Initiating Long-Term Soil Productivity Research in Missouri

Felix Ponder, Jr.

Abstract.—Management practices necessary for sustaining long-term soil productivity (LTSP) of forest lands are being defined from a network of coordinated, long-term experiments established in various ecosystems across the United States and British Columbia according to the same basic study plan. The study was established in the Ozark Region of southeastern Missouri in Shannon County in 1995. It is being led by Forest Service Research, with cooperation from the Mark Twain National Forest, Missouri's Department of Conservation and Department of Natural Resources, the Natural Resources Conservation Service, and the University of Missouri. The impacts of treatments on soil productivity and site quality will be periodically evaluated over the life of the regenerating stands at the study site. This report summarizes some of the pre-treatment data, mortality, and nutrient concentrations in herbaceous vegetation.

Results from long-term soil productivity (LTSP) studies are necessary for the development of land management practices that will sustain forest productivity in the Central Hardwood Region. Sustaining or increasing the productivity of forest land is also essential because the acreage of commercial forest is declining due to environmental constraints, increased recreational uses, and other uses while demands for timber products are increasing. Also of concern are the effects of heavy equipment (Woodbury 1930) and whole-tree harvesting (Hornbeck and Kropelin 1982) on soil productivity. The use of heavy equipment and whole-tree harvesting affect soil porosity and soil organic matter, which are believed to be the primary properties controlling forest productivity and the most impacted by forest harvesting activities. The LTSP program is based on three specific questions:

1. Are management practices degrading the long-term productivity of the land?
2. What are the principal soil processes involved?
3. Can detrimental effects be overcome by mitigation?

[1] Supervisory Research Soil Scientist, USDA Forest Service, North Central Forest Experiment Station, 208 Foster Hall, Lincoln University, Jefferson City, MO 65102.

The answers to these questions when used in conjunction with the latest soil survey information will provide a foundation of scientific knowledge to highlight site limitations and to provide interpretations for sustainable use over extensive areas.

High public interest in forest health and in the ability of forests to sustain their inherent productivity has resulted in legislation (USDA Forest Service 1983) and policies (U.S. Code of Federal Regulations 1985) that ensure research and monitoring (USDA Forest Service 1987) of management systems to prevent the impairment of the land's productivity. The 1990 National Research Council (NRC) identified critical areas of forestry research in the U.S. that needed to be strengthened, and the 1995 NRC's Forestry Research and Educational Initiative Implementation Committee recommended an initiative to focus on soil properties, processes, and plant-growth relationships as fundamental to sustaining managed forest ecosystems.

The summation of these concerns, policies, and legislation about the impacts of management activities on National Forest lands led to the initiation of a joint National Forest System/ Forest Service Research study to "evaluate timber management impacts on long-term soil productivity." The study plan calls for three levels of organic matter removal (bole only, total tree, and total aboveground biomass) and three levels of compaction (none, medium, and severe). The objectives of the program are to: (1) quantify the effects of soil disturbance from management activities on long-term soil productivity; (2) validate soil monitoring standards developed in compliance with the National Forest Management Act of 1976, which requires research and monitoring of Federal lands to safeguard the productivity of forest soils; (3) learn more about the fundamental relationships between soil properties, long-term productivity, and forest management practices; and (4) evaluate the potential for mitigating the adverse effects of disturbance.

Evidence of this interest and cooperation is exhibited in the Forest Service LTSP study that was installed in 1995 on Missouri Department of Conservation land in the Ozark Region of southeastern Missouri in Shannon County. The study is being led by Forest Service Research, with cooperation from the Mark Twain National Forest, Missouri's Departments of Conservation and Natural Resources, the USDA Natural Resources Conservation Service, and the University of Missouri. The cooperative research effort is designed to: (1) to establish experiments that focus on key soil and site properties affected by management, rather than focusing on operational practices, (2) institutionalizing the effort so the study will be maintained, measured, and reported on through a rotation (80 to 100 years), and (3) establishing the study on the most important soil-species combination. Relating changes in growth potential of the regenerating stand to changes in site organic matter and soil porosity caused by treatments will permit us to estimate the magnitude of damage to forest productivity that has been generated by disturbance.

THE STUDY SITE

The site selection team included representatives from the cooperating agencies. The installation of the LTSP study involved choosing a forest type in the Central Hardwood Region, selecting a productivity gradient within the region, identifying individual sites, and applying treatments. The initial productivity gradient for the study included sites in Missouri, Illinois, and Indiana; the installations in those States represented low, medium, and high productive sites, respectively. However, because of budget constraints and the high cost of installation and maintenance, there are no plans to install the study in Illinois and Indiana.

The Missouri LTSP study is located in the southeastern Missouri Ozarks on the Carr Creek State Forest (Missouri Department of Conservation) in Shannon County. Before the site was selected, several preliminary soil surveys were made to locate the study area on relatively uniform soils. Soil pits were dug and soils were described and analyzed with cooperation from the Missouri Department of Natural Resources, the Natural Resources Conservation Service, the Mark Twain National Forest, and the University of Missouri. Field examination included estimation of depths to restrictive layers as well as horizon thicknesses, textures, and gravel content. Mean annual precipitation in the area is 112 cm (44 in.), and mean annual temperature is 13.3°C (56°F). The site occupies the upper sideslopes of two ridges with northeastern aspects. At the beginning of the study, the site was covered by a well-stocked, mature, second-growth oak-hickory forest. Site index ranges from 74 to 80 based on black oak (*Quercus velutina* Lam.) at 50 years (Hahn 1991). The oak-hickory timber type is the major timber type in the Central Hardwood Region, occurring over a variety of soils, relief, and stand conditions.

The sloping topography (20 to 28 percent slopes) has small shallow streams that contain exposed cobbles and stones. The area is underlain mainly by Ordovician dolomite, and areas of Cambrian dolomite and Precambrian igneous rocks are also present (Missouri Geological Survey 1979). The weathering of the Ordovician and Cambrian dolomite has resulted in a deep mantle of cherty residuum (Gott 1975). Soils derived from this residuum are primarily of the Clarksville series (loamy skeletal mixed mesic Typic Paleudults). Water drains freely through the soils into subsurface channels.

EXPERIMENTAL DESIGN

The LTSP study consists of nine treatments derived from combinations of three levels of organic matter removal and three levels of soil compaction:

Organic Matter Removal	Soil Compaction
Merchantable boles removed (bole only, **BO**)	No compaction (**None**)
All living vegetation removed (whole tree, **WT**)	Intermediate compaction (**Medium**)
All living vegetation removed plus forest floor, exposing mineral soil (whole tree + forest floor, **WT + FF**)	Severe compaction (**Severe**)

Severe compaction is defined as 80 percent of the difference between the hypothetical growth-limiting bulk density (Daddow and Warrington 1983) and the bulk density of the uncompacted soil. Medium soil compaction is intermediate between severe compaction and no compaction. Each of the nine treatment combinations was replicated three times. The national study plan suggests that supplementary treatments and an uncut control area be included when space and other resources are available. Consequently, physical and chemical plot variables are also being measured in an uncut area adjacent to plots in the present study.

The nine treatment combinations of organic matter removal and compaction treatments create a gradient in organic matter removal and compaction that covers most of the harvest-related disturbances found operationally. These nine treatments are shown in table 1.

Treatment plots are artificially regenerated with tree species normally managed on the site. Competing vegetation will be eliminated chemically and/or mechanically on one-half of each plot by the third year. The contrasting treatments will be used to measure net primary productivity, study how weeds may affect soil recovery rates from compaction, and determine the impact of weed diversity on tree growth and soil properties. Effects will be analyzed statistically after years three and five, and then at 5-year intervals thereafter by analysis of variance and by regression using soil, vegetation, and climatic variables.

Plot Layout and Pre-treatment Measurements

After determining that the key soil properties did not vary significantly across the selected area, we established preliminary plot boundaries. Three replicates of nine treatment plots approximately 0.4 ha (1 ac) in size were laid out randomly in the summer of 1993. Four-meter-wide buffer strips were included around all plots. All treatment plots are separated from residual forest by a cleared area that approximates or exceeds the height of bordering trees.

The pre-harvest inventory of the overstory, understory, herbaceous layer, and dead and downed woody material was completed in the summer of 1993 by the Missouri Forest Ecosystem Project (MOFEP) forester and the botany crew of the Missouri Department of Conservation. Overstory measurements were made on 0.2-ha (0.5-ac) circular plots. All trees living and dead standing 11.5 cm (4.5 in.) d.b.h. and greater were identified and d.b.h. was measured. All live saplings between 3.8 cm (1.5 in.) and 11.2 cm (4.4 in.) d.b.h. were identified and measured on four circular 0.02-ha (0.05-ac) plots located 17.25 m (56.4 ft) from the center

Table 1.—*LTSP treatments including the nine combinations of organic matter and soil compaction.*

	Organic matter removal		
Compaction	**Bole only**	**Whole tree**	**Whole tree + Forest floor**
None	BO None	WT None	WT + FF None
Medium	BO Medium	WT Medium	WT + FF Medium
Severe	BO Severe	WT Severe	WT + FF Severe

point in each cardinal direction (N, S, E, and W). Understory woody vegetation 1.3 cm (0.5 in.) but less than 3.8 cm (1.5 in.) d.b.h. and greater than 1 m (3.3 ft) tall was measured on 0.004-ha (0.01-ac) plots that were located within sapling plots. Dead and downed woody material greater than 5 cm (2 in.) in diameter and 0.6 m (2 ft) long was inventoried (species, maximum diameter, length, and decomposition class) along each of four line intercept transects 17.25 m (56.4 ft) in length. Herbaceous vegetation was identified and counted on four 1-m^2 (11-ft^2) plots that were located 6.1 m (20 ft) from the sapling plot center along NE, SE, SW, and NW transects: a total of 16 herbaceous plots were sampled within each 0.2-ha (0.5-ac) plot.

Biomass samples were collected for overstory canopy trees, understory saplings, ground vegetation, and leaf litter/humus layer. A total of 54 trees were selected, felled, and weighed in the field during the spring of 1994. Twenty-six saplings (d.b.h. < 10 cm) and 28 midstory and overstory trees (d.b.h. > 10 cm) were selected and total tree biomass was measured. Total height, d.b.h., basal diameter, and specific crown dimensions were measured on each tree. Trees with merchantable logs were sectioned in appropriate lengths; others were cut to 2-m lengths. Sawdust samples and wood disks were collected from the end of each log section. Fresh weights of all tree logs and crown portions were measured in the field. Some merchantable logs were too large to be weighed in the field (scale limit = 500 lb). Thus, detailed log dimensions were taken to estimate volume; weight was later predicted from laboratory samples. Fresh weights of all sawdust samples, wood disks, and crown subsamples were measured separately. Woody and herbaceous ground covers were clipped separately. Samples were collected before leaf drop in the fall of 1993. Leaf litter/humus samples were collected, and leaf litter was separated from humus material. All samples were dried at 105°C for 72 hours or until a constant weight was achieved. Each sample (sawdust, leaf litter, leaf, crown components, woody and herbaceous ground covers, and humus) was then ground to a fine powder in a Wiley Mill and analyzed for macronutrient and micronutrient content. Inventory and sampling procedures are further described in Ponder and Mikkelson (1995).

In addition to soil pits, soil samples were collected with a two-person power-driven coring device. Four intact cores (7.6 cm dia. x 40 cm long) (3 in. diameter x 16 in. long) of soil per plot were collected and partitioned by soil horizon for determination of bulk density, pH, organic matter content, hydraulic conductivity, and macronutrient content (Soil Survey Staff 1984, Page *et al.* 1982, Black 1965).

Timber Harvesting

Trees and biomass were removed according to protocols in the national LTSP study plan (Powers *et al.* 1989) by means that minimized soil disturbance. Trees were harvested over a 4-month period in 1994, beginning in February and ending in May. On plots designated as uncompacted, merchantable trees were directionally felled and removed with a skyline cable logging system. Merchantable trees on remaining plots, plot borders, and the area within the study boundary were directionally felled and removed with a skidder that traveled only on designated paths within the plots and in plot borders. Remaining crowns, unmerchantable trees, dead and live snags, dead and down wood, leaf litter layer, and other debris were removed manually according to protocols. Depending on the treatment, on some plots, it was necessary to replace these materials (except the leaf/litter layer) after compaction was completed.

Post-harvest Treatment

Tree crowns were retained on bole only (BO) plots. On plots where whole trees (WT) and the leaf/litter layer (WT & FF) were removed, total aboveground biomass was removed. All understory vegetation was clipped and removed, and the forest floor was raked away to the mineral soil. Skidders and tractors were permitted on compacted plots, but not on uncompacted plots. A 14-ton vibrating sheep-foot roller was used to treat compacted plots. Severely compacted plots were compacted until there was no change in bulk density after roller passes. Soil bulk density measurements were taken after the roller made one, three, five, and eight passes over the severely compacted treatment. Changes in bulk density usually ceased after five passes. Medium compacted plots received three passes.

All plots were planted to 1-0 red oak (*Quercus rubra* L.), white oak (*Quercus alba* L.), and shortleaf pine (*Pinus echinata* Mill.) in a 6:6:1 ratio using hoedads. Several measurements were recorded for all seedlings including root collar diameter, root volume, and number of large (>1.0 mm) lateral roots. A 1-meter-radius (3 ft) area was sprayed with glyphosate around each seedling to control competing weeds and to help seedlings become established. Beginning in the second growing season and completed by the end of the third growing season, half of each plot will be kept weed-free until crown closure to permit planted trees to grow freely. The other half of the plot has been allowed to develop naturally into a more complex community of trees and other vegetation. Net primary productivity in these two plant communities will provide direct measures of productivity as influenced by the degree of soil disturbance.

Soil moisture blocks were installed at 10, 20, and 30 cm (4, 8, and 12 in.) deep between rows in the upper and lower halves of all plots in the unsprayed treatment. Soil temperature-moisture cells were installed in the upper and lower halves of weed-free plots in treatment combinations of no soil compaction, severe soil compaction, bole only removed, and whole tree plus forest floor removed at the same depths and between the same rows.

Survival, height, diameter, and crown width of planted trees will be measured at the first, second, third, and fifth year after planting and at 5-year intervals thereafter. Herbaceous or ground flora samples will be sampled on the same schedule for weight, composition, and nutrient element content. Herbaceous samples on 2.3 m^2 (25 ft^2) plots placed across the upper and lower slopes of each plot will be clipped, put into bags, air-dried before being oven dried, weighed, ground in a Wiley mill, and analyzed at the Ohio Research Analytical Laboratory for elemental analyses.

Preliminary Results and Discussion

The 1997 growing season will be the second complete growing season for the Missouri study; several of the older LTSP studies will be entering their seventh growing season. Soil compaction is a major component of the LTSP study. Bulk densities on the Missouri site were comparatively high before compaction treatments were applied (table 2). Soil bulk density generally increased with depth and number of passes. However, only mean bulk density measurements at the 22.9- to 30.5-cm depth were different ($\alpha = 0.05$) from other depths for five passes. Arriving at the moderate level of compaction was difficult because once the soil was compacted, we could not uncompact it and start over. We could only try to compact the severe level more.

Wood (stem only and whole tree) represents the majority of the biomass on the site. The Missouri plots averaged 77, 159, and 207 Mg/ ha of biomass removed for bole only, whole tree, and whole tree plus forest floor removed, respectively.

The amount of nutrients in the biomass on the Missouri site is shown in table 3. Harvesting the whole tree removed considerably more nutrients than harvesting only the merchantable part of the tree. Undoubtedly, the unmerchantable tree components and forest floor had a large concentration of nutrients. The large amount of manganese, iron, and aluminum in the total aboveground removed treatment suggests that removing the aboveground biomass removes a significant amount of these nutrients. This may also mean that these nutrients are either accumulating in the litter or

Table 2.—*Mean soil bulk density measurements following compaction with a 14-ton vibrating sheep-foot roller.*

Depth[1] (cm)	Number of passes with compactor: 0		2		3		5	
	Bulk density (g/cm^3)							
0 - 7	1.26	(± 0.28)[2]	1.40	(± 0.20)	1.53	(± 0.12)	1.32	(± 0.09)
8 - 15	1.41	(± 0.23)	1.66	(± 0.25)	1.76	(± 0.19)	1.89	(± 0.08)
16 - 23	1.49	(± 0.20)	1.92	(± 0.17)	1.77	(± 0.12)	1.88	(± 0.15)
24 - 31	1.63	(± 0.29)	1.84	(± 0.04)	1.84	(± 0.04)	2.12	(± 0.39)

[1] 2.54 cm = 1 inch.
[2] Standard deviation

Table 3.—*Nutrients removed by different harvesting treatments from the Missouri LTSP study site.*

Nutrients	Bole only		Whole tree		Total above ground	
	kg/ha					
Macronutrients						
Nitrogen	195.3	(± 58.8)[1]	540.0	(± 166.8)	810.8	(± 238.7)
Phosphorus	9.1	(± 2.3)	25.0	(± 8)	48.3	(± 17)
Potassium	108.7	(± 33.5)	255.6	(± 79)	284.9	(± 91)
Calcium	774.2	(± 238)	2,303.1	(± 474	2,819.2	(± 588.3)
Magnesium	19.9	(± 4)	52.6	(± 16.3)	81.2	(± 28)
Micronuturients						
Manganese	7.1	(± 2.2)	18.0	(± 5.6)	49.4	(± 15.3)
Iron	1.0	(± 0.3)	2.6	(± 08)	17.5	(± 5.4)
Zinc	0.5	(± 0.2)	1.6	(± 0.6)	2.6	(± 0.9
Aluminum	2.1	(± 0.7	7.6	(± 2.5)	81.1	(± 22)
Sodium	0.5	(± 0.3)	1.1	(± 0.8)	1.6	(± 0.6)
Copper	0.1	(± 0.1)	0.3	(± 0.2)	0.6	(± 0.3)
Boron	0.4	(± 0.2)	1.1	(± 04)	1.5	(± 0.6)

Harvesting treatments: Bole only, Whole tree, Total above ground.

[1] Standard deviation

they are more abundant in the understory and herbaceous layers. This warrants further study.

Many more nutrients were removed in the harvest of hardwoods (red oak, *Quercus rubra*, white oak, *Q. alba*, and hickory (*Carya* spp.) than in the harvest of shortleaf pine of similar weight (Mikkelson and Ponder 1995). Also, the comparison showed that large amounts of nutrients are in crown materials.

The number of planted seedlings that died after two growing seasons differed slightly among treatments (table 4). The number of dead seedlings was lowest in the whole tree plus forest floor removed treatment. Nearly half of the dead seedlings in the uncompacted bole only treatment were in one plot. The plot was the first plot planted, and it was planted at the end of a dry weather period. Seedlings in the plot were watered once before rain ended the dry period.

Large numbers of seedlings in all plots suffered damage from rabbits and pack rats during the winter after planting. Stems of many seedlings appeared to have been cut off 3 to 5 cm (1 to 2 in.) above the root collar. The damage appeared to be greatest near debris piles along the edge of plots. Many of the pins and flags used to identify seedlings were also missing. Nevertheless, nearly all of the damaged seedlings produced new stems in the spring of the second year and growth appeared normal.

Table 4.—*The total number of planted and mean number of dead seedlings on LTSP plots in Missouri 2 years after planting.*

	Compaction					
	None		Medium		Total above ground	
Biomass removed	Seedlings planted	No. of dead seedlings	Seedlings planted	No. of dead seedlings	Seedlings planted	No. of dead seedlings
Bole only	1,021	94 (± 76)[1]	999	40 (± 28)	691	34 (± 12)
Whole tree	967	49 (± 51)	1,306	65 (± 32)	1,433	65 (± 42)
Whole tree + forest floor	910	29 (± 21)	1,160	36 (± 17)	950	33 (± 19)

[1] Standard deviation

Plastic tree protectors were placed around all seedlings in the second year. Although preliminary observations showed that some of the protectors were missing, overall, fewer seedlings were damaged. Damaged seedlings occured where protectors were missing or had been partially destroyed.

Trends in treatment differences for nutrient concentrations in herbaceous vegetation were not apparent after year one, but both N and Al differed ($\alpha = 0.05$) between treatments after year two (table 5). Data for the 2 years showed that in year two N, K, and Ca decreased and Fe, Zn, and Al increased compared to year one.

Summary

While preliminary results can be interesting, it will be a number of years before trends and real differences can be rigorously tested and substantiated. The results will help us better understand how organic matter and compaction impact the behavior of ecosystems and how these properties of soil productivity can be manipulated to sustainability of our Nation's forests.

This is a long-term study that has been established in several ecosystems. Thirty-nine LTSP installations currently are operational in the United States, and another three are in early establishment stages in central Idaho (Powers and Fiddler, in press, 1997). Four others were installed in interior British Columbia by the B. C. Ministry of Forests and several others are planned. In all, nearly 4 dozen common-protocol installations will exist by the end of 1997 (fig. 1).

Table 5.—*Mean concentration of nutrients in herbaceous vegetation in plots of the Missouri long-term soil productivity study for year one and year two after site preparation and artificial regeneration.*

Treatment		Nutrient element						
Biomass removed	Compaction	N	P	K	Ca	Fe	Zn	Al
		Percent	*ppm*					
		Year one						
Bole only	None	1.3a[1]	748a	576a	12,051a	77a	49a	87a
Bole only	Medium	1.3a	753a	657a	20,219a	78a	43a	60a
Bole only	Severe	1.6a	821a	680a	16,739a	90a	41a	67a
Whole tree	None	1.5a	798a	554a	17,332a	76a	43a	78a
Whole tree	Medium	1.4a	1,015a	681a	26,017a	71a	33a	98a
Whole tree	Severe	1.6a	806a	670a	16,745a	83a	43a	74a
Whole tree + forest floor	None	1.4a	833a	648a	12,597a	93a	41a	72a
Whole tree + forest floor	Medium	1.4a	868a	676a	25,750a	78a	39a	82a
Whole tree + forest floor	Severe	1.3a	798a	615a	18,925a	79a	41a	74a
		Year two						
Bole only	None	1.6a	1,251a	732a	11,822a	93ab	99a	55b
Bole only	Medium	1.1b	1,031a	462a	13,179a	56b	67b	58b
Bole only	Severe	1.1b	899a	782a	11,262a	90ab	59b	111ab
Whole tree	None	0.9b	853a	522a	9,839a	71ab	45b	73b
Whole tree	Medium	1.1b	1,162a	536a	11,726a	90ab	54b	70b
Whole tree	Severe	1.2ab	930a	470a	11,481a	80ab	63b	90ab
Whole tree + forest floor	None	0.9b	783a	417a	10,429a	157a	63b	146ab
Whole tree + forest floor	Medium	1.2ab	1,357a	428a	12,358a	156a	53b	218a
Whole tree + forest floor	Severe	0.9b	777a	569a	11,603a	70ab	57b	96ab

[1] Values in a column for a year are not significantly different ($\alpha = 0.05$) when followed by the same letters.

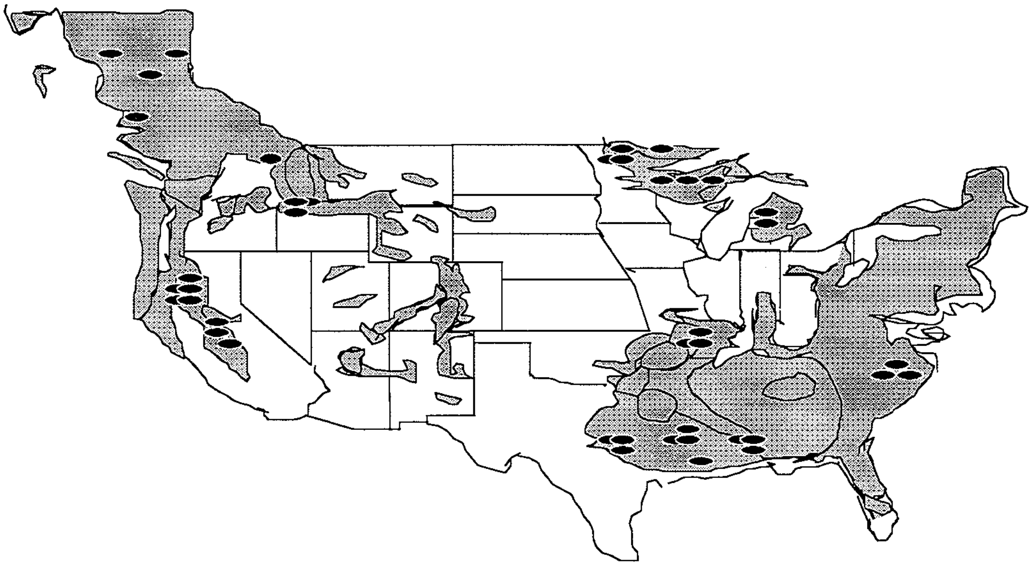

Figure 1.—General range of commercial forest in the United States and British Columbia. Ovals indicate individual LTSP installations.

LITERATURE CITED

Black, C.A., ed. 1965. Methods of soil analysis. Part 1. Physical and mineralogical properties including statistics of measurements and sampling. Monogr. No. 9, 2d ed. Madison, WI: Soil Science Society of America and American Society of Agronomy. 770 p.

Daddow, R.L.; Warrington, G.E. 1983. Growth-limiting soil bulk densities as influenced by soil texture. WSDG Rep. WSDG-Tn-00005. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Watershed System Development Group. 17 p.

Gott, J. 1975. Soil survey of the Mark Twain National Forest Area. Missouri (Parts of Carter, Oregon, Ripley and Shannon counties). Rolla, MO: U.S. Department of Agriculture, Forest Service.

Hahn, J.T. 1991. Timber resource of Missouri. Resour. Bull. NC-119. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 123 p.

Hornbeck, J.W.; Kropelin, W. 1982. Nutrient removal and leaching from a whole-tree harvest of northern hardwoods. Journal of Environmental Quality. 11: 309-316.

Mikkelson, N.K.; Ponder, F., Jr. 1995 Above-ground nutrient composition of a mature oak-hickory forest in Missouri. In: Proceedings, Society American Foresters Convention; 1995 October 28-November 1; Indianapolis, IN. Bethesda, MD: Society of American Foresters: 400-401.

Missouri Geological Survey. 1979. Geologic map of Missouri. Rolla, MO: Missouri Department of Natural Resources.

Page, A.L,; Miller, R.M.; Kenney, D.R., ed. 1982. Methods of soil analysis. Part 2. Chemical and Microbiological Properties. Monogr. No. 9, 2d ed. Madison, WI: Soil Science Society of America and American Society of Agronomy. 159 p.

Ponder, F., Jr.; Mikkelson, N.K. 1995. Characteristics of a long-term forest soil productivity research site in Missouri. In: Gottschalt, K.W.; Fosbroke, S.L.C., eds. Proceedings, 10th Central hardwood forest conference; 1995 March 5-8; Morgantown, WV. Gen. Tech. Rep. NE-197. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 272-281.

Powers, R.F.; Alban, D.H.; Ruark, G.A.; Tiarks, A.E.; Goudey, C.B.; Ragus, J.F.; Russell, W.E. 1989. Study plan for evaluating timber management impacts on long-term site productivity: a Research and National Forest System cooperative study. Jefferson City, MO: On file with: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 33 p.

Powers, R.F.; Fiddler, G.O, 1997. The North American long-term soil productivity study: progress through the first 5 years. In: Proceeding of the 18th annual forest vegetation management conference; 1997 January 14-16, 1997; Sacramento, CA. In press.

Soil Survey Staff. 1984. Procedures for collection of soil samples and methods for analysis for soil survey. Soil Invest. Rep. 1. Washington, DC: U.S. Government Printing Office.

U.S. Department of Agriculture, Forest Service. 1983. The principal laws relating to Forest Service activities. Agric. Handb. 453. Washington, DC: U.S. Department of Agriculture, Forest Service. 591 p.

U.S. Code of Federal Regulations. 1985 (July). Monitoring and evaluation. In: Part 219-Planning, Subpart A-National Forest System land and resource management planning. Chapter II, 36 CFR 219.12(K). Washington, DC: U.S. Department of Agrculture, Forest Service: 45-71.

U.S. Department of Agriculture, Forest Service. 1987. Soil quality monitoring. In: Soil management handbook 2509.18. Washington, DC: U.S. Department of Agriculture, Forest Service. Chapter 2, 42 p.

Woodbury, T.D. 1930. Development of silvicultural practices in the California National Forests. Journal of Forestry. 28: 693-700.

Printed on recycled recyclable paper.