Lake States Aspen Productivity Following Soil Compaction and Organic Matter Removal

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Abstract

Aspen (*Populus tremuloides* Michx. and *P. grandidentata* Michx.) provides wood products, watershed protection, and wildlife habitat for numerous game and non-game species across the northern Great Lakes region. Sustaining the productivity of these ecosystems requires maintaining soil productivity. Management activities that decrease soil porosity or remove organic matter can reduce productivity. We determined effects of three levels of soil compaction and organic matter removal (OMR) on aspen regeneration and growth following winter harvest of aspen-dominated stands in northern Minnesota, western Upper Michigan, and northern lower Michigan. Compaction treatments were applied to increase surface soil bulk density by either zero, 15, or 30 percent. The OMR treatments were merchantable bole harvest (MBH); total tree harvest (TTH); and total woody vegetation, plus forest floor removal (FFR). Soil compaction tended to increase mean sucker diameter and height on the sand and decrease them on the fine textured soils. Compaction greatly reduced sucker density and growth on the most productive silt-loam soil, primarily due to late spring treatment. These results apply to planning of operational harvest of aspen-dominated stands throughout the northern Great Lakes region. Sucker density increased with level of OMR on all three sites. On the sand site, mean diameter, height, and biomass were greatest with MBH and decreased significantly with increasing OMR, indicating a potential decline in productivity with repeated total tree harvesting on sand soils.

Keywords: Sustaining productivity, harvest intensity, organic matter removal, soil compaction.

Introduction

Sustaining forest productivity requires maintaining soil productivity. Management activities that decrease soil porosity and/or remove organic matter have been associated with declines in site productivity (Agren 1986, Greacen and Sands 1980, Grier et al. 1989, Standish et al. 1988). As part of an international network of cooperative studies on long-term soil productivity (LTSP) (Powers et al. 1990, Tiarks et al. 1993), we are evaluating effects of soil compaction and organic matter removal (OMR) in the aspen (*Populus tremuloides* Michx. and *P. grandidentata* Michx.) forest type across the northern Lake States region and in northeastern British Columbia (Kabzems 1996, Stone and Elioff 1998, Stone et al. 1999). The research is designed to determine how changes in soil porosity and organic matter content affect soil processes controlling forest productivity and sustainability, and to compare responses among major forest types and soil groups across the United States and Canada.

The rationale for these studies is: (1) harvesting equipment and practices affect soil properties; (2) soil properties control soil processes; (3) soil processes affect plant community composition and growth; and (4) these determine net primary production, ecosystem functions, and forest sustainability. The objectives are to monitor changes in soil properties following forest harvesting and the soil compaction and OMR treatments, and to measure responses by the forest regeneration and herbaceous vegetation. Fifth-year results from a pilot study with four treatments and two replications (Stone and Elioff 1998) and 4th-year results of the complete study with nine treatments and three replications on sand soils were reported earlier (Stone et al. 1999). This paper summarizes aspen development after five growing seasons on sites in northern Minnesota, western Upper Michigan, and northeastern lower Michigan.

Table 1—General characteristics of the aspen Long-Term Soil Productivity (LTSP) sites in the Lake States

Installation Date	National Forest	Relative Productivity	General Soil Description	Approximate Site Index[a] (m)	(ft.)
1991	Marcell	Medium	Loamy sand/clay loam till at 110 cm; well drained	21	70
1992	Ottawa	Low	Deep, calcareous clay; moderately well drained	17-18	55-60
1993	Chippewa	High	Silt loam cap/clay loam till at 30 to 40 cm; well drained	23	75
1994	Huron	Medium to low	Deep, acid sands; excessively drained	19	62

[a] Aspen, age 50

Methods

Stand and Site Conditions

Four sites were selected to represent a range of soil conditions and aspen productivity across the northern Lake States region (table 1). The overstory of each stand was dominated by aspen but included a codominant component, or a subcanopy of more tolerant conifer and northern hardwood species. The pilot study is on the Marcell Experimental Forest (part of the Chippewa NF), and represents our medium site (Stone and Elioff 1998). The surface soils are loamy sand over clay loam till at about 110 cm; site index (age 50) for aspen is about 21 m (70 ft). The least productive site is on the Ottawa National Forest (NF) in western Upper Michigan. The study is on a glacial lake plain and the soils are moderately well-drained, calcareous, lacustrine clay; site index for aspen is 17 to 18 m (55 to 60 ft). White spruce (*Picea glauca* (Moench) Voss), balsam fir (*Abies balsamea* (L.) Mill.), and red maple made up about 35 percent of the preharvest basal area. The most productive site is on the Chippewa NF in north-central Minnesota. The study is located on the Guthrie till plain; the surface soils are silt loam, formed from a loess cap 30 to 40 cm deep, over clay loam till. Site index is about 23 m (75 ft); the associated species were predominantly red maple (*Acer rubrum* L.), basswood (*Tilia americana* L.), sugar maple (*A. saccharum* Marsh.), and eastern white pine (*Pinus strobus* L.). Our medium-to-low-quality site is on an outwash plain on the Huron NF in northeastern lower Michigan; the soils are deep, acid sands with a site index of about 19 m (62 ft). Both trembling and bigtooth aspen occur on this site. The predominant associated species were red maple, red oak, black cherry (*Prunus serotina* Ehrh.), and white pine.

Design and Treatment

Three levels of harvest intensity and OMR, and three levels of soil compaction were applied to 50×50 m (0.25 ha, 0.62 ac) plots in a complete 3×3 factorial design with three replications. The compaction treatments were designed to provide: (1) no additional compaction above that due to harvesting; (2) light, to increase bulk density of the surface 10 to 20 cm of soil by 15 percent; and (3) heavy, to increase bulk density of the surface soil by 30 percent. The levels of OMR were: (1) merchantable bole harvest (MBH) to a 10 cm (4 in.) top diameter; (2) total aboveground tree harvest (TTH); and (3) total woody vegetation harvest plus forest floor removal (FFR). The FFR treatment was included to represent those areas in skid trails and landings where most, or all of the forest floor materials, are removed during harvest. It also could provide an indication of productivity trends following repeated rotations of total tree harvesting. Tops from the MBH+compaction treatments were piled adjacent to the plots and replaced after the compaction treatments were completed. Four non-cut control plots were installed in the adjacent stands, for a total of 10 treatment combinations on each site. Prior to harvest, the plots were established to minimize variation in soil properties and all trees =10 cm (4 in.) diameter at breast height were measured and their location mapped.

Ottawa—The stand was harvested between January 13 and February 3, 1992. During logging, snow depths averaged 76 to 91 cm (30 to 36 in.) and the soils were not frozen. All merchantable stems were cut by using a Caterpillar model FB-227 feller-buncher and placed in bunches between the plots. The bunches were skidded to a landing with John Deere 648D, 740A, and Timberjack 450B grapple skidders. All skidder traffic was restricted to the areas between plots. The FFR treatment consisted of manually removing all coarse woody material and then removing the forest floor materials between April 21 and May 21 by prison work crews using fire rakes; the materials were piled outside of a 5- to 10-m-wide buffer zone surrounding each treatment plot. The compaction treatments were applied between May 6 and 21 by traversing the plots with a 20.9-Mg (23-ton) Hough model H-100 front-end loader, advancing one tire width each pass. Two passes at right angles provided the light treatment, and two passes with the bucket empty and two passes with the bucket filled with soil provided the heavy compaction.

Chippewa—The stands were harvested during January and February 1993. During November and December 1992, snowfall was somewhat greater than normal and mean monthly air temperatures were slightly above average. Thus, soil frost was discontinuous initially, and ranged from 5 to 10 cm (2 to 4 inches) when logging was completed. Snow depth increased from about 30 cm (12 in.) initially to 46 cm (18 in.) during the logging operation. On the non-compacted plots, the trees were felled with chainsaws and winched off the plots with a cable skidder. On all other plots, the stems were cut with a Case-Drott model 40 feller-buncher and placed outside the plot boundaries; skidders did not enter any of the plots. The FFR treatment consisted of manually removing all coarse woody material and then windrowing the forest floor materials by using a power-driven sidewalk sweeper with a revolving wire brush head; the materials were piled outside of the 5- to 10-m-wide buffer zone surrounding the treatment plots. The light compaction treatment consisted of a double pass, at right angles, across the plots with a model D-7 Caterpillar tractor, advancing one track width each pass. The heavy compaction treatment included the light treatment followed by a double pass with a Michigan model 75C front-end loader, advancing one tire width each pass.

Huron—The stands were harvested in late January 1994; the winter was colder than normal, with several days below -30°C (-22°F). During harvest, the surface 20 to 25 cm (8 to 10 in.) of soil was frozen and covered by 35 to 40 cm (14 to 16 in.) of snow. All merchantable stems were cut with a tracked Bobcat shear or a Hydro-Ax feller-buncher, and skidded using Caterpillar 518, and Timberjack 380B grapple skidders. In mid-April, the coarse woody debris and forest floor materials were removed by using the same methods as on the Chippewa, and piled outside the 5- to 10-m-wide buffer zone around each treatment plot. In late April, when the soil was at field capacity, the compaction treatments were applied by using a 9.5-Mg (10.5-ton) Hough model 60 front-end loader, advancing one tire width each pass. The light compaction treatment was accomplished with a single pass of the loader with a tire pressure of 172 kPa (25 psi). The heavy compaction treatment included the light treatment plus a second pass of the loader, at right angles, with the bucket filled with sand and tire pressures of 276 kPa (40 psi). This provided a total machine weight of about 12.7 Mg (14 tons).

Measurements and Analyses

On each site, all measurements and sampling were made within the interior 40×40-m area of each treatment plot. In late July to early August, the 5th-year aboveground herbaceous vegetation was collected from four 1.0-m^2 subplots per plot, dried at 75°C, and weighed. In September, after five growing seasons, the basal diameter of all woody stems (>15 cm height) was measured and recorded by 2-mm diameter classes on eight 5.0-m^2 subplots per plot. Mean height of aspen suckers in each diameter class was recorded to the nearest 5-cm class. Aboveground biomass was estimated by using allometric equations developed by Perala and Alban (1994).

For each site, all subplot data were composited and treatment effects were evaluated by analysis of variance of the plot-level means. First, the overall effects of compaction level, OMR, and compaction-OMR interactions were evaluated. Few of the

Table 2—Mean 5th- year sucker density (k ha^{-1}) by level of compaction

Compaction Level	National Forest Ottawa	Chippewa	Huron
None	19.7[a]	33.2c	20.5
Light	28.9	12.6b	26.8
Heavy	28.6	4.4a	25.4
ANOVA *p*	0.092	0.000	0.123

[a] Treatment means followed by the same letter, or without letters, do not differ significantly at the $p = 0.05$ level.

interactions were significant, so the effects of compaction were evaluated across OMR levels, and the effects of OMR were evaluated across compaction levels. Comparisons among means were made with the Least Significant Difference procedure at the 95 percent confidence level (Analytical Software 1998).

Results and Discussion

Soil Compaction

The objective of the compaction treatments was to increase bulk density of the surface soil by either 15 percent or 30 percent without damaging the root systems by rutting. This was accomplished successfully on the Marcell, Ottawa, and Huron sites. However, spring and early summer rainfall was higher than normal in 1993 and delayed study installation on the Chippewa. The frequent rainfall, and the desire to avoid rutting, caused numerous delays in application of the treatments. Thus, the suckers had begun to emerge by the time the soil had drained sufficiently to complete the compaction treatments, and many were broken by the machine traffic.

Stand density—Soil compaction increased mean sucker density on the clay and sand sites; however, the differences were not significant on the sand and only marginally significant ($p = 0.092$) on the clay (table 2). The compaction treatments also tended to increase first-year sucker density in the British Columbia study, but by the 4th year the differences by level of compaction were no longer significant (Kabzems 2000a). Presumably, these initial increases were due to minor root injury during compaction. Disturbance of aspen root systems and increased soil temperatures are known to stimulate sucker production (Peterson and Peterson 1992, Schier et al. 1985). Soil compaction significantly decreased sucker density on the Chippewa installation, primarily because of the late spring treatment. On this site, effects of the compaction treatments on reducing sucker density were dramatic and not unlike many operational logging jobs in the northern Great Lakes region (Bates et al. 1990, 1993).

Diameter—Soil compaction tended to decrease mean diameter of suckers on the fine-textured soils, but the differences were significant only on the Chippewa (table 3). The decreased growth on these sites most likely is due to a combination of direct and indirect effects (Greenway 1999). Sucker growth could be reduced directly by reduced soil aeration, and indirectly by the increased sucker density. In contrast, the compaction treatments tended to increase mean basal diameter on the Huron sands, despite the substantially greater stand density (table 2). On coarse-textured soils, low to moderate levels of compaction will convert a portion of the macropore space to micropores, thereby increasing the water-holding capacity of the soil, thus decreasing water stress in the regeneration (Powers and Fiddler 1997, Powers 1999). We emphasize that these experimental levels of compaction are well below those encountered on major skid trails and landings found on conventionally harvested sites (Stone et al. 1999). On those areas, we have measured substantial reductions in both sucker density and growth. Moreover, the effects are likely to persist for decades (Grigal 2000), a century (Sharrett 1998), or possibly longer (Curran 1999).

Height—As with diameter, the compaction treatments tended to decrease mean height of suckers on the fine-textured soils, but the differences were significant only on the Chippewa (table 4). Likewise, the decrease can be attributed to the combination of reduced soil aeration and increased sucker density. On the Huron sands, increased water-holding capacity of the soil and decreased water stress in the suckers would account for the small but consistent increases in sucker height with level of compaction. Both trembling and bigtooth occur on this site, but the differences in diameter and height were not significant, so they were analyzed together.

Table 3—Mean 5th-year sucker diameter (at 15 cm) by level of compaction

Compaction Level	National Forest Ottawa	Chippewa	Huron
None	11.1[a]	21.6 c	15.9
Light	9.5	13.7 b	16.7
Heavy	9.2	10.9 a	17.0
ANOVA p	0.168	0.000	0.519

[a]Treatment means followed by the same letter, or without letters, do not differ significantly at the $p = 0.05$ level.

Table 4—Mean 5th-year sucker height (cm) by level of compaction

Compaction Level	National Forest Ottawa	Chippewa	Huron
None	134[a]	301c	218
Light	112	171b	223
Heavy	103	123a	238
ANOVA p	0.111	0.000	0.427

[a]Treatment means followed by the same letter, or without letters, do not differ significantly at the $p = 0.05$ level.

Biomass—The compaction treatments produced little difference in dry weight of aspen on the clay soil, but dramatic differences on the silt loam, primarily due to the delayed application of the treatments (table 5). On these clay sites, rutting has been more detrimental to aspen regeneration and growth than has compaction (Stone and Elioff 2000). On the sand site, compaction resulted in slight, but non-significant increases in aspen biomass. Again, the differences among sites were far greater than those of the compaction treatments. Comparison of the non-compacted plots, for example, illustrates a 10-fold difference in potential aspen productivity between the least productive clay soil and the most productive silt loam. Likewise, despite the relatively small (<5 feet) difference in aspen site index, 5th-year aspen biomass on the sand was four times that on the clay site.

Table 5—Mean 5th-year sucker dry weight (kg ha^{-1}) by level of compaction

Compaction Level	National Forest Ottawa	Chippewa	Huron
None	1,380[a]	13,260 b	4,630
Light	1,410	2,290 a	5,490
Heavy	1,260	330 a	5,870
ANOVA p	0.941	0.000	0.267

[a]Treatment means followed by the same letter, or without letters, do not differ significantly at the $p = 0.05$ level.

Table 6—Mean 5th-year sucker density (k ha^{-1}) by level of organic matter removal

Treatment[a]	National Forest Ottawa	Chippewa	Huron
MBH	20.2[b]	10.0 a	21.9
TTH	22.7	17.3 ab	24.9
FFR	30.8	22.9 b	25.9
ANOVA p	0.102	0.007	0.425

[a]MBH, merchantable bole harvest (10 cm top); TTH, total tree harvest; FFR, total vegetation plus forest floor removal.
[b]Treatment means followed by the same letter, or without letters, do not differ significantly at the $p = 0.05$ level.

Organic Matter Removal

Stand density—Winter harvesting by MBH produced abundant aspen regeneration on all three sites. After five growing seasons, sucker density ranged from 10,000 (10 k) to 22 k ha^{-1} (table 6). For perspective, with uniform distribution, the 10 k stems ha^{-1} on the Chippewa is equal to a 5-year-old sucker on every m^2 of the site. The TTH and FFR treatments further increased sucker density, frequently at the expense of the associated commercial species. The differences were marginally significant ($p = 0.102$) on the clay soils on the Ottawa, highly significant on the silt loam on the Chippewa, and non-significant on the sand soils on the Huron. Graham et al. (1963) considered a 1st-year sucker density of 15 k ha^{-1} (6 k ac^{-1}) as minimal stocking and 30 k ha^{-1} (12 k ac^{-1}) as optimal. The FFR treatment resulted in a 1st-year sucker density of >260 k ha^{-1} on the loamy sand site in

Table 7—Mean 5th-year sucker diameter (at 15 cm) by level of organic matter removal

	National Forest		
Treatment[a]	Ottawa	Chippewa	Huron
MBH	10.0 b[b]	15.5 b	19.1 b
TTH	11.5 b	17.9 c	15.4 a
FFR	8.5 a	12.8 a	15.0 a
ANOVA p	0.017	0.000	0.001

[a] MBH, merchantable bole harvest (10 cm top); TTH, total tree harvest; FFR, total vegetation plus forest floor removal.

[b] Treatment means followed by the same letter, or without letters, do not differ significantly at the $p = 0.05$ level.

Table 8—Mean 5th-year sucker height (cm) by level of organic matter removal

	National Forest		
Treatment[a]	Ottawa	Chippewa	Huron
MBH	104 a[b]	195 a	263 b
TTH	138 b	234 b	214 a
FFR	105 a	167 a	201 a
ANOVA p	0.036	0.001	0.002

[a] MBH, merchantable bole harvest (10 cm top); TTH, total tree harvest; FFR, total vegetation plus forest floor removal.

[b] Treatment means followed by the same letter, or without letters, do not differ significantly at the $p = 0.05$ level.

northern Minnesota (Alban et al. 1994), and about 220 k ha^{-1} in British Columbia (Kabzems 1996), most likely due to increased soil temperatures and removal of competing vegetation (Kabzems 2000b). By the 4th year, sucker density had declined to about 55 k ha^{-1} in British Columbia (Kabzems 2000a), and by the 5th year, to about 40 k ha^{-1} in Minnesota (Stone and Elioff 1998).

Diameter—Mean basal diameter (at 15 cm) tended to be greater with TTH on the fine-textured soils, although the difference between MBH and TTH was not significant on the Ottawa clay (table 7). The aspen on the Huron sands responded differently than those on the other sites. Mean diameter was significantly greater with the MBH treatment and declined with increasing level of OMR, as indicated by the 4th-year data (Stone et al. 1999). In fact, the smallest mean diameters occurred with the FFR treatment on all sites, indicating a potential problem of sustaining productivity with repeated total tree harvesting, particularly on sand soils.

Table 9—Mean 5th -year sucker dry weight (kg ha^{-1}) by level of organic matter removal

	National Forest		
Treatment[a]	Ottawa	Chippewa	Huron
MBH	980[b]	4,950	6,200 b
TTH	1,610	6,710	5,140 ab
FFR	1,300	4,220	4,650 a
ANOVA p	0.376	0.230	0.082

[a] MBH, merchantable bole harvest (10 cm top); TTH, total tree harvest; FFR, total vegetation plus forest floor removal.

[b] Treatment means followed by the same letter, or without letters, do not differ significantly at the $p = 0.05$ level.

Height—On the fine-textured soils, mean sucker height on the TTH plots was significantly greater than the MBH plots (table 8). As with diameter, mean sucker height on the sand site was significantly greater in the MBH treatment and declined with increasing level of OMR. This raises the question of whether the additional biomass removed by total tree harvesting is worth the cost in soil resources—nutrients, organic matter, and water-holding capacity (Stone et al. 1999). On both the Chippewa and Huron sites, the lowest mean height was in the FFR treatment, partially due to high sucker densities and the resulting intra-clonal competition. Stone et al. (2001) found that retaining 18 to 38 dominant aspen ha^{-1} (7 to 15 ac^{-1}) reduced first-year sucker density by about 40 percent and increased their basal diameter and height growth by about 30 percent.

Biomass—Dry weight production per unit area integrates sucker density, diameter, and height in a single value. On the fine-textured soils, aspen dry weight was non-significantly greater with TTH (table 9). On these sites, the TTH treatment produced intermediate sucker densities with greater mean diameter, height, and dry weight, while total woody vegetation plus FFR produced greater numbers of suckers, but with lower mean diameter, height, and dry weight. On the sand site, MBH produced the lowest number of suckers with significantly greater mean diameter and height and dry weight. The differences among sites were much greater than the treatment effects within sites. For example, mean (all treatments) 5th-year aspen dry weight on both the sand, and the silt loam site was greater than four times that of the clay.

Summary and Management Implications

Soil Compaction

Responses to soil compaction differed greatly among sites. Compaction prior to sucker emergence tended to increase sucker density, but after they had emerged, machine traffic drastically reduced sucker density, diameter and height growth, and biomass production; the differences were highly significant after five years. Compaction on the clay site produced small, but non-significant reductions in sucker diameter and height. On these kinds of soils, rutting has shown much greater impacts on aspen regeneration and growth than has compaction. In contrast, the levels of compaction applied on the sand site produced small, but non-significant increases in sucker diameter, height, and biomass. However, the more severe compaction that routinely occurs on major skid trails and landings, severely reduces both sucker density and growth. Moreover, the effects are likely to persist for decades to a century or longer. Thorough pre-harvest planning is required to designate these areas—and to minimize the area affected—in order to sustain the future productivity of these sites.

Organic Matter Removal

Harvest intensity and OMR significantly affected one or more of the regeneration parameters on each site, and the responses differed greatly by site. These 5th-year data illustrate much larger differences in productivity between sites than might be expected from site index data. Increasing levels of OMR increased sucker density on all sites. On the fine-textured soils, 5th-year sucker diameter and height were greater in the TTH treatment. On the sand soil, both the TTH and FFR treatments significantly reduced mean diameter and height. In fact, the FFR treatment generally showed the smallest diameter and height on all three sites. Treatment differences in 5th-year aspen biomass were not significant on the fine-textured soils, but declined significantly with increasing level of organic matter removal on the sand. This raises the question of whether the additional biomass gained by total tree harvesting is worth the cost in soil resources—nutrients, organic matter, and water-holding capacity. The question also needs to be addressed in other forest types on sand soils, such as jack pine (*Pinus banksiana* Lamb.) in the upper Great Lakes region.

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