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The North American long-term soil productivity experiment: Findings from the first decade of research

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Abstract

First decade findings on the impacts of organic matter removal and soil compaction are reported for the 26 oldest installations in the nation-wide network of long-term soil productivity sites. Complete removal of surface organic matter led to declines in soil C concentration to 20 cm depth and to reduced nutrient availability. The effect is attributed mainly to the loss of the forest floor. Soil C storage seemed undiminished, but could be explained by bulk density changes following disturbance and to decomposition inputs of organic C from roots remaining from the harvested forest. Biomass removal during harvesting had no influence on forest growth through 10 years. Soil compaction effects depended upon initial bulk density. Soils with densities greater than 1.4 Mg m^{-3} resisted compaction. Density recovery was slow, particularly on soils with frigid temperature regimes. Forest productivity response to soil compaction depended both on soil texture and the degree of understory competition. Production declined on compacted clay soils, increased on sands, and generally was unaffected if an understory was absent.
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1. Introduction

1.1. The problem

Forests and society have been linked since the start of the Holocene. Mostly, the linkage has been one of exploitation to satisfy human needs. By 3000 B.C., forests of Cyprus were felled to provide fuel for the smelting of copper and silver (Hermann, 1976). In China, deforestation commenced about 2700 B.C., continuing until the rise and fall of the Chou Dynasty (1127–1255 B.C.), then resuming (Hermann, 1976). Demand for charcoal by the European iron industry in the 11th and 12th centuries led to progressive deforestation (Nef, 1952), bringing some regions close to economic collapse in the 1400s. By the 16th century

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fuelwood scarcity spelled decline in European iron production (Cramer, 1984).

But times change. China today has become a world leader in rates of afforestation (FAO, 2001) and forested area has stabilized in many industrial nations. Despite this, social demand for wood and wood products, coupled with new policies restricting domestic harvests, have created markets that favor overcutting and deforestation elsewhere. Nations supporting the highest biomass per ha are particularly vulnerable and tend to show net forest loss. FAO (2001), in its recent world assessment, reported a decline in global forest area of more than 2% in the past decade. Prominent among those with high rates of deforestation are tropical nations such as Brunai, Malaysia, and Thailand (FAO, 2001), but North America is not immune. While forest area of Canada and the United States is stable or slightly increasing, Mexico shows an annual loss of 2%, placing it among the highest in the world (Stennes et al., 2005).

Where forest area has stabilized, economic forces turn many managers to shorter rotations and greater utilization. Fox (2000), Sutton (1999) and others see intensive plantation management on appropriate sites as a realistic solution to global wood needs. Nambiar (1996, 1999) agrees, but cautions that early production rates may not be sustainable without due attention to the soil. A century ago the Chief of the U.S. Bureau of Soils expressed the sanguine notion that ''The soil is the one indestructible, immutable asset that the nation possesses. It is the one resource that cannot be exhausted, that cannot be used up'' (Whitney, 1909). Despite this, soil management is seen increasingly as the underpinning of sustainable forest productivity (Adams et al., 1998; Dyck et al., 1994; Kimmins, 1996; Nambiar, 1996; Powers et al., 1990). The principle that soil management is a key to sustained productivity has been a basic theme of every North American Forest Soils Conference. How soil disturbances affect sustainable productivity remains a matter of conjecture.

New Zealanders have made a considerable effort at finding definitive answers. One notable effort was the experimental trial at Maramarua on the North Island (Skinner et al., 1989). Established in 1982, the Maramarua trial was an innovative study to determine rotation-length impacts of additive types of soil disturbance on the productivity of *Pinus radiata*. The experiment was replicated in a randomized block design on a heavy clay soil. Early findings from the Maramarua trial coupled with concerns over utilization impacts on sustainable productivity led to a more extensive network of manipulative experiments in New Zealand centering on organic matter removal (Smith et al., 2000). Findings after two decades at Maramarua (Murphy et al., 2004) show no effect of forest floor removal on plantation stem volumes. Forest floor removal and moderate compaction reduced standing volumes by 8%. Topsoil removal combined with substantial soil compaction reduced stand volumes by 42%. The Maramarua trial was a pioneering effort, but its design precluded separation of organic removal and soil compaction and its plot sizes were small and treatments were affected by neighboring plots. This paper reports another step toward resolving remaining ambiguities. Our objective is to examine the hypothesis that organic matter removal or soil compaction associated with timber harvest have universal impacts on forest productivity across a broad network of soils, climates, and forest types.

1.2. Background for the experiment

The North American long-term soil productivity study (LTSP) was founded as a continuing cooperate effort at addressing the ultimate consequences of pulse soil disturbance on fundamental forest productivity. Launched in 1989, LTSP was a research response to the National Forest Management Act of 1976 (NFMA). NFMA and related legislation required the U.S. Secretary of Agriculture to ensure, through research and monitoring, that national forests be managed to protect the permanent productivity of the land (USDA Forest Service, 1983). This seems a superfluous statement of the obvious, given that sustained forest productivity is a broadly recognized aim of modern forest management (American Forests and Paper Association, 2000; Montreal Process Working Group, 1998; United Nations, 1992) and has been a Forest Service goal since the agency was founded. It is remarkable only in that NFMA may be the world's first modern mandate for a forestland ethic that carries the weight of law. This mandate predates the Montreal Process (Canadian Forest Service, 1995)

and the environmental surge toward ''green certification'' (Anonymous, 1995) by more than a decade.

''Land productivity'' was never defined in NFMA. Presumably, it encompasses a site's capacity to produce a cornucopia of timber, wildlife, watershed, fishery, and aesthetic values. All are legitimate expressions of land productivity, but some are less tangible, more subjective, and more variable temporally than others. With guidance from the U.S. Office of General Council, the Forest Service defined land productivity as the carrying capacity of a site for vegetative growth (USDA Forest Service, 1987). This makes sense, because the capacity of a site to capture carbon (C) and grow vegetation is central to its potential for producing all other values.

But trying to measure the productive potential of a site directly by assaying trends in tree or stand growth is fraught with frustrations and uncertainty. Growth trends in operational stands vary with stand age, structure, stocking and treatment history (Powers, 2001), and usually lack reference controls for comparison. Alternatively, soil-based indices of productive potential have been proposed as a more objective measure of a site's capacity for vegetative growth (Burger, 1996; Powers et al., 1990). The USDA Forest Service has adopted this approach and first approximation working standards are in place throughout the federal regions (Page-Dumroese et al., 2000; Powers et al., 1998). Meant as monitoring tools, these standards are presumed to reflect a site's potential, and to mark thresholds for significantly impaired productivity.

With few exceptions (Ballard and Pritchett, 1975; Burger and Kelting, 1999; Froehlich and McNabb, 1984; Gale and Grigal, 1988; Powers, 1980), correlations between soil monitoring variables and potential productivity tend to be anecdotal or regionally restricted in North America, and others used by the Forest Service are mainly conceptual. Because they are conceptual and somewhat subjective, they can be challenged as being too lenient or too stringent. Furthermore, monitoring thresholds based on conceptual linkages to productivity may not be persuasive to professionals faced with day-to-day field operations and pressures to meet production goals. Exactly ''what is convincing'' prompted an extensive review of the world's literature and revealed that two ecosystem properties – site organic matter and soil porosity – were most apt to impact long-term productivity (Powers et al., 1990). While these site and soil properties seem to have singular importance, existing information is sparse, site specific, often contradictory, and too anecdotal to be broadly useful. Consequently, we proposed a nationally coordinated field experiment to address the issue directly and unambiguously (Powers et al., 1990).

1.3. The study

The LTSP program rests on the principle that within the constraints of climate, a site's potential productivity is governed strongly by physical, chemical, and biological soil processes affected readily by management. Two key properties directly affected are soil porosity and site organic matter. Porosity and organic matter regulate fundamental site processes through their roles in water and gas exchange, physical restrictions on rooting, microbial activity, soil aggregate stability, and overall resource availability (Fig. 1). Therefore, porosity and organic matter were targeted for specific manipulation in large-scale, long-term experiments. Treatments were chosen to encompass the range of possibilities occurring under management. The experiment was designed to address 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 dissipate with time, or can be mitigated by management practices
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

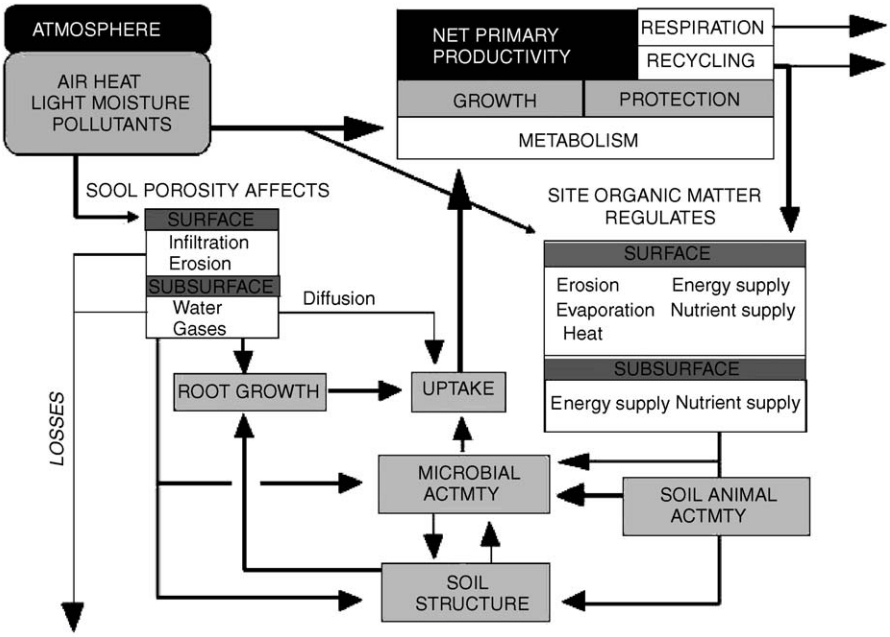


Fig. 1. Conceptual model suggesting the overriding influence of soil porosity and site organic matter on fundamental processes that regulate primary productivity within climatic constraints (modified from Powers et al., 1998). This is the model that guided the LTSP experimental design.

The study was targeted at forest types, age classes, and soil conditions apt to fall under active forest management involving harvesting, thinning, or fuel modification. These were fully stocked, young-growth, even-aged stands i.e. not ''ancient forests'' or non-forested openings. Preliminary 0.4 ha plots were identified and surveyed through a systematic grid sampling procedure for variability in soil and stand conditions. We chose this plot size in order to minimize edge effect from establishment to the culmination of mean annual stem volume increment, a common standard for evenage physical rotations (Powers, 2001). Plots with comparable variability at a given location (similar soil type, stand density, and amounts of soil disturbance) were chosen for the experiment. Pretreatment samples were taken to quantify standing biomass and nutrient capital in the overstory, understory, and forest floor. Plots were then harvested under close supervision and treatments were imposed randomly. The main effect treatments were as follows:

Main effect	Symbol	Description of treatment
Modify site organic matter	OM_0	Tree boles removed. Retain crowns, felled understory, and forest floor
	OM_1	All aboveground living vegetation removed. Forest floor retained
	OM_2	All surface organic matter removed. Bare soil exposed
Modify soil porosity	C_0	No soil compaction
	C_1	Compact to an intermediate bulk density
	C_2	Compact to a high bulk density

Compaction treatments were applied by a variety of mechanical means when soils were near field capacity and particle resistances were low. The method of treatment was immaterial because the goal of the C_2 treatment was to increase soil bulk density to 80% of the density level proposed by Daddow and Warrington (1983) as limiting to root growth. Hypothesis 1 can then be addressed by comparing vegetative productivity across the nine factorial combinations of these

Table 1
Absolute and proportional amounts of biomass and nitrogen removed by the three organic matter treatments on representative LTSP sites

Location	Life zone	Forest type (years)	Biomass removed (Mg/ha) (% of aboveground total)			Nitrogen removed (kg/ha) (% of aboveground total)		
			OM_0	OM_1	OM_2	OM_0	OM_1	OM_2
British Columbia	BM	Subboreal spruce (140)	126 (56)	158 (71)	223 (100)	195 (18)	253 (24)	1068 (100)
Minnesota	CTM	Trembling aspen (60)	175 (61)	214 (75)	286 (100)	194 (30)	316 (48)	653 (100)
Idaho	CTM	Mixed conifer (120)	160 (61)	191 (73)	261 (100)	190 (22)	410 (48)	846 (100)
California	WTD	Mixed conifer (108)	252 (47)	473 (89)	532 (100)	218 (20)	609 (57)	1064 (100)
Missouri	WTM	Central hardwoods (75)	96 (42)	175 (77)	228 (100)	195 (24)	540 (67)	811 (100)
North Carolina	WTM	Pine and hardwoods (65)	146 (65)	168 (75)	223 (100)	98 (19)	159 (30)	523 (100)
Louisiana	STM	Loblolly pine (52)	133 (77)	153 (88)	173 (100)	134 (38)	229 (65)	352 (100)

OM_0: bole only removed; OM_1: whole tree removed; OM_2: whole tree + understory and forest floor removed. Life zone codes after Holdridge (Lugo et al., 1999); BM: boreal moist; CTM: cool temperate moist; WTD: warm temperate dry; WTM: warm temperate, moist; STM: subtropical moist.

plots without confounding by uncontrolled variables. Replicating this experiment across an array of soil types and Holdridge Life Zones (Lugo et al., 1999) gave us a rigorous test of Hypothesis 2. Most installations also received 0.2 ha split plot treatments of vegetation control/no vegetation control, affording two measures of productivity: a simplified measure of trees, only, and a more complex measure of trees and other regional vegetation. This enables us to study the significance of more diverse plant communities on soil fertility processes (Hypothesis 4). Many installations also included mitigative treatments following OM_2C_2 treatments, such as fertilization and/or soil tillage, thereby addressing Hypothesis 3.

We had two reasons for choosing these levels of organic matter manipulation. First, they encompass the extremes in organic matter removal likely under any operational practice short of removing surface soil or extracting roots. Second, they produce a step series of nutrient removal that is disproportionate to biomass loss. Table 1 illustrates these points using seven typical LTSP sites arrayed along a climatic gradient. It shows that overstory trees commonly contain three-quarters or more of site aboveground organic matter with half or more partitioned into boles (OM_0 biomass removals varied between 42 and 77% of the aboveground total). In general, the forest floor accounts for less than one-quarter of aboveground organic matter (note the biomass difference between OM_1 and OM_2 treatments).

Nitrogen (N) shows a different trend. Although tree boles account for most aboveground organic matter in mature forests, they hold less than one-third of the aboveground N capital. On average (and in the absence of frequent disturbance), the forest floor of mature stands contains as much N as boles and crowns, combined (note the difference between OM_1 and OM_2 treatments). Even on a Louisiana site subject to repeated underburning, the forest floor contained only 12% of the aboveground biomass but more than one-third of the N (Table 1). Furthermore, the proportion of aboveground N in the forest floor varies with climate. In moist boreal forests of British Columbia where wildfire is infrequent and decomposition is slowed by low temperature and perhaps by partial anaerobia, the forest floor accumulates far more N than is contained in the vegetation. Under warmer, more humid conditions, the forest floor decomposes rapidly and is a relatively low reservoir of N. Regardless of climatic region, the understory in mature forests is only a minor component of site organic matter or N (only a few percentage points of the aboveground total after canopies have closed).

2. Methods

2.1. Establishment

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. Trees matching the preharvest forest type were planted to a density of 1680 stems ha^{-1}. Clonal forest types such as *Populus* spp. regenerated vegetatively from sprouts. The first LTSP installation was established in 1990 on the Palustris Experimental

Forest in the subtropical, dry loblolly pine (*Pinus taeda*) forest type of the Louisiana Coastal Plain. The following year saw units established at Challenge Experimental Forest in the warm, temperate dry mixed conifer (*Abies*/*Pinus*/*Pseudotsuga*) forest of California's Sierra Nevada, and at Marcell Experimental Forest in the glacial till landscape of Minnesota's boreal, moist aspen (*Populus grandidentata*/*tremuloides*) forest. In 1992 units were established on the Croatan National Forest of North Carolina's Lower Coastal Plain pine–hardwood forest (warm, temperate moist) and at Priest River Experimental Forest in the cool, temperate moist mixed conifer (*Picea*/*Pinus*/*Pseudotsuga*) forest type of northern Idaho. The experiment expanded quickly to other sites and Life Zones, including Missouri's warm, temperate moist central hardwood forests in 1994. British Columbia's Ministry of Forests adopted the LTSP concept in 1990 as a high priority program for Interior BC (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 the two programs merged in 1996 to expand the network. Today, the total number of installations with the core design stands at 62. Combined with nearly four-dozen closely related affiliate installations, these comprise the world's largest coordinated research network addressing basic and applied issues of forest management and sustained productivity (Fig. 2).

2.2. Post-treatment measurements

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 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

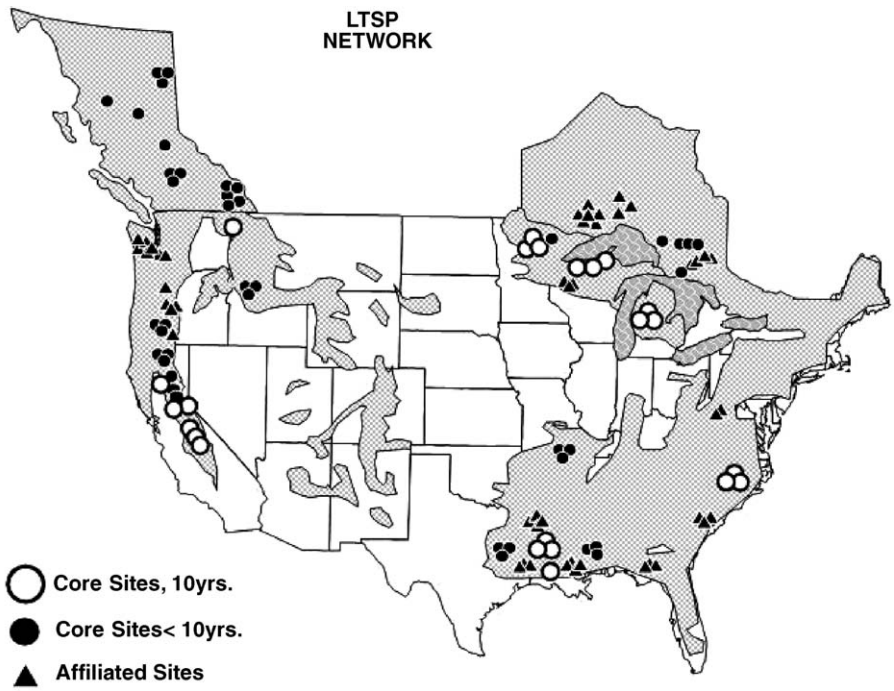


Fig. 2. Core and affiliate LTSP installations relative to the approximate range of commercial forest in the United States and two Canadian provinces. Large open circles indicate installations with 10 years of data.

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 C and N by dry combustion, and a variety of other nutrients by standard extractants followed by inductively coupled plasma spectrometry and atomic absorption spectrometry.

While early findings have been reported for individual sites or small clusters of similar sites (Alban et al., 1994; Amaranthus et al., 1996; Gomez et al., 2002; Powers and Fiddler, 1997; Stone and Elioff, 1998), most have dealt with stand conditions short of crown closure and results may not be indicative of long-term trends when sites are stocked at leaf area carrying capacity. More recently, Powers et al. (2004), Sanchez et al. (in press), and Scott et al. (2004) have summarized findings for stands at multiple sites separated geographically and climatically.

We have resisted making a synopsis of cross-site comparisons until trees had reached a decade of growth. While a decade may seem a long observational period for many studies, crown canopies on the most severe treatments still have not closed on many treatment plots nor yet reached a leaf area index of three or more marking stable productivity (Landsberg and Gower, 1997). We believe, however, that growth and soil chemistry oscillations from initial perturbations have dampened enough to give us an early glimpse of longer-term trends. This paper constitutes the first effort at summarizing findings of main effect treatments from 26 United States installations in the Lake States, South, and West—those installations that have reached 10 growing seasons. Statistical analyses are principally of two types: analysis of variance, and least squares regression and analysis of covariance via standard procedures (Muller and Fetterman, 2002). Our report examines the impacts of extreme treatments to test Null Hypotheses 1 and 2. Detailed interactions among treatments and effectiveness of mitigative treatments will be discussed in later papers as more installations approach leaf area carrying capacity. Our findings carry the caveat that trends may change when data are available from all LTSP installations.

3. Findings at 10 years

3.1. Characteristics of installations

The 26 oldest LTSP installations are the basis for this paper (Table 2). They differ markedly in climate and geology and encompass seven states and five Holdridge Life Zones. Complete dry matter removal varied six-fold, from about 150 Mg ha^{-1} in Michigan's aspen forests to nearly 650 Mg ha^{-1} in mixed-conifer forests of California (a range in N removal between 330 and 1300 kg ha^{-1}). Forest floor biomass varied from nearly nothing (the periodically underburned Malbis site in Louisiana) to as much as 150 Mg ha^{-1} (the Chippewa sites in Minnesota). Results of the main effect treatments are as follows.

3.2. Soil chemistry

3.2.1. Organic matter and carbon

We tested the hypothesis that removing aboveground organic matter leads to declines in soil organic C by comparing concentrations 10 years after harvest in our extreme organic matter removal treatments (OM_0 versus OM_2). Soil compaction was held at C_0 so as to examine the specific effect of organic matter removal on soil chemistry. Ten-year soil C concentrations at 24 installations spanning six states decreased with depth, averaging 28.6, 16.5, and 5.2 g kg^{-1} in the OM_0 treatment for 0–10, 10–20, and 20–30 cm depths, respectively (Fig. 3). They varied from a high of 144 g kg^{-1} near the soil surface to a low of 1 g kg^{-1} at 20–30 cm. Regardless of depth, organic C concentration in <2 mm soil fractions was generally unaffected by complete removal of surface organic matter (OM_1 versus OM_2) if OM_0 C concentrations were between 20 and 40 g kg^{-1}. However, polynomial trends (Table 3) suggest 10-year declines of 13% or greater for soils testing less than 10 g C kg^{-1} or at 0–10 cm, and declines of 6% or greater for soils testing above 50 g C kg^{-1}. Organic C trends were similar in the 10–20 cm depth zone, although declines were greater in soils with high C concentrations. Using OM_0 C concentrations as a standard, 10-year declines exceeded 25% for soils testing greater than 80 g C kg^{-1} (Table 3). Concentrations below 20 cm were not significantly different at $P < 0.10$. Equations in Table 3 suggest that soils testing less than 2.5 g C kg^{-1}

Table 2
Site and pretreatment stand characteristics of LTSP installations achieving 10 years of growth

Location	Installation name	Life zone	Forest type	Elevation (m)	Annual precipitation (cm)	Soil origin	Soil family	General texture	Stand age (years)	Preharvest biomass (kg/ha)		
										Overstory	Understory	FF
California	Blodgett	WTD	Mixed conifer	1350	1651	Andesite	Mesic Ultic Haploxeralfs	Loamy	65	352451	240	78724
California	Central	WTD	Mixed conifer	1685	114	Granodiorite	Mesic Tyouc Dystroxerepts	Sandy loam	117	422111	94	80455
California	Challenge	WTD	Mixed conifer	790	173	Metabasalt	Mesic Typic Palexerults	Clayey	108	473348	576	60926
California	Owl	WTD	Mixed conifer	1805	114	Granodiorite	Mesic Tyouc Dystroxerepts	Sandy loam	115	576071	34	72233
California	Vista	WTD	Mixed conifer	1560	76	Granodiorite	Mesic Typic Dystroxerepts	Sandy loam	132	373609	43	72567
California	Wallace	WTD	Mixed conifer	1575	178	Volcanic ash	Mesic Andic Xerumbrepts	Loamy ash	230	450193	83	115757
Idaho	Priest River	CTM	Mixed conifer	900	85	Volcanic ash	Frigid Andic Xerochrepts	Loamy ash	120	191250	1750	68000
Louisiana	Glenmora	STD	Pine–hardwoods	61	147	Marine sediments	Thermic Glossaquic Paleudalfs	Sandy loam	52	153000	4200	5900
Louisiana	Malbis	STD	Pine–hardwoods	52	150	Marine sediments	Thermic Plinthic Paleudults	Loam	45	91000	5100	0
Louisiana	Mayhew	STD	Pine–hardwoods	61	147	Marine sediments	Thermic Chromic Dystraquerts	Clay loam	55	236200	1700	15400
Louisiana	Metcalf	STD	Pine–hardwoods	61	147	Marine sediments	Thermic Aquic Glossudalfs	Loam	55	203200	1800	20500
Michigan	Huron (3 reps)	CTM	Aspen	240	75	Outwash sand	Frigid Typic Udipsamments Frigid Entic Haplorthods	Sandy	35	98000	350	48000
Michigan	Ottawa (3 reps)	BM	Aspen	350	77	Lacustrine clay	Frigid Vertic Glossudalfs	Loamy clay	60	106000	1200	128000
Minnesota	Chippewa (3 reps)	BM	Aspen	410	64	Loess/till	Frigid Haplic Glossudalfs	Loamy	70	256000	580	130000
Mississippi	Freest-2	STD	Pine–hardwoods	69	150	Marine sediments	Thermic Aquic Paleudalfs	Loamy	57	143500	3500	8300
Mississippi	Freest-3	STD	Pine–hardwoods	69	150	Marine sediments	Thermic Aquic Paleudalfs	Loamy	57	153100	2200	9500
North Carolina	Goldsboro	WTM	Pine–hardwoods	7	136	Marine sediments	Thermic Aquic Paleudults	Loamy sand	65	167800	3190	52410
North Carolina	Lynchburg (2 reps)	WTM	Pine–hardwoods	7	136	Marine sediments	Thermic Aeric Paleaquults	Loamy sand	65	167800	3190	52410

Life zone codes after Holdridge (Lugo et al., 1999); BM: boreal moist; CTM: cool temperate moist; WTD: warm temperate, dry; WTM: warm temperate, moist; STD: subtropical dry; STM: subtropical moist.

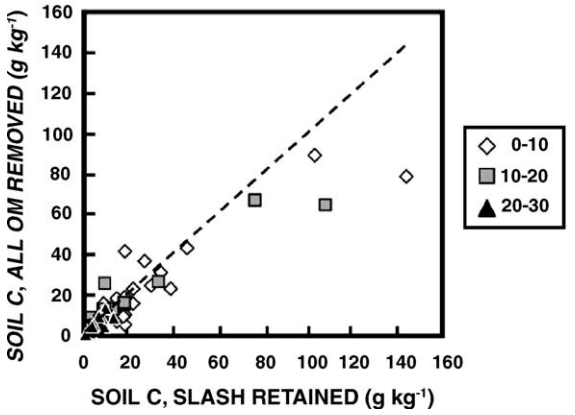


Fig. 3. Concentration of organic soil C at 10 years for three soil depths as influenced by slash retention or complete removal of all surface organic residues. Depths are indicated by symbols and each data point represents a replicated treatment plot. Basis: 21 LTSP installations in five states with complete data sets. Dashed line indicates 1:1 parity between treatments.

1 in their surface 10 cm would be depleted of organic C in 10 years if all surface residues were removed. Interestingly, soil C concentrations in the OM_1 treatments averaged 23% higher at 0–10 cm than the average for the OM_2 treatment ($P = 0.05$). They also were higher than in the OM_0 treatment, though the probability of chance differences was greater ($P = 0.08$).

While there clearly are differences among treatments in soil C concentrations, have absolute changes occurred since harvest? Volumetric soil samples collected pre- and post-harvest at three standard depths from 13 replicated installations in Minnesota (3), Michigan (3), North Carolina (3) and Louisiana (4) (the only sites for which analyses were available for all intervals) were sieved to 2 mm and analyzed for organic C (the sole exception was Louisiana, where preharvest samples were taken only from the 0–15 cm depth). Concentrations were expanded with fine fraction bulk densities to estimate absolute quantities of soil C ha^{-1} and 10-year trends are shown for the OM_2C_0 treatment in Fig. 4. As expected, all sites showed highest absolute amounts of soil C in the surface 10 cm. But surprisingly – given a few years of fallow condition following harvest that should stimulate soil respiration – soil C quantities generally were similar to or significantly greater ($P < 0.05$) after 5 or 10 years than at preharvest, particularly in the upper 10 cm. No differences were found between OM_1 and OM_2 treatments at either 5 or 10 years ($P > 0.50$). Presence or absence of a forest floor had no apparent influence on absolute quantities of C in the soil fine fraction.

3.2.2. Nutrient availability

Li et al. (2003), studying N mineralization in situ on the North Carolina installations, found that 2- and 5-year rates of N availability were affected less by main effect treatments than by subtle differences in soil drainage class and by presence or absence of understory vegetation. Overall, net mineralization rates declined about 80% between years 2 and 5, but rates were unaffected in either year by organic matter removal. Sanchez et al. (in press), sampling the same plots 5 years later, found no effect of organic matter removal on total soil N. However, they did conclude that removal was associated with a substantial decline in soil P availability at all depths to 30 cm, with the decline associated primarily with OM_2. Five-year data from an assortment of LTSP sites in the southern Coastal Plain (Sanchez et al., in press) showed that both OM_1 and OM_2 treatments led to significant declines in extractable soil phosphorus (P) in Louisiana and Texas sites, and to significant declines

Table 3
Statistical parameters of the relationship by soil depth between C concentrations (g kg^{-1}) in the <2 mm soil fraction where logging slash had been retained (OM_0) and where all surface organic matter had been removed (OM_2) a decade earlier

Soil depth (cm)	Model	Adj. R^2	$P > F$ slope = 1	$P > F$ intercept = 0
0–10	$OM_2 = 1.200\,OM_0 - 0.004\,OM_0^2 - 2.915$	0.85	<0.01	<0.02
10–20	$OM_2 = 1.168\,OM_0 - 0.005\,OM_0^2 - 0.707$	0.93	<0.01	0.02
20–30	$OM_2 = 1.732\,OM_0 - 0.065\,OM_0^2 - 1.642$	0.69	0.41	0.52
All depths	$OM_2 = 1.058\,OM_0 - 0.003\,OM_0^2 - 0.242$	0.90	<0.01	<0.01

All models are tested against the hypothesis that OM_0 and OM_2 soil C concentrations are not significantly different at 10 years (primary slope = 1.0, intercept = 0.0).

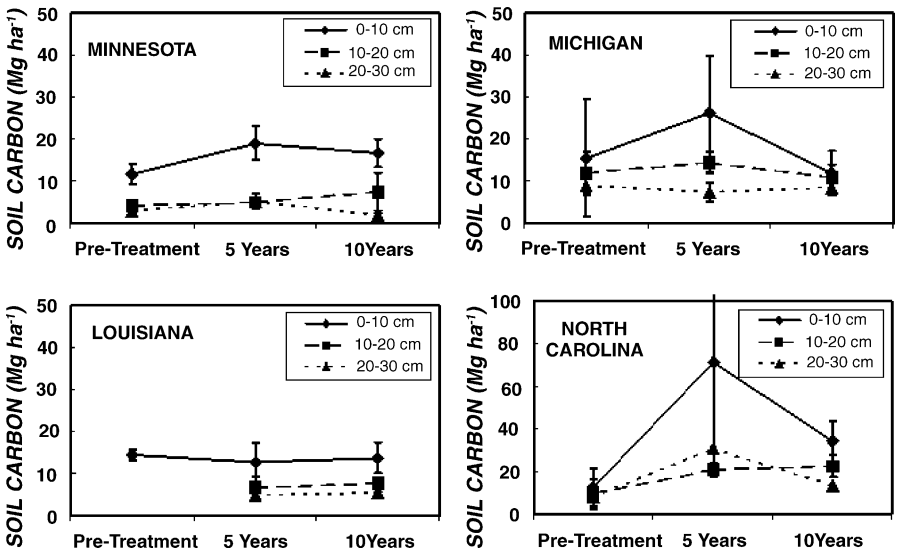


Fig. 4. Means and standard errors of fine fraction organic soil C stored at three soil depths before and after the OM_2C_0 treatment in Minnesota (Chippewa National Forest, three installations, fine-loamy soil textures); Michigan (Huron-Manistee National Forest, three installations, sandy soil textures); Louisiana (Kisatchee National Forest, four installations, loamy to clayey soil textures); North Carolina (Croatan National Forest, three installations, loamy soil textures). Soil depths are indicated by symbols. In Louisiana, pretreatment samples were taken only to 15 cm.

in both foliar N and P concentrations due to forest floor removal when data from all states were pooled.

As part of a graduate thesis, Craigg examined treatment effects on potential soil N availability a decade after treatment on four contrasting LTSP sites in California. Both chemical and microbial indices of N availability were applied to soil samples taken at surface (0–10 cm) and subsurface (10–20 cm) depths throughout the year, and all methods, sampling dates and depths led to the same conclusions. Namely, that complete organic matter removal was associated with significant ($P < 0.05$) and substantial declines in soil C and N concentrations, as well as measures of potential N availability (Table 4). Using the anaerobic incubation technique (Powers, 1980) and the 10–20 cm soil depth zone as an example, the decline in potential N availability was due primarily to the loss of the forest floor (Fig. 5).

3.2.3. Productivity

To test the hypothesis that site organic matter removal affects forest productivity we compared total standing biomass at 10 years for our 26 sites covering 4 regions: 1 from the Idaho Panhandle, 6 from

Table 4
Concentrations of organic C, N, and two measures of N availability in soil of four non-compacted LTSP sites in California after 10 years (Craigg, unpublished)

Treatment	C (g kg^{-1})	N (g kg^{-1})	Anaerobic N (mg kg^{-1})	KCl N (mg kg^{-1})
0–10 cm				
Slash retained	108.0	6.47	43.2	40.6
All OM removed	78.4	5.24	22.2	31.4
P	0.04	0.05	0.02	<0.01
10–20 cm				
Slash retained	85.3	5.85	36.7	30.4
All OM removed	61.2	4.76	23.2	24.9
P	0.12	0.04	0.02	0.04

P = probability that mean differences are due to chance.

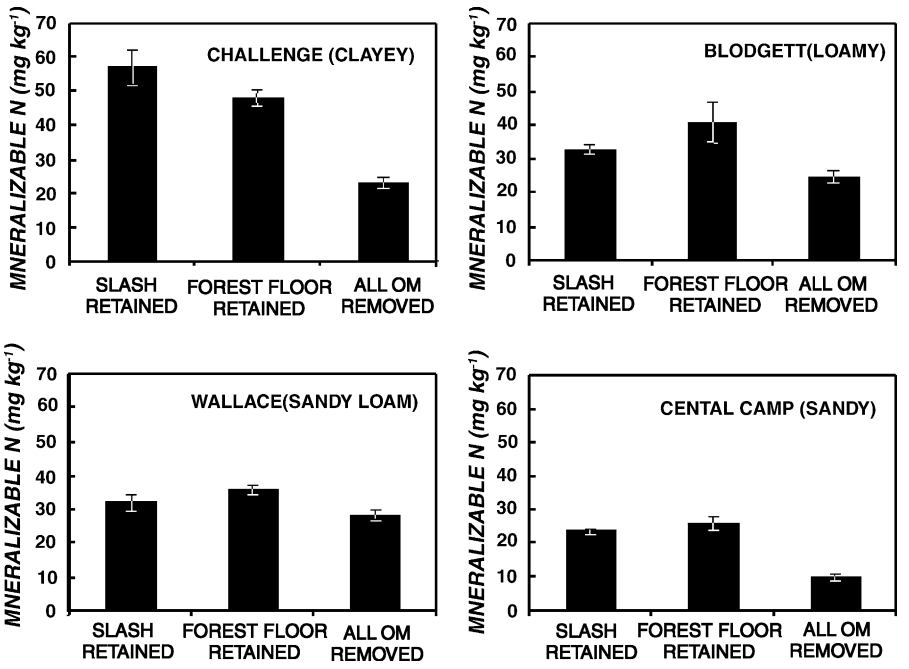


Fig. 5. Means and standard errors of mineralizable N at 10–20 cm soil depth for varying levels of surface organic matter retention or removal. Basis: four California LTSP installations at 10 years (Craigg, unpublished). Standard errors represent sampling variation within individual treatment plots.

California's Sierra Nevada, 9 from the Lake States, and 10 from the Southern Coastal Plain. Planting through logging slash sometimes reduced tree survival. Therefore, we combined the standing biomass of both planted trees and understory vegetation on non-herbicide plots to better reflect true site potential (Fig. 6). Combining all data, the linear trend determined by regression equation (1) indicates no general decline in productivity with organic matter removal ($P > F = 0.88$):

$$\mathrm{OM_2\ biomass} = 5.99 + 0.98\,\mathrm{OM_0\ biomass}, \quad \mathrm{Adj.}\ R^2 = 0.58 \tag{1}$$

Of the three forest types, only Lake States aspen showed reductions in productivity as indicated by a significantly lesser regression slope ($P > F = 0.08$):

$$\mathrm{OM_2\ aspen\ biomass} = 3.84 + 0.64\,\mathrm{OM_0\ aspen\ biomass}, \quad \mathrm{Adj.}\ R^2 = 0.59 \tag{2}$$

Similar results for aspen were reported by Alban et al. (1994).

3.3. Soil compaction

3.3.1. Physical changes

Soil bulk densities in the top 30 cm averaged 1.28 Mg m^{-3} for our sites before treatment and

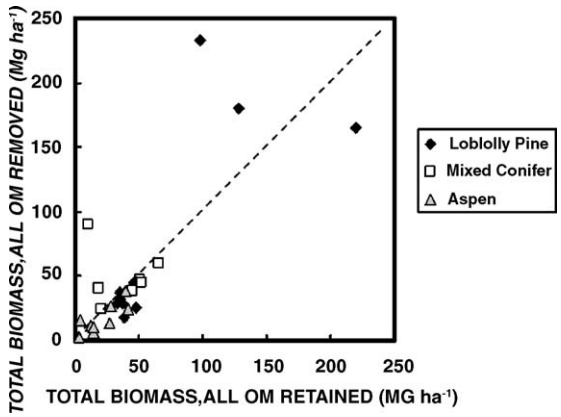


Fig. 6. Standing biomass at 10 years of all vegetation (trees plus understory) as affected by minimal (OM_0) and complete (OM_2) removal of surface organic matter. Basis: 26 LTSP installations in seven states coded by general forest type (see Table 2). Dashed line indicates 1:1 parity between treatments.

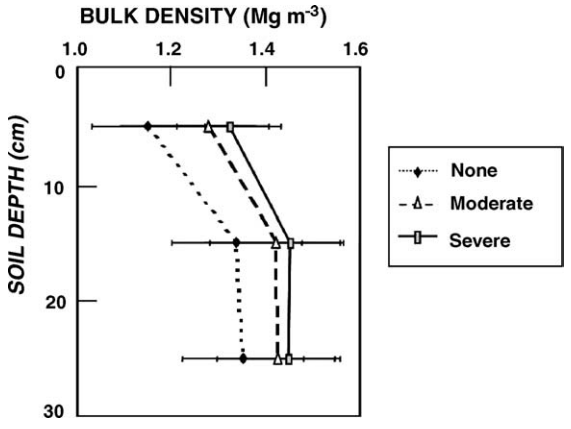


Fig. 7. General trend in soil bulk density with depth immediately following compaction treatment. Means from multiple LTSP installations in several states with complete data sets. Bars indicate standard errors.

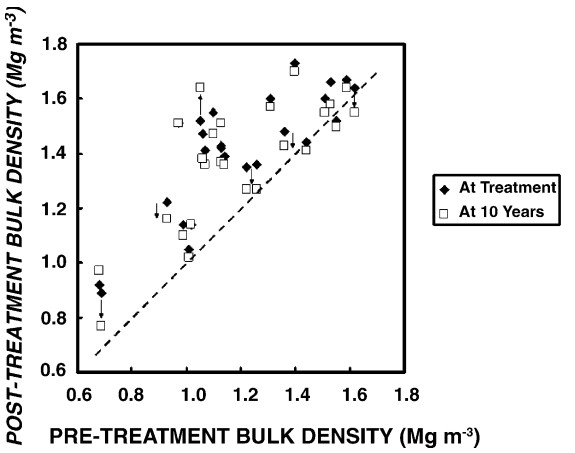


Fig. 8. Effect of C_2 treatment on 10–20 cm soil bulk density immediately after treatment (filled diamonds) and after 10 years (open squares), relative to density before treatment. Arrows indicate degree of recovery after one decade. Dashed line indicates 1:1 parity between treatments.

increased with soil depth to 30 cm (Fig. 7). Compaction treatments increased bulk densities by similar amounts (about 0.11 Mg m^{-3}) at all measured depths (Fig. 7). On average, density differences were small between the C_1 and C_2 (moderate and severe) treatments and were maximal at 10–20 cm. Accordingly, we focus on this depth zone for further analyses. Pretreatment densities averaged 1.17 Mg m^{-3} in this zone, but the range was wide (0.58–1.62 Mg m^{-3}). We recognize that we did not achieve our C_1 goal of a value half way between C_0 and C_2. But we do not believe we could have achieved greater soil compaction on the sites in this study (C_2 truly represents an extreme change). Consequently, our analyses will center only on comparisons between the two extreme treatments, C_0 and C_2.

Severe soil compaction increased bulk density an average of 18% in the 10–20 cm depth zone (Fig. 8). However, not all sites responded similarly and the degree of increase depended on the initial bulk density. As initial bulk density increased, the relative change due to severe compaction declined. Very little compaction occurred if initial soil bulk densities (P_b) were greater than 1.4 Mg m^{-3} (the Louisiana and Mississippi sites with soils derived from marine sediments, Table 2). The relationship was linear but weak:

$$\text{percentage increase in } P_b = 67.36 - 39.64\,P_b \text{ initial}, \quad \text{Adj. } R^2 = -0.44 \tag{3}$$

Absolute increases in soil bulk density were greater in the middle ranges of initial density than at lower or higher. The relationship, again weak, was related to initial bulk density as a second-order polynomial:

$$\text{absolute change in } P_b = 1.42\,P_b \text{ initial} - 0.72(P_b \text{ initial})^2 - 0.40, \quad \text{Adj. } R^2 = -0.38 \tag{4}$$

Did soils recover from compaction in 10 years? Resampling the same plots a decade after treatment reveals that some recovery occurred, but it was slight (Fig. 8). Installations showing substantial compaction but negligible recovery were from Idaho, Michigan, and Minnesota (Table 2). Covariance analysis of regression of P_b *initial* versus P_b *10 years* indicates no differences in slope ($P > F = 0.98$) or intercept ($P > F = 0.68$). Put simply, soils rarely recovered from severe compaction in 10 years, regardless of their initial bulk densities.

3.3.2. Productivity

Planting procedures at the California installations included creating small planting holes of friable soil using a power auger, and this was applied to all treatments—not merely those involving soil compaction. Augering was done to ensure seedling survival following spring planting in California's summer-dry

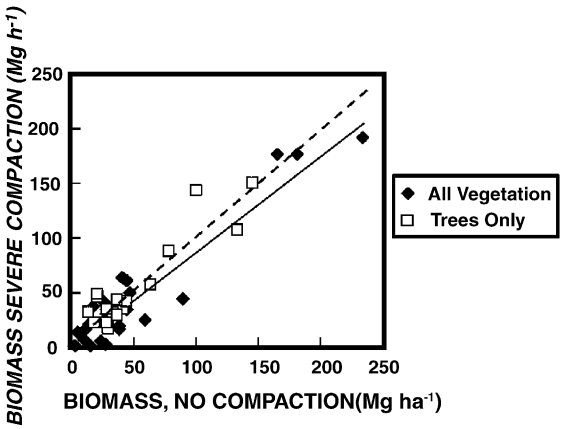


Fig. 9. Effect of severe soil compaction on standing biomass of all installations at 10 years. Filled diamonds: combined biomass of trees and understory; open squares: biomass of trees on plots free of understory. Dashed line indicates 1:1 parity between treatments. Solid line indicates statistically significant trend of combined overstory and understory biomass on C_2 treatments. Tree biomass on understory-free plots was not affected by compaction.

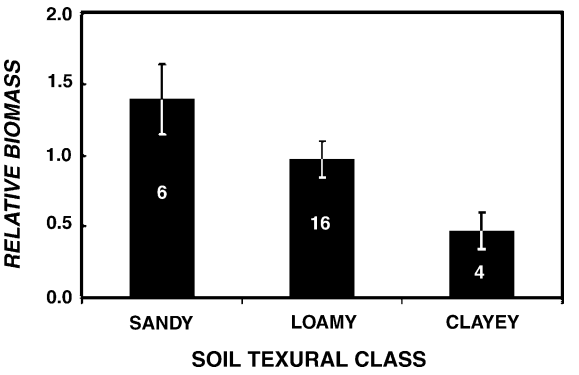


Fig. 10. Relative response (biomass compacted/biomass uncompacted) of all aboveground vegetation at 26 installations to severe soil compaction by predominant soil textural class. Bars indicate standard errors. Number of sites shown for each textural class.

climate and should have minimal effect on infiltration rates or gas exchange in the larger soil volumes exploited by roots over 10 or more years. We tested the hypothesis that compaction has no consistent effect on forest productivity by regressing 10-year total biomass (trees + understory), as well as tree biomass on understory-free plots, for severely compacted plots in 26 installations against biomass on paired plots not receiving compaction. We centered on OM_2 to remove organic matter as a confounding variable. A significant departure of the regression slope from parity or an intercept of zero would indicate the effect that soil compaction had on productivity. Fig. 9 suggests that when all vegetation is considered, total production is somewhat less on severely compacted plots than on non-compacted plots. While the regression intercept of 1.59 does not differ from zero ($P > F = 0.74$), the slope is significantly less than 1.0 ($P = 0.08$). This means that sites were affected proportionate to their inherent productivity:

$$\text{total biomass } C_2 = 1.59 + 0.88 \text{ total biomass } C_0, \quad \text{Adj. } R^2 = 0.88 \tag{5}$$

In contrast, severe soil compaction had no significant effect on productivity of trees growing free of understory competition ($P > F = 0.38$).

Yet, not all sites responded negatively to severe compaction and some showed substantially positive responses. We examined whether soil texture might account for response differences by dividing our 26 installations into three broad soil textural classes: sands, loams, and clays. We then calculated relative response to compaction by dividing the total biomass on severely compacted plots by the biomass on their non-compacted pairs. Fig. 10 indicates that productivity on sites with sandy soil textural classes was enhanced more than 40% by severe compaction while that on clayey soils was reduced by half. Substantial differences in numbers of sites per textural class precluded a rigorous comparison by analysis of variance.

4. Discussion

4.1. Organic matter

We conclude from Fig. 3 that pulse removal of surface organic matter can have a statistically significant impact on soil organic C concentration after one decade. The effect was greatest at the surface but declined quickly with depth and differences were not evident below 20 cm (Table 3). Other studies generally show that retaining surface residues reduce soil temperature and evaporative moisture loss (Li et al., 2003; Powers et al., 1998). Almost certainly, decline in surficial C concentration traces to two

causes: (1) reduced input from surface materials, and (2) accelerated microbial respiration of labile soil organic matter and CO_2 efflux during the fallow period when the surface soil is warm and moist on otherwise well-drained sites (Gordon et al., 1987). Assuming that precipitation patterns remain stable, this condition should persist until the new forest has fully occupied, shaded, and dried the surface profile through transpiration. Li et al. (2003), in an earlier study of our North Carolina installations, found no decline in absolute quantities of soil C between years 2 and 5 for any treatment, although OM_2 values were significantly lower than where surface materials had been retained. Our data spanning twice this period confirm that if forest floors were retained, there was no general decline in soil C with time. Further, we found that soil C concentrations were higher in the OM_1 treatment than in either the OM_0 or OM_2. Our data also reveal sizable gains from the preharvest condition for the North Carolina installations, and similar patterns were found elsewhere (Fig. 4).

This presents an interesting conundrum. On one hand, soil carbon concentrations decreased significantly following the removal of all surface organic matter. On the other, slash removal seemed not to reduce (and in some cases, apparently increased) soil C storage to 30 cm through 10 years. We foresee three possible causes. One is unintentional, systematic bias. Namely, that soil sampling patterns changed after the initial stands were harvested and that post-harvest sampling occurred nearer to stumps. Root and litter decay following harvest could lead to localized pockets of high concentrations of soil C (Van Lear et al., 2000). Sampling nearer to stumps could increase organic matter concentrations and bias our soil C estimates. However, sampling generally followed a systematic pattern that was the same before harvest and after. While we cannot dismiss this explanation entirely, we doubt that it accounts for much of the increase.

A second possibility is that soil bulk densities increased following tree harvest. This could occur from accelerated heterotrophic respiration (Chen et al., 2000; Gordon et al., 1987). With CO_2 efflux – particularly without understory regrowth – soil particles would settle, leading to a natural densification of the soil mass. This would be most noticeable in surface horizons due to higher concentrations of C there, and to warmer conditions enhancing microbial activity. Applying fine fraction C concentrations to elevated soil mass per unit depth could lead to apparent gains in absolute C mass to a specific depth (but not necessarily for a diagnostic soil horizon). We believe that this partly explains the appreciable gains noted for the Michigan and North Carolina installations in Fig. 4. On the Michigan sites, soil bulk densities at 0–10 cm increased an average of 32% by year 5 but stabilized thereafter. Densities at the same depth in North Carolina increased an average of 35%. Soils in Louisiana and Minnesota increased by lesser amounts (−1 and 15%, respectively). Analysis of C_0 bulk density changes from these and other LTSP sites indicates that most change occurs in the first year following harvest (Page-Dumroese et al., 2005). However, adjusting for increased bulk density explains only a third of the nearly 11 Mg C ha^{-1} gain in the surface 10 cm of soil in Michigan and the 59 Mg ha^{-1} gain in North Carolina. How do we account for 5-year gains of more than 7 Mg C ha^{-1} in sandy soils of Michigan and nearly 40 Mg C ha^{-1} in North Carolina with complete removal of surface organic matter and (at North Carolina), complete control of new understory vegetation?

A third explanation lies in the precursors of fine fraction soil C. We believe that soil C may show absolute fine fraction gains on a given plot because of decomposition inputs from root systems of the previously harvested forest. Such organic fractions would be too coarse to pass a 2 mm sieve until they had decomposed—a process accelerated by soil microclimate following harvest. At the same time, removing surface organic matter short-circuits inputs from the forest floor. The net effect is that a surface soil of a given treatment plot may show a net gain after several years (even when stripped of all surface organic matter as in Fig. 4), but a net loss when compared with another plot where surface residues were retained and available for decomposition and incorporation as in Fig. 3.

Ten-year absolute gains in soil C for Michigan, Minnesota and Louisiana range up to 9 Mg ha^{-1} in the upper 30 cm (Fig. 4). Such gains seem plausible if we assume that about one-quarter of vegetative biomass remains in perennial roots after harvest (Cairns et al., 1997), translating at 47% C to 12, 13, and 21 Mg C ha^{-1} for Michigan, Minnesota and Louisiana

stands, respectively. The proportion of these large root masses in fine roots and mycorrhizae available for rapid decomposition seems a plausible explanation for increases in fine fraction soil C. The unusually large increases in North Carolina are another matter. Using the same rationale, perennial roots remaining after harvesting 171 Mg ha^{-1} of standing biomass (Table 2) would contribute approximately 57 Mg ha^{-1} for potential decomposition, or about 27 Mg C ha^{-1}—still less than the gain of 40 Mg ha^{-1} soil C when Fig. 4 is corrected for bulk density and generous, based on other studies of loblolly pine root mass (Van Lear and Kapeluck, 1995). The discrepancy probably traces to the unusually high variance reported at 5 years for 0–10 cm soil C in North Carolina. Recognizing this, the principal investigator doubled the sampling intensity at year 10, resulting in a lower variance. If the apparent gain at 10 years is used, the true gain corrected for a 35% increase in bulk density is only 14 Mg C ha^{-1}. This is plausible if half the estimated root biomass decays in the first decade. But given evidence that little surface C makes its way into the soil (Johnson and Todd, 1992; Ross et al., 2001), why did not forest floor C simply respire as CO_2? The soils at North Carolina have an aquic moisture regime, which probably accounts for the reduced N mineralization reported by Li et al. (2003). These same wet conditions would reduce CO_2 respiratory efflux.

Because the presence of forest floor had only a minor effect on soil C in the first decade, we conclude that soil C inputs depend only slightly on decomposition of fresh surface residues in the forest types we studied. We believe that the primary inputs to soil C come from the decay of fine roots that remained from the previously harvested stand. This, bolstered by an annual turnover of senescing fine roots and mycorrhizae of new vegetation, could readily account for substantive gains in fine fraction soil C near the surface. We also speculate that under drier conditions, most surface C is respired rather than incorporated. In a Tennessee study more than a decade after harvesting a mixed-hardwood forest, Johnson and Todd (1992) found no differences in soil organic matter beneath previous piles of logging slash and units free of slash. Ross et al. (2001), studying pine plantations on droughty Australian soils, concluded that most soil C accrues from fine root turnover and not from surface litter.

We suggest that under moderate and warmer climates, C mainly is respired as CO_2 as surface residues decompose, and very little C is incorporated into the soil. Under wetter and possibly cooler conditions, much of the C in surface residues eventually may be incorporated. On the other hand, fine roots decaying from harvested stands should provide major C inputs that should be detectable by the 5th to 10th year. Van Lear et al. (2000) found that soil C concentrations were more than an order of magnitude greater in the vicinity of roots remaining from a stand harvested 16 years earlier than in the general soil. The effect was evident to as much as a meter depth. Root decay apparently follows a simple Q_{10} model of rate increasing with temperature (Chen et al., 2000), and should be quite rapid in soils of the warm, humid Southern Coastal Plain and in those dominated by a Mediterranean climate. We conclude that organic C from logging slash most likely respires as CO_2 during decomposition and contributes relatively little to soil C. And while organic N mineralized during decomposition presumably is released to the soil, it either is immobilized quickly (explaining the results in Li et al., 2003), or the increment is undetectable through conventional analysis when diluted by the larger reservoir of total soil N (Sanchez et al., in press).

Still, the forest floor is a potentially important reservoir for labile N and its N content often equals – and usually exceeds – the content of N in logging slash (Table 1). Sizable declines in soil C and N concentrations (Table 4) and consistent declines in potentially mineralizable N from forest floor removal (Fig. 5) highlight the forest floor effect on soil fertility processes—at least, for the droughty California sites studied by Craigg. There, declines in C and N with forest floor removal may be due as much to reduced microbial decomposition due to drier soil conditions that occur when the soil surface is bared (Powers and Fiddler, 1997) as to lessened inputs from the forest floor. Scott et al. (2004), studying LTSP findings after 5 years in four states in the humid Southern Coastal Plain, found that foliar concentrations of both N and P were significantly less in the OM_2 treatment and that growth was reduced by forest floor removal on sites of lowest productivity. In our large data set, complete removal had no discernable, unambiguous impact on productivity measured at 10 years (Fig. 6) despite

sizable reductions in soil C (Fig. 3) or N availability on the sites we examined (Table 4). For the California mixed conifer examples (Fig. 5), only one of the four sites tested at a level low enough to approach a deficiency threshold of 12 mg N kg^{-1} (Powers, 1980).

For loblolly pine, some sites were affected while others were not. Scott et al. (2004) found that bole volumes at 5 years on Mississippi sites were 40% lower on OM_2 plots than on OM_0. At 10 years total biomass differences aboveground were now only 29% ($P = 0.08$). Most likely, the appreciable early decline is due to reduced availability of soil P (Scott et al., 2004), and illustrates the importance of organic sources of P on sites where it is scarce mineralogically. Reduced volume growth reported for the North Carolina installations at year 5 (Scott et al., 2004) were not evident in heights or diameters at year 10 (Sanchez et al., in press), or in total aboveground biomass ($P = 0.25$). Nor were there significant differences among treatments in foliar concentrations of N ($P = 0.45$) or P ($P = 0.99$) (Sanchez et al., in press). Perhaps the transient nutrient deficiency was corrected by inputs from root decay over the first decade, as well as by high rates of internal cycling as plantations approach crown closure. Powers (1999) found that by 80% crown cover, 60% of the foliar N and 80% of the foliar P are retranslocated before leaf senescence. Regardless, we believe this illustrates the value of long-term studies. Early findings may or may not forecast long-term trends.

Except for our nine aspen installations, removing all surface organic matter had no noticeable impact on vegetative growth through the first decade. Alban et al. (1994) showed that aspen responded to forest floor removal by generating a high density of root suckers in the first year after harvesting. By the third year, most of these had died from intense competition and densities had dropped to the level of those on plots where residues had been retained. Aspen biomass on the OM_2 plots was significantly less than on the C_0 plots. If the decline in nutrient availability attributed to forest floor removal on our California plots is a universal phenomenon – and if it forecasts eventual growth declines – we may have a useful soil-based tool for gauging the impacts of disturbance on soil quality and sustainability as proposed by Powers et al. (1998).

4.2. Soil compaction

Although compaction treatments increased soil bulk densities at all measured depths, mean differences between the C_1 and C_2 treatments were small (Fig. 7). While it is possible that the C_2 treatments were simply not severe enough to produce clear separation (or that the C_1 treatments were too great), the more likely explanation (supported by Fig. 8) is that soils with initially high bulk densities could not be compacted much further. Sites with the highest pretreatment bulk densities (all 1.4 Mg m^{-3} or greater) showing the least density increases from compaction were those from Louisiana and Mississippi (Table 2). Perhaps these southern sites reflect impacted old fields abandoned after decades of agriculture. Despite a Herculean effort at treatment, in no instances were we able to achieve our targets of 80% of the density values proposed as growth-limiting by Daddow and Warrington (1983). Probably this is because we compacted when soil moistures were near field capacity. Once macropores are compressed, further compaction is difficult because micropores are filled with water. Our soils with initially high densities also had finer textures (silts and clays). Their relatively greater micropore space and water retention made them naturally resistant to densification (Froehlich and McNabb, 1984). Sites with the lowest rates of recovery from extreme compaction were those in Idaho, Michigan and Minnesota—all sites with frigid soil temperature regimes (Table 2). Perhaps freeze–thaw cycles in cool temperate and boreal life zones are not particularly effective at remediating compaction below 10 cm.

There are several reasons that severe soil compaction had a more pronounced effect on better sites than poorer (Fig. 9). For one thing, more productive sites had potentially more to lose. For another, the most productive sites were in North Carolina (Table 2), and soil densities there were increased by 0.34–0.54 Mg m^{-3}—more than on any other installations. Soils there are aquic Paleudults and aeric Paleaquults, and have the highest moisture regimes of any installation. Results suggest that root aeration was substantially impaired—a prospect in keeping with an aeration porosity loss below 0.1 m^3 m^{-3} that is generally considered a threshold for root respiration (Grable and Siemer, 1968) and in keeping with the

aeration/compaction predictive model developed for loblolly pine roots by Siegel-Issem et al. (2005). The fourth most productive site, Challenge (Table 2), is a fine-textured Palexerult. An earlier study on that same site showed that low-tension soil moisture storage was reduced substantially by severe compaction. Furthermore, soil strength was increased to 3 MPa or more to a depth of 45 cm—even in the spring when soil moisture is high and strengths are at their lowest (Gomez et al., 2002). Root growth activity is severely restricted as soil strength approaches 3 MPa (Greacen and Sands, 1980). Low moisture availability coupled with very high strength largely explains the growth reduction at Challenge.

Effects of soil compaction on productivity depended on soil texture. In general, clayey soils showed the greatest growth reductions, while loams (including volcanic ashes) were intermediate. On sandy soils, productivity generally was enhanced by compaction (Fig. 10). The sandy sites in our study were physiologically droughty, either by climate (Mediterranean on the granodiorite sites in California) or depth (the outwash sands in Michigan). Therefore, any treatment that would improve water availability should improve growth. On a similar granodiorite LTSP site in California, 4-year volume growth was nearly tripled by compaction (Gomez et al., 2002). Soil compaction increased soil moisture availability to a depth of 45 cm and improved xylem water potential during summer drought. Siegel-Issem et al. (2005) show that increasing soil bulk densities slightly in these soils can have a substantial effect on soil water holding capacity. Presumably, the effect is due to reduction of average pore diameter and a subsequent increase in the volume of low-tension water films in soils that otherwise would be excessively drained.

Total productivity was influenced both negatively and positively by soil compaction. But why was productivity apparently not affected when trees were free of understory competition (Fig. 9)? A possible explanation is that without a competing understory, trees in the early years have greater access to old root channels, which would not have been affected by the compaction process. In a simple but elegant experiment, Nambiar and Sands (1992) demonstrated that trees in non-compacted soils and in severely compacted soils receiving perforations to simulate root channels grew well and at identical rates. However, trees growing in compacted soils lacking simulated root channels experienced both water and nutrient deficiency and were stunted. Subsequent excavation revealed that tree roots grew laterally once they reached the compacted layer until they encountered a perforation simulating a root channel. There, 20 or more rootlets would converge and grow through the perforation into non-compacted soil beneath the compaction zone. Van Lear et al. (2000), studying a young pine stand on an eroded Piedmont soil, reported much greater stem numbers and root densities of naturally regenerated pines in the vicinity of stumps from the previous stand. Productivity also decreased with distance from stumps. They attributed this to more favorable growth conditions in the vicinity of large, decomposing roots from the previous stand. We speculate that the same phenomenon is occurring on our severely compacted sites free of understory vegetation. Lacking understory competition, trees would exploit the available soil resource and eventually tap old root channels or friable soil in the vicinity of large root crowns. Lacking understory control, ubiquitous weeds would occupy such favorable microsites quickly to the exclusion of tree roots. We also suspect that the early advantage of access to old root channels and root crown microsites will dissipate as stand densities increase and intertree competition rises.

5. Conclusions

Findings from a broad range of LTSP sites indicate that complete removal of surface organic matter leads to significant and universal declines in soil C concentration after 10 years and (at least on the California installations) to reduced N availability. The effect is apparent to a soil depth of 20 cm and due to the loss of the forest floor, not logging residues. Absolute mass of soil C shows little change, however. This apparent contradiction can be attributed to post-treatment soil densification (more soil mass per unit depth) from rapid respiration of residual organic matter, followed by increased C inputs into the soil fine fraction due to root decomposition from the harvested stands. To detect absolute change, future sampling strategies should consider diagnostic soil horizons as well as standard depth classes, and should

include organic matter in detritus greater than 2 mm in size. Changes noted in soil C and N had no general effect on standing forest biomass at 10 years. The notable exception was for aspen stands of the Lake States, possibly reflecting severe mortality of suckers following an early positive response to litter removal.

Soil bulk density was increased by compaction treatments, but increases were greater for soils of low to moderate initial densities and soils with initial bulk densities greater than $1.4\,\mathrm{Mg\,m^{-3}}$ showed little increase. Diminished increase can be attributed to finer pore sizes at higher bulk densities and the difficulty of compressing water-filled soil pores. Density recovery was very slow. Soils with frigid temperature regimes recovered least of all. Forest productivity response to soil compaction depended both on soil texture and on whether an understory was present. Growth tended to be reduced by compaction on clayey soils and increased on sandy soils. Effects are attributed to losses of aeration porosity on clays and improvements in available water holding capacity on sands. Trees growing without understory competition generally were unaffected by severe soil compaction through the first 10 years. But 10-year production generally was less on severely compacted plots if an understory was present. Presumably, this reflects differential degrees of root competition for soil resources and access to old root channels. In time, compaction effects should be more evident in stands lacking an understory.

Even at 10 years the LTSP study is in its infancy. Installations were established over several years, and only the oldest and most productive are approaching site carrying capacity. Only one-third of our installations have reached a decade in age, and it is possible that trends will change as more sites come on line. Given that caveat, we present these early findings as a platform for assessing longer-term trends.

Acknowledgements

The success of the LTSP program reflects the vision of a cadre of exceptionally dedicated people. Chief among them are these USDA Forest Service retirees: David Alban (NC Research Stn.), Pete Avers and Nelson Loftus (Washington Office), Chuck Goudey (Pacific Southwest Region), Jerry Ragus (Southern Region), and Allan Tiarks (SO Research Stn.), all of whom were there at the beginning, as were Dick Cline and Dick Fitzgerald of the Washington Office. We also are grateful to Terry Craigg, USDA Forest Service, Deschutes National Forest, for sharing unpublished data from his graduate work.

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