Pseudotsuga menziesii* of harvest age. After inspecting these stands, we enlisted the aid of the

Priest Lake Ranger District Supervisory Forester and the Idaho Panhandle National Forest Soil Scientist. This group (District, Forest, Experimental Forest, and Research Scientist) reached consensus on an initial site after visiting each stand and conducting initial soil surveys.

23.4.4.1 Administrative Hurdles

We found that the experimental design and criteria for establishing plots with no compaction and removing slash and surface organic matter would be difficult to administer under current timber sale standards. The Supervisory Forester had to author a set of special provisions for the sale contract to ensure rigid adherence to the overall LTSP study design. This took considerable time at the Ranger District, but provisions were set soon enough to advertise the sale and begin logging in fall 1991.

23.4.4.2 Approach

The Priest River Experimental Forest site was ideal from a soils perspective. It is a level area adjoining the Priest River, has a deep (30 cm) volcanic ash-cap over lacustrine sediments, and had few coarse fragments in the surface soil. Because the soils were fairly uniform, we concerned ourselves with ensuring that the aboveground components were also fairly uniform. During the summer of 1991, temporary 1-acre plot boundaries were established in the areas that had similar tree diameter distributions and understories. Soil samples were collected on a 66-ft (20 m) grid to a depth of 12 in. (30 cm). Understory vegetation was characterized by type and samples were collected for total biomass. *Armillaria* spp. root disease also was a concern, so all plots were surveyed preharvest, and one treatment plot had all stumps pulled to see if we could rid that plot of *Armillaria* infection. Forest floor samples were collected at each soil sampling point and analyzed for dry mass and nutrient content. Five downed wood transects were completed in each treatment plot.

In early fall 1991, after all the preharvest soil and vegetation samples had been collected, work began to clear a landing/staging area and to improve the approach of the haul road to the county road. All buffers were harvested first and trees were felled directionally to avoid damaging a study plot. Buffers were harvested before study plots and slash was piled outside the plot boundaries where appropriate. Because harvesting equipment was excluded from plots, we established a skid trail down the center of each plot so that a grappler could reach and extract trees. Logging was halted when fall rains and snow made completion impossible without damage to the study plots. Logging resumed the following spring and the sale was completed.

The next hurdle following harvest was applying LTSP treatments. With some adjustments, surface organic matter removal was straightforward where compaction was intended. Our plan was to use a bulldozer to mechanically pile slash and surface organic matter off the plot, but we found that pushing materials with a dozer

Fig. 23.11 Both research and national forest personnel monitor logging operations. Close cooperation in monitoring is critical to success

blade gouged the soil and caused tracks to spin and mix the surface mineral soil. Thus, the operator was instructed to back drag the blade (traveling in reverse with the blade down) and this achieved the desired objectives (Fig. 23.11). The plot was then compacted and, if required, organic matter replaced with a grapple arm. On plots with organic matter removal but no compaction, we used the grapple arm to remove what could easily be reached and we hand-raked the rest. Materials were carried from the plot on tarps and then returned following compaction. Compaction level was monitored after each equipment pass so that we could achieve the levels of compaction necessary for the study. Stumps made uniform compaction difficult and the bulldozer had to drive closely on all sides to compact the soil.

Plot treatments were completed in late April 1992 and tree planting began in May. Researchers placed the trees on an 8 × 8-foot grid and seedlings were dibble planted through the organic matter. No "scalps" were created and in some cases, trees were planted directly into decayed (class V) logs. *Pinus monticola* and *Pseudotsuga menziesii* were double planted in pure blocks in each quarter acre. After 2 years, the inferior tree was rogued from the double plantings.

23.4.4.3 Subsequent Treatments

Naturally occurring understory vegetation was controlled with hexazinone on half of each treatment plot in the first year and double-planted trees were rogued in the third year by removing the least vigorous tree. Plots have been remeasured at regular 5-year intervals.

23.4.4.4 Important Findings

The Priest River installation was a single replicate and not meant to stand alone, but one clear finding was how readily the volcanic ash-cap soil could be compacted.

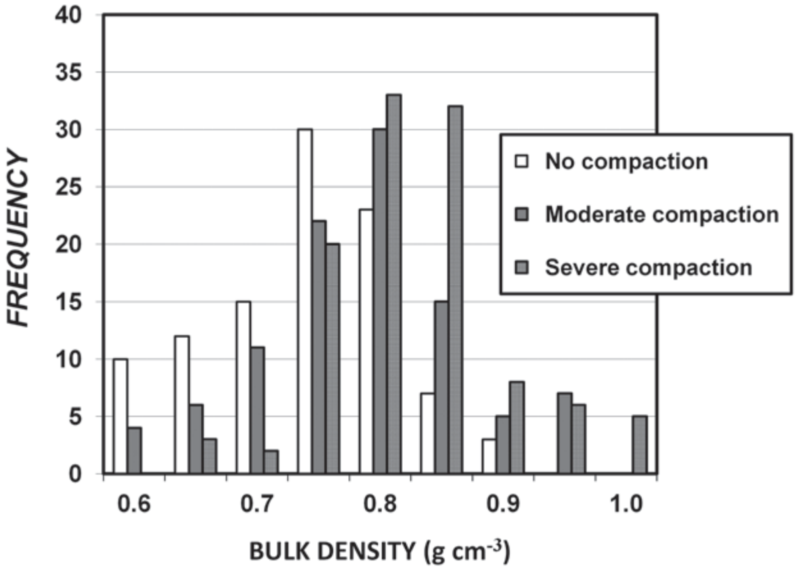

Fig. 23.12 Change in distribution of ash-cap soil bulk density in each compaction treatment at the Priest River Experimental Forest

Fewer than five passes were needed to achieve moderate compaction on this fine-textured soil, and fewer than ten passes achieved severe compaction. The ash-cap soil has a very low bulk density (0.6–0.7 Mg m^{-3}), and bulk density increased ~60% above preharvest conditions on severely compacted plots (Page-Dumroese et al. 2006). Work detailed the first intensive information on how the distribution of compaction (measured by bulk density cores) changes after deliberate compaction (Fig. 23.12), and established the soil-monitoring value of a recording soil penetrometer in ash-cap soils (Page-Dumroese et al. 2006; Johnson et al. 2007). Additionally, the LTSP installation on ash-cap soils was key to our finding of relatively minor short-term impacts on tree growth from compaction (Fleming et al. 2006) but large impacts on ectomycorrhizal colonization (Amaranthus et al. 1996). Data from this site also launched a northwest-wide workshop and proceedings on the properties and management of ash-cap soils (Page-Dumroese et al. 2007). Information from this installation has helped define the characteristics of ash-cap soils in revising regional soil quality standards.

The Priest River LTSP installation also was the first in a global series of studies that used a standard substrate (*Pinus taeda* and *Populus tremuloides*) in the mineral soil to evaluate compaction and organic matter removal impacts on belowground decomposition processes (Jurgensen et al. 2006). Current literature on litterbag studies suggested that clearcutting slowed decomposition on the soil surface and that unharvested stands had much faster surface decomposition rates. However, our work showed that decomposition accelerated in the mineral soil in the harvested plots, particularly the compacted plots, because—unlike soil surface conditions—

soil moisture was usually higher. In the uncut stand, mineral soil temperatures usually were cooler, thereby slowing decomposition rates (Collins 2009).

23.5 Lessons Learned

Our collective experience in establishing a large-scale field experiment using four Experimental Forests as trial horses led to agreement on points that should be helpful to future scientists contemplating manipulative experiments on federal lands and perhaps beyond. We group them into three categories.

23.5.1 Administrative and Philosophical Issues

- Experimental Forests have a major advantage over other federal lands because they are dedicated to research and demonstration, which may streamline the NEPA process.
- Success for a national network requires both vertical and horizontal buy-in from research scientists and the local Ranger Districts, vertically through research and administrative arms of the USDA Forest Service in Washington.
- “Grassroots” studies can expand to national and international scope if the concept is appealing, there is careful planning, and there is commitment from a cadre of individuals treated as peers.
- Innovation, rather than rigid conformity, is a critical element because it sparks creativity.
- To endure, experiments must have attributes robust enough to address concerns important now and in the future.

23.5.2 Technical Installation Issues

- Research must be involved directly with developing contracts for accomplishing the various tasks as well as overseeing all on-the-ground operations.
- Pretreatment sampling of prospective treatment plots is important. Watch for microrelief subtleties suggesting localized poor drainage once the existing forest is harvested and the transpiration pump is gone.
- To provide adequate buffers and staging area, the candidate area for an LTSP installation needs a total area twice to three times that needed for treatment plots.
- Buffers should surround a treatment plot. The minimum practical width is 20 ft. Buffers should be logged before the treatment plots.
- Daily inspection of contracted field work is critical.
- Submerchantable stems should be felled prior to felling large trees in a treatment plot. Felling large trees atop smaller trees cushions the impact, reducing unwanted compaction and ground damage during yarding operations.

- Directionally fell all large trees toward the nearest plot side by premarking the direction of fall and jacking trees as necessary to ensure this.
- To achieve the desired compaction levels, test strips must be established at each new site because soil types differ.
- Soil compaction cannot be achieved satisfactorily if logging slash or forest floors are present.
- Soil compaction can be followed with soil penetrometer measurements to quickly assess the uniformity of compaction.
- Slash and forest floor should be scalped at each planting spot to enhance seedling survival. Otherwise, air pockets may be created in the planting hole, leading to seedling mortality in a droughty climate.
- Herbicides are the most effective means for controlling unwanted vegetation in trees-only plots. Hand grubbing or mowing will be ineffective and will require yearly maintenance.

23.5.3 Issues Involving Subsequent Measurements

- If scheduled measurements cannot be accomplished with research personnel, they can be handled efficiently with service contracts, provided that (1) quality control standards are built into the contract; (2) there is continual Forest Service inspection; and (3) there is rapid turnaround in quality control of collected data.
- Use multiple-year contracts for data collection. This allows the same contractor to become familiar with standards and apply these same standards evenly to all sites.
- Contracts must include remeasurement penalties for inaccurate data. This illustrates the need for timely quality control.

23.6 Summary: The Pivotal Role of Four Experimental Forests

The Palustris, Challenge, Marcell, and Priest River Experimental Forests were pilots for LTSP. Unique treatments were applied in strange combinations, and we had no precedent for how to install them efficiently. Experimental Forests gave us the freedom and flexibility needed for innovation and daily adjustments, and offered unique advantages. Each Experimental Forest came with a charted history of treatment and forest development. Further, categorical exclusions for research of limited extent reduced the time and cost spent in the NEPA process. Unless we recognize the importance of this independence, the value of Experimental Forests will be lessened. Each forest had sufficient infrastructure (good roads and in several cases lodging, office, storage, and laboratory facilities) to expedite the work. And in all cases, Experimental Forests afforded administrative stability and exceptional protection from intrusion. They also have high visibility and draw many visitors each year from scientific, professional, and lay sectors of society. They are showcases for both past and ongoing research.

We proved that a grassroots effort by a small cadre of motivated individuals could expand to a major network if you believe strongly enough in the cause. The LTSP effort stands as an extraordinary example of collaboration between research and management arms of the USDA Forest Service at all levels. Our collective experiences gained on these four Experimental Forests set a research trajectory that has bridged affiliation boundaries and even political borders, and our efforts have influenced other programs. Coordination for the National Fire and Fire Surrogate Study (Weatherspoon 2000) was patterned on the successful organizational structure of the LTSP network. Internationally, the Center for International Forestry Research coordinated a sustainable productivity research network in short-rotation tropical plantations patterned on LTSP and a similar program in Australia. Core treatments involved several intensities of organic matter treatment (Tiarks et al. 1998). In common with LTSP, each site had a complete set of treatments that could be analyzed independently of other sites. And based on the experience of LTSP, workshops were held every 1–2 years to coordinate the research. Proceedings of these workshops were published by CIFOR, the latest in 2008 (Nambiar 2008).

Several major questions remain: (1) Will soil properties return to pretreatment levels? (2) How will soil compaction and organic matter removal, applied as a pulse disturbance, effect total biomass yield at the end of a rotation? (3) How do we maintain the essentials of a long-term experiment in the face of an economic crisis of unprecedented proportion?

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