INTRODUCTION / INTRODUCTION

# Long-Term Soil Productivity: genesis of the concept and principles behind the program[1]

**Robert F. Powers**

**Abstract:** The capacity of a forest site to capture carbon and convert it into biomass defines fundamental site productivity. In the United States, the National Forest Management Act (NFMA) of 1976 mandates that this capacity must be protected on federally managed lands. Responding to NFMA, the USDA Forest Service began a soil-based monitoring program for its managed forests. Lacking an extensive research base, soil-based standards were predicated largely on professional judgment. To provide a stronger foundation, a national program of Long-Term Soil Productivity (LTSP) research was established. The LTSP program addresses both short- and long-term consequences of site and soil disturbance on fundamental forest productivity. Research centers on two key properties affecting a site's long-term productive capacity, site organic matter and soil porosity, each of which is readily influenced by management. A coordinated research network of more than 100 field installations in the United States and Canada is examining how pulse changes in these properties affect soil processes supporting vegetative growth and potential productivity. Results from installations with ≥5 years of response were presented on the 10th anniversary of LTSP, and the latest findings are assembled here. This paper describes the evolution of the study and the characteristics of the oldest field installations.

**Résumé :** La capacité d'une station forestière de fixer le carbone et de le convertir en biomasse définit la productivité de base de cette station. Aux États-Unis, la loi sur l'aménagement des forêts nationales de 1976 (NFMA) exige que cette capacité soit protégée sur les terres gérées par le gouvernement fédéral. En conformité avec cette loi, le service des forêts de USDA a initié un programme de suivi basé sur le sol pour ses forêts aménagées. Étant donné le nombre restreint de travaux de recherche, les normes relatives au sol ont été basées en grande partie sur le jugement professionnel. Dans le but de fournir des bases plus solides, un programme de recherche sur la productivité des sols à long terme (PSLT) a été mis sur pied. Le programme de recherche PSLT porte sur les conséquences à court terme et à long terme des perturbations de la station et du sol sur la productivité de base de la forêt. La recherche se concentre sur deux propriétés clés qui affectent la capacité de production à long terme d'une station : la matière organique de la station et la porosité du sol, chacune étant directement influencée par l'aménagement. Un réseau coordonné de recherche comptant plus de 100 installations sur le terrain aux États-Unis et au Canada étudie comment les changements rythmiques dans ces propriétés affectent les processus du sol qui supportent la croissance végétale et la productivité potentielle. Les résultats provenant d'installations qui ont cinq ans ou plus ont été présentés lors du 10$^{e}$ anniversaire du programme PSLT et les dernières conclusions sont regroupées ici. Cet article décrit l'évolution de l'étude et les caractéristiques des plus vieilles installations sur le terrain.

[Traduit par la Rédaction]

## Introduction

The Long-Term Soil Productivity (LTSP) program began in 1989 as a "grass roots" proposal that grew to be a national program of the USDA Forest Service. LTSP was founded to examine the long-term consequences of soil disturbance on fundamental forest productivity. The concept caught the imagination of others. Soon, partnerships and affiliations were forged among public and private sectors in the United States and Canada. Today, more than 100 LTSP and affiliated sites comprise the world's largest coordinated research network addressing basic and applied science issues of forest management and sustained productivity. Studies range from applied growth and yield monitoring, through elucidating mechanisms controlling carbon capture above and below ground, to developing indices of soil quality practicable in monitoring. Results from installations with ≥5 years of response were presented at a recent anniversary symposium, updated, and assembled here.

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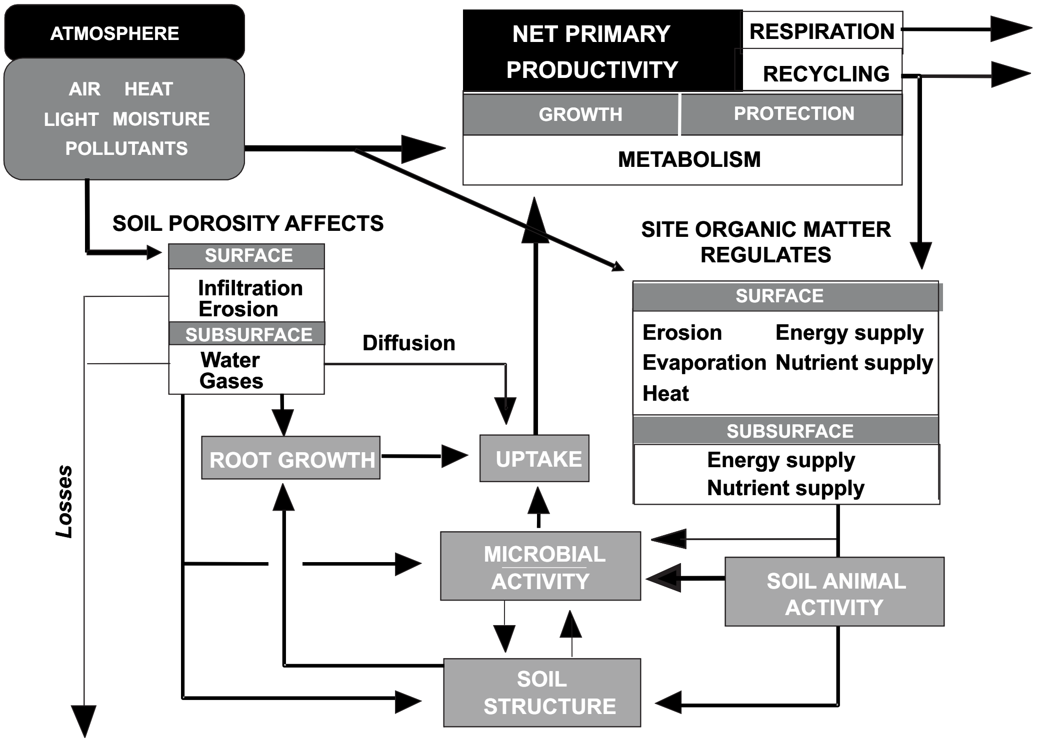
**Fig. 1.** Conceptual model of the roles of soil porosity and site organic matter in regulating soil and site processes affecting net primary productivity within the constraints of climate and genotype (from Powers et al. 1990).



This paper describes the evolution of the study and the characteristics of the oldest field installations.

## Background

### Historical basis

The LTSP program began in response to the National Forest Management Act (NFMA) of 1976 and related legislation (USDA Forest Service 1983). NFMA requires the US Secretary of Agriculture to ensure, through research and monitoring, that forest management practices do not permanently impair the productivity of the land. This requirement seems superfluous because sustaining productivity is an obvious aim of modern forest management. It is remarkable only in that NFMA may be the first mandate for a national forest land ethic that carries the weight of law. NFMA precedes the Dutch Soil Protection Act of 1987 and Australia's National Forest Policy Statement of 1992 by more than a decade (Nambiar 1996; Powers et al. 1998). Thus, it is a legislative landmark.

Responding to NFMA, an independent committee of scientists was appointed to form a framework for implementing the law. Their recommendations led in 1985 to a Code of Federal Regulations for Forest Planning (USDA Forest Service 1985). One notable element was to require the Forest Service to monitor the effects of forest management prescriptions, including "significant changes in land productivity". This monitoring requirement was developed more than a decade in advance of The Montreal Process (Canadian Forest Service 1995) and the environmental surge toward "green certification" (Anonymous 1995).

The Forest Service knew that clear and objective definitions were key to addressing its monitoring charge. "Land productivity" was a central issue. Broadly, it could be defined as a site's capacity to produce a cornucopia of timber, wildlife, watershed, fishery, and aesthetic values. All these values are legitimate expressions of land productivity, but some are less tangible, more subjective, and temporally less stable than others. Instead, and with guidance from the US Office of General Council, a fundamental definition emerged. Land productivity was defined as the carrying capacity of a site for vegetative growth. This definition was useful, because the capacity of a site to capture carbon and grow vegetation is central to its potential for producing all other values. In turn, "carrying capacity" was defined as average periodic dry matter production when the site is fully stocked (at its maximal stable leaf area). "Significant change" was defined as the level of reduced carrying capacity that could be detected with operational monitoring technology. Given the vagaries of annual fluctuations in dry matter production, consensus opinion held that a departure from base line would have to exceed 15% to be deemed significant (USDA Forest Service 1987). But what variables should be monitored?

### Direct measures

Site index, the height reached by a stand's tallest trees at a reference age, is the traditional gauge of site quality and potential productivity in the United States. Site index is popular because it largely is independent of stand density and is easily measured (Smith et al. 1997). However, its value in monitoring productivity is limited for several reasons:

(1) Stand age often is difficult to determine in natural stands, and small errors can compound into larger errors in the site index estimate.
(2) The concept is suited mainly for even-aged, pure stands.
(3) Stand density measures are not considered. Therefore, site index may not reflect the actual productive potential

**Table 1.** Absolute and proportional amounts of biomass and nitrogen removed by the three organic matter removal treatments on sites representative of Long-Term Soil Productivity installations.

| | | | Biomass removed (Mg/ha) (% of aboveground total) | | | Nitrogen removed (kg/ha) (% of aboveground total) | | |
|---|---|---|---|---|---|---|---|---|
| Location | Life zone[a] | Forest type | $OM_0$ | $OM_1$ | $OM_2$ | $OM_0$ | $OM_1$ | $OM_2$ |
| British Columbia | BM | Mixed conifer | 126 (56) | 158 (71) | 223 (100) | 195 (18) | 253 (24) | 1068 (100) |
| Minnesota | CTM | Aspen | 175 (61) | 214 (75) | 286 (100) | 194 (30) | 316 (48) | 653 (100) |
| California | WTD | Mixed conifer | 252 (47) | 473 (89) | 532 (100) | 218 (20) | 609 (57) | 1064 (100) |
| Missouri | WTM | Central hardwood | 96 (42) | 175 (77) | 228 (100) | 195 (24) | 540 (67) | 811 (100) |
| Louisiana | STM | Pine hardwood | 133 (77) | 153 (88) | 173 (100) | 134 (38) | 229 (65) | 352 (100) |

**Note:** $OM_0$, bole only removed; $OM_1$, whole tree removed; $OM_2$, whole tree plus understory and forest floor removed.

[a] After Holdridge (1947). BM, boreal moist; CTM, cool temperate moist; WTD, warm temperate dry; WTM, warm temperate moist; STM, subtopical moist.

for a unit area, for example, sites with stony soils that limit stocking.

(4) Trees currently holding a dominant position are assumed to have been dominant throughout stand development. But past thinning of larger trees may have converted lower crown classes to de facto dominants.
(5) Because site index is based on cumulative height, it will be slow to reflect major impacts to the site caused by intermediate treatments or by climate change.

Stand volume growth is the historical measure of forest productivity in the United States. It is popular because it focuses directly on the product of traditional timber management: the production of merchantable wood. But like site index, volume growth also is variable and imprecise. Stands consist of trees, and tree growth is affected by age, stage of stand development, stocking, genetic variation, competition from other plants, and past management history. Focusing only on trees also can be misleading, particularly during early stand development. Understory competition often affects early stand composition and growth. Therefore, practices such as blading slash and topsoil into windrows that may impair site quality in the long run can favor early growth simply because of lessened competition (Allen et al. 1991; Stransky et al. 1985). Even if site quality has not been impaired, volume growth rates vary with time, because tree and stand growth are related linearly to canopy light interception (Cannell 1989). Therefore, stem volume growth increases as canopies expand to intercept more light and trees capture more of a site's productive potential. Growth rates per hectare follow a sigmoidal trend, rising slowly, then more rapidly, leveling as the foliar canopy stabilizes, and ultimately declining as the stand enters senescence and a high proportion of annual assimilate is spent in maintenance respiration (Waring and Schlesinger 1985; Powers 2001). But even at full stocking, stem volume is only one index (albeit a large one) of a site's capacity for dry matter production. While stem volume correlates closely with stem biomass, it does not account for dry matter captured by other parts of the tree and the understory. These forest components are measurable, but only with great difficulty. Even if measured accurately, they suffer all the temporal and spatial problems noted previously.

## Indirect measures

Recognizing the problems of direct measures of potential site productivity, Burger (1996) and Powers et al. (1990) called for an alternative that is unbiased and independent of stocking and genetic considerations of current forest growth. Because soil is affected readily by management and is a major factor determining potential productivity within the constraints of climate, they proposed that the basis for alternative indices should center on the soil. The notion that soil attributes might be useful monitoring indicators is rooted in agronomy. In 1992, a special symposium of the American Society of Agronomy addressed the theme "Defining Soil Quality for a Sustainable Environment". The ensuing publication (Doran et al. 1994) framed the soil quality concept as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant andanimal health." Doran and Parkin (1994) proposed a primary set of 16 agricultural soil quality indicators related to these attributes. These ranged in complexity from such simple measures as soil depth, to ratios of soil respiration, to microbial biomass. More recently, indicators have been proposed for forestry (Burger and Kelting 1998; Powers et al. 1998; Van Miegroet et al. 1994) and summarized by Schoenholtz et al. (2000).

## The national forest approach

The USDA Forest Service also saw the value in soil properties as an independent basis for monitoring potential productivity. In 1987 the Watershed and Air Management division of National Forest Systems adopted a program of soil quality monitoring that was based on the following rationale (Powers and Avers 1995).

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

Monitoring soil and site processes directly is not feasible. Instead, the Forest Service proposed a monitoring strategy based on measurable soil variables that either reflect, or are correlated with, important site processes. For example,

| Site process | Key soil monitoring variables |
|---|---|
| Soil erosion | Soil loss thresholds, percent soil cover, presence of rills, etc. |
| Nutrient availability | Forest-floor presence, soil organic matter content, surface soil loss through erosion or displacement, etc. |
| Water availability | Infiltration rate, saturated hydraulic conductivity, soil bulk density, soil organic matter, plant water potential, soil moisture, etc. |
| Gas exchange | Soil bulk density, air permeability, puddling, presence of mottles, waterlogging, etc. |
| Root activity | Soil bulk density, soil strength, soil structure, water-table depth, etc. |

Key soil monitoring variables were identified that (1) had a known or presumed correlation with potential productivity and (2) could be measured operationally with a reasonable degree of statistical confidence, for example, ±15%, of the true site mean. Presumably, any appreciable change in a key soil monitoring variable suggests a change in the potential productivity of a site. Threshold standards would be set for each variable to indicate when significant changes had occurred in potential productivity. This approach makes sense as a first approximation. A problem with this strategy is that the correlation between a soil variable and productivity may vary by soil type and climate. Recognizing this potential stumbling block, the Forest Service asked each administrative region in the United States to identify the soil variables thought to be key for that region and to develop appropriate threshold standards. Examples are given in Powers and Avers (1995) and Powers et al. (1998). But another and more fundamental problem is that correlations between soil monitoring variables and potential productivity are mainly conceptual. Because they are conceptual and somewhat subjective, they can be challenged.

### Research coordination

Recognizing the problems inherent in developing soil quality monitoring standards based largely on professional judgment, Forest Service Research was asked to help. The request was made informally by Peter E. Avers, National Leader of the USDA Forest Service Watershed and Air Management Staff, to David Alban of the North Central Research Station and me on a field trip during the 1986 Soil Science Society of America Meeting in New Orleans, Louisiana. I thought more about the matter, and the following year I invited a handful of colleagues to California for a field visit with Peter and me to explore the idea. This led to a small but seasoned team of agency scientists and managers (see authors, Powers et al. 1990) who assembled in 1988 in St. Louis, Missouri, to address the problem. Our first step was to recognize that some of what passed for "professional knowledge" was actually opinion and that much of the remainder rested on anecdotal evidence. This meant that the scientific basis for soil quality monitoring was shaky, which led to our second step, namely to conduct a critical analysis of world literature for (1) sound and unambiguous evidence of declines in a site's productive potential due to management and (2) a clue as to unifying soil and site factors apt to cause such declines. Extensive literature review revealed that the two ecosystem properties most likely to impact long-term productivity were declines in site organic matter and soil porosity.

While agreeing that organic matter and soil porosity were of paramount importance, the team concluded that existing information was sparse, site specific, and too anecdotal to be broadly useful. They agreed that more fundamental work was needed, and they proposed a nationally coordinated field experiment to address the issue directly and unambiguously. The proposal was reviewed domestically and internationally, and a final study plan was prepared (Powers et al. 1989). Undoubtedly, this was the most broadly reviewed study plan ever produced by the USDA Forest Service. In 1989 the study plan was approved in Washington, D.C., by the deputy chiefs for Research and National Forest systems, and 10-year funding was secured for implementing the study as a national effort on public lands. The overview was published and circulated widely (Powers et al. 1990, 1996; Powers and Avers 1995).

## The study

### A conceptual model

The program now known as LTSP is predicated on the principle that within the constraints of climate, a site's potential net primary productivity is strongly regulated by physical, chemical, and biotic soil processes that are affected readily by management. The key properties affected directly by management are soil porosity and site organic matter. These two properties regulate critical site processes through their roles in microbial activity, soil aggregate stability, water and gas exchange, physical restrictions on rooting, and resource availability, as illustrated conceptually in Fig. 1.

Site organic matter and soil porosity are easily affected by forest management operations. Therefore, they were targeted for specific manipulation in large-scale, long-term experiments. The experiments are conducive to addressing four hypotheses:

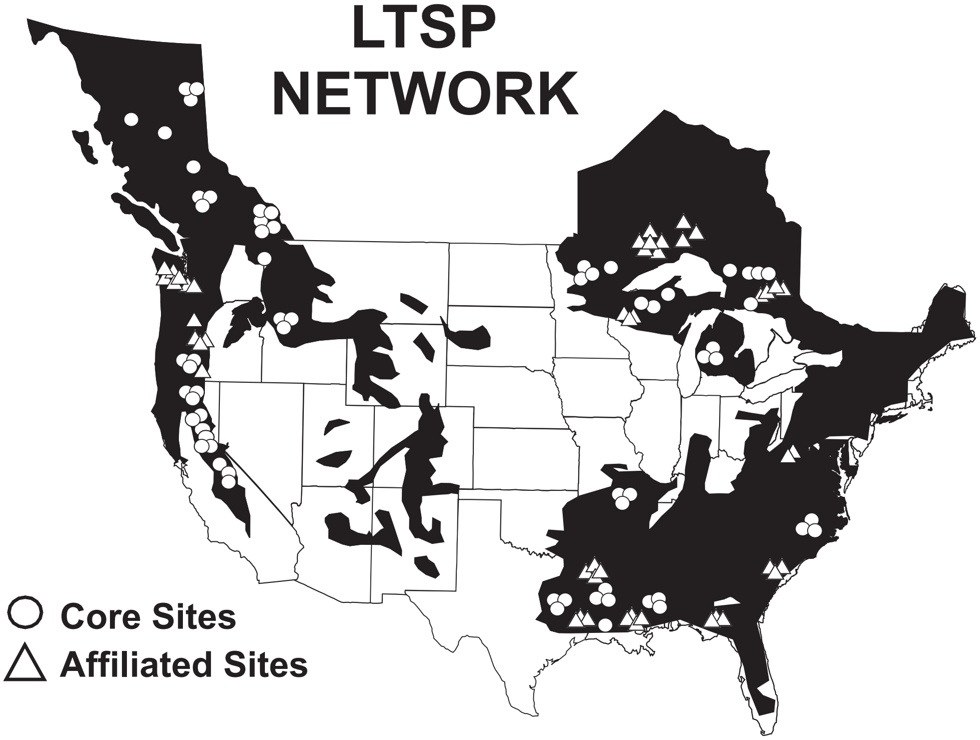
| Null hypothesis | Alternative hypothesis |
|---|---|
| (1) Pulse changes in site organic matter and (or) soil porosity do not affect the sustained productive potential of a site (sustained capacity to capture carbon and produce phytomass). | Critical changes in site organic matter and (or) soil porosity have a lasting effect on potential productivity by altering soil stability, root penetration, soil air, water, and nutrient balances, and energy flow. |
| (2) If impacts on productivity occur from changes in organic matter and porosity, they are universal. | The biological significance of a change in organic matter or porosity varies by climate and soil type. |
| (3) If impacts do occur, they are irreversible. | Negative impacts are reversible. |
| (4) Plant diversity has no impact on the productive potential of a site. | Diverse communities affect site potential by using resources more fully or through nutrient cycling changes that affect the soil. |

### Implementing the research

#### *Selecting sites and applying treatments*

The study was targeted at forest types, age-classes, and soil conditions that are likely to come under active forest management. With very few exceptions these were fully stocked, mature, even-aged stands, that is, not "ancient forests" or nonforested openings. Notable exceptions were four California stands that, because site quality was so poor, took more than two centuries to reach sawtimber size. Preliminary plots of 0.2 or 0.4 ha were identified and surveyed for variability in soil and stand conditions. Those with comparable variability were then sampled to quantify standing biomass and nutrient capital in the overstory, understory, and forest floor (Madgwick and Satoo 1975). Stands were then harvested and treatments imposed randomly. Treatments were chosen to create extreme ranges in site organic matter and soil porosity. They were selected not so much to mimic common opera-

**Fig. 2.** Distribution of North American Long-Term Soil Productivity (LTSP) core experiments and affiliated installations. Shaded area represents forest area capable of producing 1.4 $m^3$ of wood per hectare annually (modified from Powers 1999).



tional practices, but rather to bracket the extremes in disturbance likely to occur under present or future management. The main effect treatments were as follows:

| Main effect | Symbol | Description of treatment |
|---|---|---|
| Modify site organic matter | $OM_0$ | Tree boles removed. Crowns, felled woody and herbaceous understory, and forest floor retained. |
| | $OM_1$ | Boles and crowns removed. Felled woody and herbaceous understory and forest floor retained. |
| | $OM_2$ | All aboveground biomass removed. Bare soil exposed. |
| Modify soil porosity | $C_0$ | No soil compaction. |
| | $C_1$ | Compacted to an intermediate bulk density. |
| | $C_2$ | Compacted to an unusually high bulk density. |

There are two reasons for choosing these levels of organic matter manipulation. First, they encompass the extremes in aboveground organic matter removal apt to occur when forests are harvested for wood. Second, they produce a step series of nutrient removal that is disproportionate to biomass loss. The latter is particularly important because concerns and conjecture over nutrient drain from increased biomass removal and slash treatment have persisted for decades (Boyle and Ek 1972; Grigal 2000; Leaf 1979), particularly with respect to nitrogen, phosphorus, and calcium (Dyck et al. 1994; Morris 2001). Table 1 illustrates these points using six typical LTSP sites arrayed along a climatic gradient. It shows that overstory trees contain roughly four-fifths of site aboveground organic matter, with about two-thirds occurring in boles. The forest floor and understory account for the remainder above ground. This means that as organic matter removal ascends from $OM_0$ to $OM_2$, there is a lessening withdrawal from the site's original aboveground total. Nitrogen shows a different trend. Although half or more of aboveground organic matter may be in tree boles, this component accounts for a much smaller fraction of the aboveground nitrogen capital in mature stands. On average, in the absence of frequent fire, the forest floor of mature stands contains as much nitrogen as that in boles and crowns combined. However, the actual proportion of aboveground nitrogen in the forest floor varies with climate (Table 1). In moist boreal forests of British Columbia, where decomposition is slowed by cool temperatures and perhaps by partial anaerobia, the forest floor accumulates far more nitrogen than is contained in the vegetation. Under warm, humid conditions, the forest floor decomposes rapidly and is a relatively small reservoir of nitrogen. Regardless of life zone, the understory in mature forests is only a minor component of site organic matter or nitrogen (only a few percentage points of the aboveground total after canopies have closed). Thus, this "stair step" series of nitrogen removals spans the quantities apt to be removed under management. Further, it provides a means for evaluating the significance of aboveground nutrient pools relative to their lability (Grigal 2000).

Generally, all factorial combinations of main effect treatments were applied, producing nine core combinations of organic matter removal and soil compaction. In a few cases, because of space limitations, only the "four-corners" treatments

**Table 2.** Site and pretreatment stand characteristics of core and affiliate Long-Term Soil Productivity installations achieving 5 years of

| Location | Installation name | Lat. (°) | Long. (°) | Life zone[a] | Forest type | Elevation (m) | Annual precipitation (cm) |
|---|---|---|---|---|---|---|---|
| British Columbia | Kiskatinaw | 57.97 | 120.47 | BM | Aspen | 720 | 48 |
| British Columbia | Log Lake | 38.88 | 122.61 | BM | Mixed conifer | 785 | 62 |
| British Columbia | Skulow Lake | 52.32 | 121.92 | BM | Mixed conifer | 1050 | 43 |
| British Columbia | Topley | 52.32 | 126.31 | BM | Mixed conifer | 1100 | 53 |
| California | Aspen | 40.71 | 121.09 | CTD | Mixed conifer | 1798 | 67 |
| California | Blodgett | 38.88 | 120.64 | WTD | Mixed conifer | 1320 | 165 |
| California | Brandy | 39.55 | 121.04 | WTD | Mixed conifer | 1130 | 190 |
| California | Bunchgrass | 40.59 | 121.41 | CTD | Mixed conifer | 1524 | 91 |
| California | Central | 37.32 | 119.48 | WTD | Mixed conifer | 1685 | 114 |
| California | Challenge | 39.48 | 121.22 | WTD | Mixed conifer | 790 | 173 |
| California | Cone | 40.73 | 121.12 | CTD | Mixed conifer | 1959 | 69 |
| California | Lowell | 39.26 | 120.78 | WTD | Mixed conifer | 1270 | 173 |
| California | Owl | 37.24 | 119.41 | WTD | Mixed conifer | 1805 | 114 |
| California | Rogers | 39.78 | 121.32 | WTD | Mixed conifer | 1200 | 170 |
| California | Vista | 37.38 | 119.56 | WTD | Mixed conifer | 1560 | 76 |
| California | Wallace | 38.97 | 120.64 | WTD | Mixed conifer | 1575 | 178 |
| Idaho | Priest River | 48.35 | 116.84 | CTM | Mixed conifer | 900 | 77 |
| Idaho | Council (3) | 45.00 | 116.59 | CTM | Mixed conifer | 1575 | 68 |
| Louisiana | Glenmora | 31.74 | 92.48 | STD | Pine–hardwood | 61 | 147 |
| Louisiana | Malbis | 31.02 | 92.63 | STD | Pine–hardwood | 52 | 150 |
| Louisiana | Mayhew | 31.73 | 92.57 | STD | Pine–hardwood | 61 | 147 |
| Louisiana | Metcalf | 31.72 | 92.57 | STD | Pine–hardwood | 61 | 147 |
| Michigan | Huron–Manistee (3) | 44.64-44.65 | 83.53–83.52 | CTM | Aspen | 240 | 75 |
| Michigan | Ottawa (3) | 46.63 | 89.21 | BM | Aspen | 350 | 77 |
| Minnesota | Chippewa (3) | 47.29–47.32 | 94.36–94.53 | BM | Aspen | 410 | 64 |
| Minnesota | Marcell | 47.53 | 93.47 | CTM | Aspen | 435 | 77 |
| Mississippi | Freest-1 | 31.50 | 88.92 | STD | Pine–hardwood | 69 | 147 |
| Mississippi | Freest-2 | 31.55 | 89.01 | STD | Pine–hardwood | 69 | 147 |
| Mississippi | Freest-3 | 31.53 | 89.00 | STD | Pine–hardwood | 69 | 147 |
| Missouri | Carr Ck (3) | 37.00 | 91.33 | WTM | Hwds-pine | 250 | 112 |
| North Carolina | Goldsboro | 34.92 | 76.80 | WTM | Pine–hardwood | 7 | 136 |
| North Carolina | Lynchburg (2) | 34.92 | 76.80 | WTM | Pine–hardwood | 7 | 136 |
| Ontario | Tunnel Lake | 46.41 | 83.36 | CTM | Mixed pine | 228 | 87 |
| Ontario | Nemagos Lake | 47.63 | 83.24 | BM | Jack pine | 457 | 84 |
| Ontario | Superior 1 | 47.58 | 82.79 | BM | Jack pine | 458 | 82 |
| Ontario | Superior 2 | 47.58 | 82.81 | BM | Black spruce | 461 | 83 |
| Ontario | Superior 3 | 47.57 | 83.84 | BM | Jack pine | 426 | 85 |
| Ontario | Fensom 1 | 89.41 | 49.07 | BM | Mixed conifer | 442 | 61 |
| Ontario | Fensom 2 | 89.38 | 49.08 | BM | Mixed conifer | 450 | 61 |
| Ontario | Fensom 3 | 89.39 | 49.07 | BM | Black spruce | 442 | 61 |
| Ontario | Geraldton | 86.96 | 49.75 | BM | Mixed conifer | 350 | nd |
| Ontario | Road 620 | 89.48 | 49.07 | BM | Black spruce | 435 | 69 |
| Ontario | Supawn 1 | 86.24 | 50.42 | BM | Mixed conifer | 277 | nd |
| Ontario | Supawn 2 | 86.23 | 50.43 | BM | Black spruce | 274 | nd |
| Ontario | Whitefin 1 | 89.45 | 49.01 | BM | Black spruce | 480 | 65 |
| Ontario | Whitefin 2 | 89.44 | 49.02 | BM | Black spruce | 480 | 65 |
| Texas | Kurth-1 | 31.11 | 95.15 | STD | Pine–hardwood | 88 | 109 |
| Texas | Kurth-2 | 31.11 | 95.15 | STD | Pine–hardwood | 88 | 109 |
| Texas | Kurth-3 | 31.11 | 95.15 | STD | Pine–hardwood | 88 | 109 |

**Note:** nd, information not determined or not available.

[a] After Holdridge (1947). BM, boreal moist; CTD, cool temperate dry; CTM, cool temperate moist; WTD, warm temperate dry; WTM, warm temperate

[b] Canadian soil classification based upon Soil Classification Working Group (1998). US soil classification based upon Soil Survey Staff (1996).

growth by 2004.

| | | | Preharvest biomass (kg/ha) | | |
|---|---|---|---|---|---|
| Soil origin | Soil classification[b] | Stand age (years) | Overstory | Understory | Forest floor |
| Glacial fluvial | Gleyed Gray Luvisol, Orthic Luvic Gleysol | 100 | 520 000 | nd | 54 913 |
| Glacial till | Orthic Humo-Ferric Podzol, Gleyed Eluviated Dystric Brunisol | 140 | 174 800 | nd | 78 230 |
| Glacial till | Orthic Gray Luvisol | 110 | 64 400 | nd | 41 065 |
| Glacial till | Orthic Gray Luvisol, Gleyed Gray Luvisol | 140 | 169 600 | nd | 75 329 |
| Volcanic ash | Frigid Ultic Haploxeralfs | 262 | 170 815 | 209 | 54 654 |
| Volcanic mudflow | Mesic Ultic Haploxeralfs | 65 | 352 224 | 240 | 78 724 |
| Volcanic mudflow | Mesic Ultic Haploxeralfs | 115 | 357 453 | 511 | 65 587 |
| Vilcanic ash | Frigid Typic Vitrixerands | 242 | 206 663 | 577 | 53 358 |
| Granodiorite | Mesic Tyouc Dystroxerepts | 117 | 422 111 | 94 | 80 455 |
| Metabasalt | Mesic Typic Palexerults | 108 | 473 348 | 576 | 60 926 |
| Volcanic ash | Frigid Ultic Haploxeralfs | 258 | 212 633 | 2 672 | 63 634 |
| Volcanic mudflow | Mesic Ultic Haploxeralfs | 117 | 438 176 | 674 | 83 820 |
| Granodiorite | Mesic Tyoic Dystroxerepts | 115 | 576 071 | 34 | 72 233 |
| Granodiorite | Mesic Pachic Xerumbrepts | 112 | 493 934 | 324 | 76 901 |
| Granodiorite | Mesic Typic Dystroxerepts | 132 | 373 609 | 43 | 72 567 |
| Volcanic ash | Mesic Andic Xerumbrepts | 230 | 450 193 | 83 | 115 757 |
| Volcanic ash | Frigid Andic Xerochrepts | 120 | 191 250 | 1 750 | 68 000 |
| Basalt | Mesic Typic Hapludand | 100 | 252 000 | 157 | 72 450 |
| Marine sediments | Thermic Glossaquic Paleudalfs | 52 | 153 000 | 4 200 | 15 900 |
| Marine sediments | Thermic Plinthic Paleudults | 45 | 91 000 | 5 100 | nd |
| Marine sediments | Thermic Chromic Dystraquerts | 55 | 236 200 | 1 700 | 15 400 |
| Marine sediments | Thermic Aquic Glossudalfs | 55 | 203 200 | 1 800 | 20 500 |
| Outwash sand | Frigid Typic Udipsamments, Frigid Entic Haplorthods | 35 | 98 000 | 350 | 48 000 |
| Lacustrine clay | Frigid Vertic Glossudalfs | 60 | 106 000 | 1 200 | 128 000 |
| Loess–till | Frigid Haplic Glossudalfs | 70 | 256 000 | 580 | 130 000 |
| Outwash sand–till | Frigid Oxyaquic Hapludalfs | 70 | 211 000 | 2 780 | 99 000 |
| Marine sediments | Thermic Aquic Paleudalfs | 57 | 138 100 | 2 300 | 8 900 |
| Marine sediments | Thermic Aquic Paleudalfs | 55 | 143 500 | 3 500 | 8 300 |
| Marine sediments | Thermic Aquic Paleudalfs | 57 | 153 100 | 2 200 | 9 500 |
| Cherty dolomite | Mesic Typic Paleudults | 75+ | 183 600 | 2 100 | 5 798 |
| Marine sediments | Thermic Aquic Paleudults | 65 | 167 800 | 3 190 | 52 410 |
| Marine sediments | Thermic Aeric Paleaquults | 65 | 167 800 | 3 190 | 52 410 |
| Glacial outwash | Orthic Humo-Ferric Podzol | 57 | 175 000 | nd | 68 376 |
| Glacial outwash | Orthic Dystric Brunisol | 68 | 167 000 | nd | 84 222 |
| Glacial outwash | Orthic Dystric Brunisol | 65 | 100 700 | nd | 93 400 |
| Glacial outwash | Orthic Dystric Brunisol | 75 | 121 500 | nd | 68 900 |
| Glacial outwash | Orthic Dystric Brunisol | 82 | 133 100 | nd | 106 800 |
| Glacial till | Orthic Dystric Brunisol | 100 | 136 800 | 900 | 41 800 |
| Glacial till | Orthic Dystric Brunisol | 100 | 166 400 | 400 | 63 100 |
| Glacial till | Gleyed Dystric Brunisol | 100 | 144 500 | 1 000 | 64 100 |
| Glaciofluvial | Orthic Humo-Ferric Podzol | 115 | 174 700 | 125 | 90 900 |
| Organic (peat) | Hydric Fibrisol | 85 | 64 500 | 6 000 | 277 350 |
| Glaciofluvial | Orthic Humo-Ferric Podzol | 105 | 176 800 | 800 | 45 000 |
| Organic (peat) | Mesic Fibrisol | 100 | 83 000 | 5 000 | 253 500 |
| Organic till | Terric Fibrisol | 120 | 108 300 | 4 300 | 246 800 |
| Organic till | Terric Fibrisol | 110 | 121 700 | 5 100 | 111 100 |
| Marine sediments | Thermic Oxyaquic Glossudalfs | 57 | 231 400 | 1 500 | 15 900 |
| Marine sediments | Thermic Oxyaquic Glossudalfs | 57 | 208 700 | 2 300 | 13 400 |
| Marine sediments | Thermic Oxyaquic Glossudalfs | 57 | 228 600 | 3 000 | 12 700 |

moist; STM, subtopical moist.

($OM_0C_0$, $OM_0C_2$, $OM_2C_0$, $OM_2C_2$) could be installed. A set of four to nine such treatments, all on a single soil type and place, constituted an installation. In most situations, installations were replicated by soil type, producing a block of treatments on sites of similar soil, usually at geographically separate locations.

Harvesting was accomplished by several methods, including innovative means of achieving full suspension to avoid mechanical ground impacts. Soil porosity was modified by compacting the soil to levels approaching a theoretical "growth-limiting bulk density" that varies with soil texture (Daddow and Warrington 1983). Methods for accomplishing this were left to the individual principal investigator. Methods ranged from simple (multiple passes by logging skidders) to complex (vibrating stamping pads mounted on an excavator). Regardless, the goal was to achieve a desired change in soil physical properties, not to compare the types of compacting machinery (which vary greatly in static ground pressure). Because LTSP is focused on forests likely to be managed for wood production, a "nonharvested reference stand" was not part of the experimental design. Often, unharvested portions of the original stand were fundamentally different from the areas chosen for the experiment. But in a few cases the experimental area was bordered by mature, unharvested forest sufficiently similar to the experimental unit that they could serve as an untreated reference. The LTSP study is planned to be extended until at least the culmination of mean annual volume increment, which is defined as a "physical rotation", a period as brief as two decades for tropical forests or as much as 80 years in boreal forests (Powers 2001). To minimize edge effects over such a prolonged period, treatment plots were large (0.4 ha) and separated from residual stands by a distance at least equivalent to the height of bordering trees.

Treatment plots were large enough (0.4 ha) to include several rows of buffer trees to avoid edge effect problems as time passed and measurement trees grew. Plots were regenerated with the native tree species of interest, either planted to a density of 1680 stems·ha$^{-1}$ or regenerated vegetatively from sprouts (*Populus* spp.). Measurement trees were separated from outer plot boundaries by several rows of buffer trees. Except for aspen (*Populus*) forests and the mixed-conifer sites of interior British Columbia, all main effect treatment plots were split. One half of each plot is kept weed free by regular applications of herbicides, and the other half is allowed to develop naturally (thereby producing side-by-side subplots with simple and diverse forest communities). The density of aspen sprouting and administrative policies surrounding herbicide use in British Columbia precluded weed control as a practicle subtreatment on certain installations. Where possible, extreme treatments ($OM_2C_2$) were applied as additional replicates and mitigative measures were added, such as fertilization to replace nutrients and subsoiling to alleviate compaction. Each field installation was equipped with an automated climatological monitoring station, thereby linking all sites into a network characterized by precipitation, temperature, solar radiation, and relative humidity. The first LTSP installation was established in 1990 on the Palustris Experimental Forest in the loblolly pine (*Pinus taeda* L.) forest type of the Louisiana Coastal Plain. The following year saw units established in the mixed-conifer (*Abies–Pinus–Pseudotsuga*) forest of California's Sierra Nevada and in the glacial till landscape of Minnesota's aspen (*Populus deltoides* Bartr. ex Marsh. – *Populus tremuloides* Michx.) forest. Expansion has continued to the present.

### *Posttreatment measurements*

Although many measurements could be taken, principal investigators agreed that a reduced set of eight core measurements were critical to the success of the LTSP program. Beyond treatment establishment, funds were extremely limited. Therefore, minimum measurement intervals were identified for each variable (Powers and Avers 1995):

| Measurement variable | Minimum measurement interval |
|---|---|
| Climatological data | Continuous |
| Soil moisture and temperature | Monthly |
| Soil bulk density | Every 5 years |
| Soil strength | Seasonally every 5 years |
| Soil organic matter content and chemical composition | Every 5 years |
| Water infiltration and saturated hydraulic conductivity | Every 5 years |
| Plant survival, growth, damage from pests, net primary productivity | Every 5 years |
| Foliar chemistry and standing nutrient capital | Every 5 years |

Tree and understory dimensions (survival, height, diameter, coverage) were measured on each treatment plot at a minimum of 5-year intervals. Destructive sampling (harvesting, drying, weighing) was confined to the buffer strips that surrounded measurement plots. Dimensional data were converted to biomass per hectare by felling trees in the buffers and regressing their component biomass against their basal areas and heights. Resultant equations developed for each site were applied to trees inventoried on measurement plots to arrive at an estimate of stand biomass (Madgwick and Satoo 1975). Soils were sampled at the same intervals for three depths (0–10, 10–20, and 20–30 cm) using conventional volumetric techniques (cores or irregular holes) at an intensity of 25–50 sample points·ha$^{-1}$. Fine fractions passing through a 2 mm sieve were assayed for organic carbon and nitrogen by dry combustion and a variety of other nutrients by standard extractants followed by inductively coupled plasma spectrometry and atomic absorption spectrometry.

## Partnerships

As the LTSP program gained momentum it drew widening attention. British Columbia's Ministry of Forests had adopted the concept in 1990 as a high-priority program for interior British Columbia (Hope et al. 1992). Two installations were established by 1994 and several more followed (Holcomb 1996). Independently, the Canadian Forest Service began experiments in Ontario that closely paralleled the LTSP design and were merged with the main program in 1996 to expand the network. Today, the total number of installations with the core design stands at 62 (Fig. 2). In the United States, forest industry expressed concerns that the experiment highlighted only "negative" impacts of management and that LTSP included few treatments aimed at enhancing site productivity. Accordingly, LTSP leaders invited leaders from private and public forest management groups to a 1995 working session in St. Louis, Missouri, to air concerns and to find ways of improving the study and strengthening the network. Emerging was an expanded affiliation that included studies on industrial lands and elsewhere. Conditions for affiliation are that (1) studies have certain elements in common with the LTSP experimental design (at least the $OM_0C_0$ treatment), (2) treatment plots be large enough to have minimal edge effect once trees attained leaf area carrying capacity, and (3) members agree to share findings and provide mutual support (Powers et al. 1996). These affiliate sites have brought the LTSP network to more than 100 installations (Fig. 2), making it the world's largest coordinated effort aimed at understanding how pulse disturbances affect sustained forest productivity.

## The symposium

The Louisiana symposium celebrated the 10th anniversary of the first LTSP installation. The symposium's purpose was to present findings, but organizers recognized the risk that very early results may not be indicative of long-term trends. Accordingly, papers centered on installations that had completed ≥5 years of growth (Table 2). We understood that installations established at the higher latitudes would be in a much earlier stage of stand development than those in regions of milder climates, where crown closure may already have occurred. Given this caveat, we believe that 5 years constitutes the earliest possible indication of long-term trends where conditions favor rapid growth. At the same time, 5 years may be a reasonable period for investigating significant soil phenomena. Following oral presentations, authors were asked to prepare summary papers dealing with a particular topic (tree growth, understory behavior, physiological responses, changes in soil physics, chemistry, and biology), as well as a synopsis integrating the major findings from all 5-year sites. This, then, is the first exposure of integrated findings to the scientific community from an uncommonly broad network joined by camaraderie and a sense of scientific mission.

I write this in the aftermath of Hurricane Katrina. Ironically, the Gulf Coast region, marked by devastation and bathed in despair, is the birthplace of LTSP. Both the concept for the experiment and the first installation were born in Louisiana. Hurricane Katrina hammered home the message that carefully laid plans may be altered swiftly and cataclysmically by unforeseen events. In fact, the fate of our Louisiana and Mississippi installations is not known fully as of this writing. Some may see in this a reason to turn from long-term research to short-term studies with lessened risk. Indeed, many scientific careers have been predicated on just such a philosophy. Yet, forest management itself is fraught with risk because it is a long-term venture. Should we then turn away from forest management, too? I think not. I hope we will embrace long-term studies and face risk bravely. Many matters of significance to forest science and to society cannot be addressed in any other way.

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