The North American Long-Term Soil Productivity Study: Collaborations to Understand Forest Responses to Land Management

Deborah S. Page-Dumroese[1]

ABSTRACT.—The Long-Term Soil Productivity (LTSP) Study is one of the most successful and extensive collaborative science efforts undertaken by the USDA Forest Service. It was launched through a back-of-the-bus conversation about problems arising from the National Forest Management Act of 1976 and rose as a grassroots effort to determine how soil compaction and organic matter removal are linked to both tree and stand productivity. It has sparked collaborations at all levels of the agency and with universities, non-profits, and other research organizations, nationally and internationally, with the common goal of sustaining forest productivity in perpetuity while continuing to provide ecosystem services after timber harvesting.

BACKGROUND

The National Forest Management Act of 1976 (NFMA) mandated that national forests be managed without impairment of the productivity of the land (USDA Forest Service 1993). This included a call for the USDA Forest Service to conduct the research, monitoring, and assessment to ensure sustained yield in perpetuity while protecting all resource values. Furthermore, one key section of the resulting framework was that the Forest Service was required to monitor the effects of forest management prescriptions. The need for monitoring presented a problem because the monitoring work had not been completed on a comprehensive level. Monitoring the effects of forest management was the topic of discussion in 1989 during a field tour on which the Forest Service National Soils Program Leader for the National Forest System arm of the Forest Service remarked to scientists from the Research branch that the national soils program needed help. This grassroots effort started the North American Long-Term Soil Productivity (LTSP) Study (Powers 2006; Powers et al. 2005, 2014) and it predated many other national and international efforts at sustainable forestry or green certification by more than a decade.

Once the Forest Service, with help from the Office of General Council, defined *land productivity, carrying capacity,* and *significant change* (Powers et al. 2014), the decision was made that a productivity decline of 15 percent or greater would have to occur to be measureable under operational conditions (USDA Forest Service 1987). But how do you monitor these changes? The Watershed and Air Management division of the National Forest System (NFS) took the lead with the philosophy that:

- Management practices create soil disturbance.
- Soil disturbance affects soil and site processes.
- Soil and site processes control forest productivity.

At this same time soil quality standards were being developed across national forests, but there were no clear baselines or agreement on what constituted enough soil disturbance to result in a decline in forest productivity. During the development stages of LTSP an extensive literature

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[1] Research Soil Scientist, USDA Forest Service, Rocky Mountain Research Station, 1221 South Main, Moscow, ID 83843. To contact, call 208-883-2339 or email at debbie.dumroese@usda.gov.

review revealed that forest productive capacity declined when there were soil organic matter losses or a decrease in soil porosity (compaction). Both compaction and organic matter loss can be managed through silvicultural prescriptions and forest management, but it was unclear where to draw the lines.

In 1988, a study plan for a national, coordinated research project to determine the long-term effects of soil disturbance on fundamental (including both understory and overstory growth and diversity) forest productivity was sent to Forest Service research silviculturists and soil scientists and their counterparts in Regional Offices, as well as scientists at universities and other research organizations. The study plan was the most widely reviewed of its kind in the history of the Forest Service (Powers et al. 2014)! Finally, in 1989 the study plan was presented to the joint Deputy Chiefs for NFS and Research and Development (R&D) and was approved. Installation costs were covered from excess timber sale receipts administered through the Washington Office and Forest Service Regional Offices.

THE COLLABORATIONS BEGIN

At each installation, the initial collaborations involved the principal investigator from many of the Research Stations and the Regional and Forest Soil Program managers and silviculturists from the participating Forest Service Region. National oversight was provided by four members of the Washington Office representing timber and soil interests—two from R&D and two from NFS. This oversight committee, Regions, and R&D scientists helped identify soil and forest types to help focus the LTSP experiment and encouraged cooperation among participating National Forests and Ranger Districts. Once sites were chosen, the collaborations extended to local foresters, soil scientists, hydrologists, and timber sale administrators. It also extended to universities and other research organizations because this study resulted in well defined treatments that could be used for large- and small-scale studies. In addition, many researchers wanted to work on these study sites because they were installed on national forests and could be counted on to be maintained for longer than a few years.

Because LTSP focused on commercial forest types, NFS personnel were essential to the success of this endeavor. Study sites were selected based on the presence of soil that supported productive, mature forests typifying those under management. Once sites were identified by NFS, pretreatment data were collected (e.g., soil bulk density, forest floor depth, downed wood, understory biomass, overstory height, and diameter). Plots were laid out and treatments were implemented following a standard template of three levels of organic matter removal (bole only, whole tree harvesting, and whole tree harvesting plus forest floor removal) and three levels of compaction (none, moderate, and severe). Plots size was 1 acre (0.4 ha).

Harvest operations were administered by NFS. Often trees were directionally felled to reduce the impacts on soils. In general, the plots were harvested, treatments installed, and trees planted. Many of the sites also used herbicide on one-half of each plot to measure tree growth only and the other half was allowed to regenerate with a natural understory to measure overstory and understory growth. Responses were measured as dry matter production over time (net primary productivity).

There were no historical guidelines for how to go about installing a replicated study of such large scope. Therefore, the oversight and regional committees agreed that Experimental Forests would be the sites of the pilot installations. Experimental Forests in the Southern, Pacific Southwest, North Central, and Intermountain Research Stations were selected. The benefit of using Experimental Forests is that they are under the jurisdiction of the Research Stations, so treatments could be easily installed, have high visibility, and have a close rapport with Ranger District and NFS personnel. Experimental forests also have lodging available, thereby reducing the cost of travel.

SOME ADMINISTRATIVE HURDLES

As might be expected with a large-scale field experiment, each researcher at each experimental forest had to deal with a few hurdles. However, the collaborative effort and support from R&D, NFS, industry, and universities helped overcome these hurdles. For example, NFS had to deal with logistical issues related to how to harvest trees while limiting logging equipment to buffer areas or how to effectively compact the soil over a large 1-acre plot. Many researchers also depended on university collaborators to help with graduate students or laboratory space. Furthermore, our industry collaborators were able to include harvest and site preparation practices that were new and innovative.

THE COLLABORATION EXPANDS

It wasn't long after the first four study sites were installed that our colleagues in Canada began installing similar study sites in British Columbia and Ontario. The installation at the Priest River Experimental Forest is a replicate for two study sites in British Columbia, and data and samples are shared with Canadian research colleagues. Furthermore, there are international LTSP installations in China and Australia (Smaill et al. 2008). The grassroots LTSP effort that was started by a small cadre of motivated researchers and forest managers has now expanded into a major network. It is an extraordinary example of collaboration between research and management arms of the Forest Service that has expanded to include colleagues and partners from various land management agencies, industry, and universities and is a model for how an elegant experimental design can draw in partners. The collective experiences gained from the first few installations set a research trajectory that bridges affiliations and political borders.

HAS LTSP IMPROVED LAND MANAGEMENT?

Forest development is a slow process and so making sense of the data has also been slow. However, in 2006 many of the researchers produced a special issue in the journal Forest Ecology and Management that summarized the first decade of data from 26 installations in the United States and Canada. In these papers the group noted several key responses to the treatments:

- Complete removal of the surface organic matter resulted in a decline in soil C concentration to a depth of 20 cm and reduced nutrient availability after 10 years (Powers et al. 2006), but this was not detected at the 5-year measurements (Sanchez et al. 2006). Furthermore, removal of the surface organic matter had a greater impact on CO2 efflux than clearcut harvesting (Fleming et al. 2006a).
- Biomass removals during harvest operations had no influence on forest growth through 10 years (Powers et al. 2005).
- The amount of compaction that could be achieved was dependent on the initial bulk density; sites with a high initial bulk density could not be compacted as much as those with a low initial bulk density (Page-Dumroese et al. 2006).
- Soil density recovery was slow in soils with a frigid temperature regime and at depths up to 30 cm (Page-Dumroese et al. 2006).
- Microbial biomass, respiration, and fungal phospholipid fatty acids declined after harvesting in a Mediterranean-type climate (Busse et al. 2006).

- In the southeast, a bulk density increase of less than 10 percent resulted in a significant reduction of loblolly pine (Pinus taeda L.) growth (Carter et al. 2006).
- Soil compaction combined with intact forest floors generally benefited conifer survival and growth, regardless of climate or species. In addition, compaction with forest floor removal generally increased survival but had limited effects on individual tree growth (Fleming et al. 2006b).

In addition, Cline et al. (2006) notes that there were five key findings after the first decade that have a direct impact on forest management and soil quality: (1) surface organic matter is the link between most management systems and sustainable site productivity; (2) nutrient deficiencies can be corrected; (3) soil texture is the key variable that affects surface and mineral soil organic matter and site productivity; (4) tree residues left on-site enhance soil organic matter; and (5) productive, healthy forests provide many ecosystem services. Page-Dumroese (2010) published a list of publications (over 200) associated with the LTSP sites that highlight the benefits of this study to management and research.

Since 2010, several more studies have been published. For example, in a summary of 45 of the LTSP installations in North America, Ponder et al. (2012) indicated few consistent effects from both organic matter removal and compaction. Furthermore, combining the loss of surface organic matter with severe compaction resulted in lesser gains in planted tree biomass production. In California, the 12 LTSP installations there had a 15 percent increase in planted tree biomass on a plot-scale basis, which was attributed to improved seedling survival and reduced competing vegetation on plots with understory vegetation control (Zhang et al. 2017). Longer-term measurements from the LTSP network show that in aspen (*Populus tremuloides*) stands in the Lake States region, forest floor removal resulted in soil carbon (C) and calcium reductions over a 20-year period, which may have resulted in reductions in aspen growth that were not noted during previous measurements (Slesak et al. 2017). Consistent changes in microbial populations on harvested sites indicate that there was an expansion of desiccation- and heat-tolerant organisms and a decline in ectomycorrhizae on plots with organic matter removed from sites that were 11 to 17 years old (Wilhelm et al. 2017). These results make it clear that early results may not dictate the trajectory of stand growth for an entire rotation, results across numerous sites may be variable, and the later expression of site changes may have significant impacts on potential site productivity.

ORGANIC MATTER REMOVAL

For many years, land managers have known about the importance of coarse wood for many ecosystem services (e.g., infiltration, water quality, biodiversity; Rochelle 2008). The LTSP program has shed additional light on the importance of also maintaining the forest floor throughout harvest operations across many ecosystems. Removal of surface organic matter had a statistically significant impact on soil C concentrations after one decade (Powers et al. 2005) and this 10-year finding is different from the work in North Carolina where there were no declines in soil C among the treatments after 5 years (Sanchez et al. 2006). Other studies have shown that retaining surface organic matter can also reduce soil temperature and evaporative moisture loss (Li et al. 2003, Powers et al. 1998).

LTSP has shown that maintenance of surface organic horizons is important for nutrient and carbon cycling, but also to maintain tree growth. However, the relationship between surface organic horizons and tree growth is different on some sites. For example, Alban et al. (1994) showed that aspen responded to organic matter removal by generating a high density of root suckers after the first year, but by the third year, most of these had died from increased competing vegetation. Scott et al. (2004) found that bole volumes at year 5 in Mississippi were 40 percent lower on plots with all the surface organic matter removed as compared to those where it was retained; after 10 years the difference was only 29 percent. On these plots, declines in productivity were associated with the reduced availability of soil P (Scott et al. 2004). In California, after 5 years there were no differences in tree biomass, periodic annual increment, or competing vegetation on any of the organic matter removal plots. Vegetation control, however, was the single most important factor affecting tree biomass after 20 years (Zhang et al. 2017). The LTSP results illustrate the value of long-term studies spread across numerous forest and soil types; early or site results may or may not forecast long-term trends or results from other sites.

COMPACTION

When compacting the plots, we set out to have study plots with a clear difference between the moderate and severe compaction level, but the end result was a small difference between these two levels across many soils and sites (Page-Dumroese et al. 2006). This is because some soils already had a high bulk density (1.4 Mg m^{-3} or greater) and could not be readily compacted beyond this level. Compaction was carried out when the plots were at or near field capacity. Therefore, once macropores are compressed, further compaction was difficult because the micropores were filled with water. Soils with the lowest recovery rates are in Idaho, Michigan (clay soils), and Minnesota—all sites with a frigid soil temperature regime. This means that the freeze-thaw cycle in cool temperate or boreal life zones is not particularly effective at remediating compaction below 10 cm (Page-Dumroese et al. 2006).

On the North Carolina sites, soil bulk density on fine loamy soils increased by 0.34–0.54 Mg m^{-3}, which resulted in reduced root aeration and impaired tree growth (Sanchez et al. 2006). In California, soil moisture storage on clay soils was substantially reduced by compaction and reduced tree growth (Powers et al. 2006). Effects of soil compaction are generally related to soil texture with the greatest reductions in tree growth occurring on fine-textured soils; clayey soils had the greatest volume loss, loamy soils (including volcanic ash-cap soils) had intermediate growth reductions, and sandy soils generally had growth increases due to compaction. The increased growth on sandy soils is associated with an increase in available water storage in micropores (Powers et al. 2006).

SOIL MONITORING

In forestry, there is a strong link between science and policy and the science must be translated into tools for a wide audience. When NFMA was signed it, along with several other Acts (e.g., NEPA, Clean Water Act; Cline et al. 2006), they set forth three points that supported the need for a long-term soil monitoring program. The first was that land management should not produce substantial and permanent impairment of site productivity. Second, trees should only be harvested where soil, slope, or watershed conditions would not be irreversibly damaged. Third, tree cutting should protect soils, watershed, fish, wildlife, recreation, and esthetic resources, and the regeneration of trees. From language in NFMA, the Forest Service was the first land management agency to develop soil quality standards, but they were not perfect! Blanket soil quality standards were used in nearly every Forest Service Region and little validation had been done to determine if they were adequately assessing changes in long-term productivity (Page-Dumroese et al. 2000). The soil quality standards usually reflected best professional judgment rather than documented evidence and were intended as early warning signs rather than absolute limits (Powers et al. 1998). As the LTSP Study was being developed, soil quality standards were also being tested in several lawsuits. Therefore, when the request for a coordinated LTSP effort to determine how soil organic matter loss and compaction altered productivity came to R&D, it was the perfect opportunity to test soil quality indicators and validate the standards.

One tangible product of the LTSP study that helps land managers was the development of a reliable, cost effective, statistically valid, and easy-to-use soil monitoring protocol. This protocol leveraged the findings of LTSP in the United States and Canada, work done developing uniform and unambiguous definitions for soil disturbance categories that relate to stand productivity and hydrologic function (Curran et al. 2007), and the pioneering efforts in the Pacific Northwest Region to develop visual disturbance classes (Howes et al. 1983). The Forest Soil Disturbance Monitoring Protocol (FSDMP) was developed as a multifaceted tool that uses visual disturbance classes and a standard method for collecting data (Page-Dumroese et al. 2009). One advantage of a consistent tool is that all disciplines or the public can use it and get similar results. The FSDMP considers soil resilience coupled with the degree, duration, distribution, and location of disturbance. It provides useful indicators of a change in soil disturbance level that can be linked to LTSP findings or more local validation data. Several authors (Burger and Kelting 1999, Heninger et al. 1997, Kneeshaw et al. 2000, Powers et al. 1998) have identified attributes of indicators for sustainable forest management and soil monitoring, and many of these were incorporated into the FSDMP. The FSDMP is scientifically sound, operationally feasible, socially responsible, and credible, and uses a common language and standard method. This makes the results easy to interpret and to link to silviculture prescriptions so that best management practices can be developed for current and new harvest technologies.

WHERE DO WE GO FROM HERE?

The LTSP collaborative effort has proven that a grassroots effort led by a small group of motivated forest managers and researchers could expand into a major network. It stands as an exceptional example of research and management collaborations for shared stewardship of vegetation, soil, and water resources of the Forest Service at all levels of the agency and this research is internationally recognized. Our accomplishments bridge affiliations and political boundaries, have influenced other programs in the United States and abroad, and have resulted in tangible benefits to national forest management and the public.

After 20 years, the LTSP results suggest that forest site productivity in North America is generally highly resistant and resilient to a one-time clearcut harvesting, compaction, and organic matter removal disturbance. Overall, results of planted seedlings and soil properties have shown consistent results from biomass and organic matter removals. This large network of sites has improved our knowledge of both continental and local-scale fundamentals of sustaining forest growth and soil health and has informed regional-to-local guidelines regarding forest harvesting and biomass removal (or retention) levels.

We still have some unanswered questions including: (1) Will soil properties return to predisturbance levels within a rotation? (2) How will soil compaction and organic matter removal, applied as a pulse disturbance and/or with intermediate thinning, affect total biomass yield at the end of a rotation? (3) How do we maintain these study sites into the future in the face of limited budgets? These questions are essentially the same ones asked by Powers et al. (2014). Our network continues because Forest Service, universities, and international partners have skin in the game and will collect core data as best they can, when they can. But longer-term funding and a new cadre of Forest Service managers and researchers are still needed to ensure that each site is intact to reach rotation age.

The LTSP Study sites continue to evaluate how management activities, specifically timber harvesting, compaction, and organic matter removal, influence ecosystem function across diverse sites. As such, they are particularly valuable for determining local impacts on soil physical, chemical, and biological properties. Our initial hypothesis that impacts would be universal has not played out and points out the value of repeated sampling to demonstrate decadal scale processes. We have informed policy decisions and land management to ensure sustained forest productivity, biodiversity, and clean, consistent water supplies. Continued measurement of these sites will lead to understanding how future environmental stressors (e.g., climate change, additional harvesting) might alter both aboveground and belowground productivity.

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