Soil properties and aspen development five years after compaction and forest floor removal

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Stone, D. M. and Elioff, J. D. 1998. **Soil properties and aspen development five years after compaction and forest floor removal.** Can. J. Soil Sci. **78**: 51–58. Forest management activities that decrease soil porosity and remove organic matter have been associated with declines in site productivity. In the northern Lake States region, research is in progress in the aspen (*Populus tremuloides* Michx. and *P. grandidentata* Michx.) forest type to determine effects of soil compaction and organic matter removal on soil properties and growth of aspen suckers, associated woody species, herbaceous vegetation, and on stand development. Four treatments: (1) **total tree harvest** (**TTH**); (2) **TTH plus soil compaction** (**CPT**); (3) **TTH plus forest floor removal** (**FFR**); and (4) **TTH plus CPT + FFR** were applied after winter-harvest of a 70-yr-old aspen stand growing on a loamy sand with a site index$_{(age\ 50)}$ of 20.7 m. The CPT treatment significantly increased bulk density and soil strength of the surface 30 cm of soil and neither have recovered during the 5 yr since treatment. The CPT plots had 19.6 thousand (k) suckers ha^{-1}, less than half that of the TTH and FFR treatments; mean diameter (19.4 mm) and height (271 cm) were greatest on the TTH plots. The disturbance treatments (CPT, FFR, and CPT + FFR) each reduced biomass of foliage, stems, and total suckers compared with the TTH treatment. Total aboveground biomass (herbs + shrubs + suckers) was less than half that of TTH plots. There were 5.0 k saplings (suckers >2.5 cm DBH) ha^{-1} on the TTH plots, but fewer than 1.0 k ha^{-1} in the other treatments. The disturbance treatments decreased 5-yr growth of potential crop trees, delayed early stand development, and temporarily reduced stockability and site productivity of an aspen ecosystem.

Key words: Soil compaction, organic matter removal, site productivity, stand development

Stone, D. M. et Elioff, J. D. 1998. **Propriétés du sol et croissance du peuplier faux tremble cinq ans après compaction et enlèvement de la couche organique du sol**. Can. J. Soil Sci. **78**: 51–58. Les activités d'exploitation forestière qui diminuent la porosité du sol et enlèvent la matière organique à se soldent generalement par une baisse de la productivité. Dans le nord de la région des grands Lacs aux USA, des recherches ont été entreprises dans la tremblaie (*Populus tremuloides* Michx. et *P. grandidentata* Michx.) pour déterminer les effets du compactage du sol et de l'enlèvement de la matière organique sur les propriétés du sol et sur la croissance des rejets de peupliers, et des espèces ligneuses et herbacées associées, ainsi que sur l'évolution du peuplement. Après la coupe d'hiver d'une tremblaie de 70 ans installée sur un sable loameux affecté d'un indice de productivité stationnelle (à 50 ans) de 20,7 m, 4 traitements étaient comparés : (1) coupe à blanc (TTH), (2) TTH plus compactage du sol (CPT) et (3) TTH plus décapage de la couche organique du sol (FFR) et (4) TTH plus CPT et FFR. Le traitement CPT produisait un accroissement significatif de la densité apparente et de la résistance à la pénétration des 30 cm supérieurs du sol et dans les 5 ans de l'expérience aucun de ces deux caractères n'étaient revenus à l'état initial. Les placettes CPT portaient 19,6 mille rejets par hectare, soit moins de la moitié que dans les traitements de coupe à blanc avec ou sans enlèvement de la couche organique. Le diamètre et la hauteur moyenne les plus grands, soit respectivement 19,4 mm et 271 cm, étaient observés dans les traitements de coupe à blanc. En regard du traitement de coupe à blanc sans perturbation, les traitements avec perturbation : compaction, enlèvement de la couche organique ou les deux ensemble, se soldaient tous par une réduction de la biomasse en feuilles, en tiges ou totale des rejets. En outre, la biomasse aérienne totale (plantes herbacées, buissons et rejets) y était plus que de la moitié inférieure. On comptait 5 000 gaulis arbres (rejets de plus de 2,5 cm dhp) par hectare dans les parcelles coupées à blanc sans perturbation du sol. Par comparaison il n'y en avait plus que 1 000 dans les traitements avec perturbation. Ces derniers diminuaient la croissance au bout de 5 ans des arbres potentiellement exploitables, ralentissaient la reconstitution du peuplement et réduisaient temporairement la densité de peuplement et la productivité stationnelle de la tremblaie.

Mots clés: Compactage du sol, enlèvement de la couche organique, productivité stationnelle, reconstitution du peuplement

Forest management activities that decrease soil porosity and remove organic matter have been associated with declines in site productivity (Agren 1986; Greacen and Sands 1980; Standish et al. 1988; Grier et al. 1989). As part of a cooperative study between the National Forest System and Forest Service Research (Powers et al. 1990; Tiarks et al. 1993) on **long-term site productivity** (**LTSP**), we are monitoring effects of soil compaction and organic matter removal in the aspen (*Populus tremuloides* Michx. and *P. grandidentata* Michx.) forest type in the northern Lake States region. The overall study is designed to determine how changes in soil porosity and organic matter content affect fundamental soil processes controlling forest productivity and sustainability; and secondly, to compare responses among major forest types and soil groups across the United States and Canada. The objective of this installation was to monitor changes in soil properties following forest harvesting and application of soil compaction and forest floor removal treatments, and to measure responses by the forest regeneration and herbaceous vegetation. We report results on aspen stocking and growth; biomass production of aspen and associated vegetation after five growing seasons; and on forest floor characteristics and physical soil properties 5 yr after treatment.

MATERIALS AND METHODS

Stand and Site Conditions

The study was on the Marcell Experimental Forest, in Itasca County, northern Minnesota (47°30′N, 93°30′W). The climate is continental with warm summers (mean July temperature 19°C), cold winters (mean January temperature –16°C), and 770 mm of precipitation, about half of which occurs during the growing season. The site was occupied by a fully stocked, 70-yr-old stand of predominantly trembling and bigtooth aspen. Basal area averaged 40.7 m^2 ha^{-1}, 88% was aspen and the balance was primarily red maple (*Acer rubrum* L.) and paper birch (*Betula papyrifera* Marsh.). The most prevalent shrub on the area was beaked hazel (*Corylus cornuta* Marsh.); the predominant herbs were large-leaf aster (*Aster macrophyllus* L.) and wild sarsaparilla (*Aralia nudicaulis* L.). The soil is classified as Cutaway loamy sand (loamy, mixed, Arenic Eutroboralf) (Soil Survey Staff 1975); site index$_{(age\ 50)}$ for aspen was 20.7 m. Alban et al. (1994) reported detailed stand conditions and a representative soil profile description.

Treatment and Sampling

The aboveground portion of the stand was harvested in February 1991 with a John Deere model 643D feller-buncher and a John Deere model 548D grapple skidder. At harvest, the soil was frozen to at least 30 cm and had a 40-cm snowpack. Four treatments: (1) total-tree harvest (TTH); (2) TTH plus soil compaction (CPT); (3) TTH plus forest floor removal (FFR); and (4) TTH plus CPT + FFR were randomly assigned and applied to 0.16-ha, 30- by 40-m plots plus a 5-m-wide buffer zone. Two **non-cut control** (**NCC**) plots were installed in the adjacent stand, for a total of five treatment combinations. During late April, the forest floor was hand-raked from three plots and piled outside the buffer. In early May, while the soil was near field capacity and before the aspen suckers began to develop, four plots were compacted by four or five passes with an 8,100-kg, rubber-tired roller pulled by a D-6 Caterpillar tractor. Two compaction treatments were planned to increase mean bulk density of the surface 10 to 20 cm of soil by about 15 and 30%. However, the equipment used did not provide the force required for the higher level, and the increase averaged about 22%. Because the differences in bulk density were not significant, the treatments were combined to provide two replications for the CPT and CPT + FFR treatments. When this was determined, the suckers had begun to develop so it was impossible to install a second plot for the FFR treatment without seriously damaging the suckers. Thus, there were two plots for all treatments except the FFR.

In early August 1995, after five growing seasons, the herbaceous vegetation was collected from 12, 0.5-m^2 subplots per plot, dried at 75°C, and weighed. Basal diameter of all woody plants (>15 cm height) was measured and recorded by 2-mm diameter classes on 12, 4.0-m^2 subplots per plot. Mean height of aspen suckers in each diameter class was recorded to the nearest 5-cm class. Basal diameter, diameter at 1.37 m (DBH), and height of all aspen saplings (suckers >2.5 cm DBH) were measured separately.

In May 1996, 5 yr after treatment, soil strength of the surface 40 cm was measured at 12 locations on each plot using a Rimik model CP20 recording penetrometer with a 30°, 1-cm^2 conical tip. Mean soil strength data were calculated for each 10-cm depth interval. Near each measurement point, a 6.35-cm-diameter core sample of the surface 30 cm of soil was collected with a hand-driven sampler (Ruark 1985). The forest floor of each core was separated, dried at 75°C, and weighed. Subsamples were analyzed for total carbon (C) and total nitrogen (N) by gas chromatography (Pella 1990a,b) The mineral soil of each was separated in 10-cm depth increments, weighed fresh, air dried, passed through a 2-mm sieve, and the weight of soil and coarse fragments was determined. A 100-g subsample of each was oven dried at 105°C and weighed. Bulk density of each sample was calculated and corrected for the difference between air dry and oven dry weight. The volume of coarse fragments was calculated using a specific gravity of 2.65 Mg m^{-3}.

Data Analyses

The aboveground biomass of shrubs, aspen suckers, and saplings was estimated using allometric equations for each species developed by Perala and Alban (1994). The form of the equations is:

$$\text{Component weight} = \text{Constant} \times D15\text{^}b \times Age\text{^}c \times \text{Soil and other treatment multipliers}$$

where weight, D15 and Age are in grams, millimetres and years, respectively.

For saplings, DBH is used instead of D15 (Appendix). All subplot data were composited and treatment effects were evaluated by one-way analysis of variance of the plot-level means (Analytical Software 1996). Comparisons among means were made with the Least Significant Difference procedure at the 95% confidence level.

RESULTS

Soil Properties

Mean values of physical properties for the five non-compacted, vs. the four compacted plots are summarized in Table 1. Compaction significantly increased bulk density of each 10-cm depth increment; the difference was greatest in the surface 10-cm. Density of the fine fraction (<2 mm) followed the same pattern. Coarse fragment content increased from about 3% at the surface to about 10% at the 20 to 30-cm depth. There were no significant treatment differences in coarse fragment content, fine fraction volume, nor field-moist water content at any of the three depths.

Mean soil strength was slightly lower on non-cut plots than on those that were harvested, but the difference was significant only for the 20- to 30-cm depth (Fig. 1). Compared with the three harvested plots, CPT (n = 4) significantly increased soil strength at all four depths. Bulk density values of the TTH and CPT treatments were essentially equal to those of samples collected in May 1991, shortly after the treatments were applied (Fig. 2). The mean values were slightly higher in 1996, but all were within 0.1 Mg

Table 1. Physical soil properties 5 yr after compaction

Variable	Treatment	Depth increment (cm) 0 – 10	10 – 20	20 – 30
Bulk density (total) ($Mg\ m^{-3}$)	Control[z]	1.05*a*	1.37*a*	1.44*a*
	Compacted[y]	1.23*b*	1.47*b*	1.58*b*
Bulk density (fine fraction) ($Mg\ m^{-3}$)	Control	1.00*a*	1.27*a*	1.33*a*
	Compacted	1.18*b*	1.37*b*	1.46*b*
Coarse fragments (% volume)	Control	2.6	6.8	8.8
	Compacted	3.3	7.7	10.5
Fine fraction (% volume)	Control	97.4	93.2	91.2
	Compacted	96.7	92.3	89.5
Water content ($m^3\ m^{-3}$)	Control	0.20	0.17	0.14
	Compacted	0.22	0.19	0.16

[z]Means of five non-compacted plots.
[y]Means of four compacted plots.
a,*b* Parameter means within columns followed by the same letter, or without letters do not differ significantly.

m^{-3} of the 1991 samples. Likewise, the soil strength values are similar to those measured in 1991, particularly in the surface 20 cm (Fig 3). The 1996 data indicate a small decrease at the 20- to 30-cm depth on the TTH plots and a slight increase in the CPT treatment, both probably due to sampling variation.

On the FFR plots (n = 3), the forest floor averaged 1.9 cm thick and 54 Mg ha^{-1}, both significantly lower than that of the TTH and NCC treatments (Table 2). Total C and N on the FFR plots was about half that of the other treatments and the differences were significant 5 yr after treatment (Table 3). The FFR treatment did not affect total C or N in any of the mineral soil samples. Total N in the forest floor plus mineral soil was somewhat less than that of the other treatments, but not significantly.

Aspen Development

After five growing seasons, there were 40.4 k aspen suckers ha^{-1} (>15 cm in height) on the TTH plots and 40.6 k ha^{-1} in the FFR treatment (Table 4). Soil compaction significantly decreased sucker density to 19.6 k ha^{-1}. Stand density on the CPT + FFR plots averaged 33.8 k ha^{-1}, not significantly different from the other harvested treatments. Basal diameter on the TTH and CPT plots was significantly greater than for both treatments that included forest floor removal. Height of suckers on the TTH plots averaged 271 cm, significantly greater than all other treatments except CPT. Dry weight of foliage, stems, and total weight of suckers on the TTH plots were significantly greater than those of all other treatments (Table 5).

There were 5.0 k aspen saplings ha^{-1} (suckers >2.5 cm DBH) on the TTH plots and less than 1.0 k ha^{-1} in each of the other treatments (Table 6). Mean DBH and height were somewhat greater, and dry weight of each of the sapling components greatly exceeded that of all other treatments, but there were too few in the other treatments for valid statistical comparisons. There were no sapling-size suckers on the NCC plots. Herbaceous biomass averaged 1200 kg ha^{-1} on the CPT plots, significantly greater than the 750 kg ha^{-1} in the TTH and FFR treatments (Fig. 4). Biomass of shrub species did not differ significantly by treatment. Total aboveground biomass on the TTH plots averaged 16.5 Mg ha^{-1}, nearly double that of all other treatments.

DISCUSSION

Soil Properties

HARVESTING. Forest harvesting when the soils were frozen and snow-covered had little effect on most of the physical properties measured. A possible exception may be soil strength. The relatively small but consistent differences between the NCC and TTH plots (Fig. 1) is noteworthy for two reasons. First, in companion work on sand soils, we

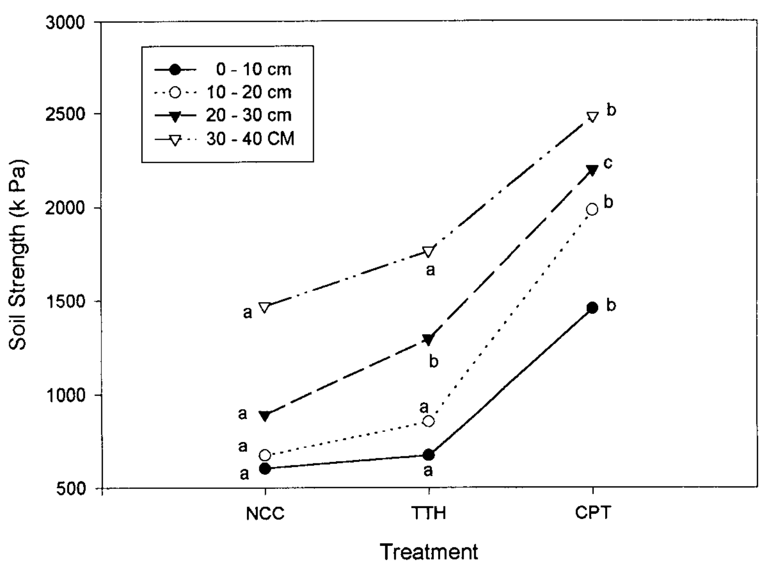

Fig. 1. Soil strength 5 yr after harvest and treatment. Treatment means for each depth followed by the same letter do not differ significantly at $P \leq 0.05$.

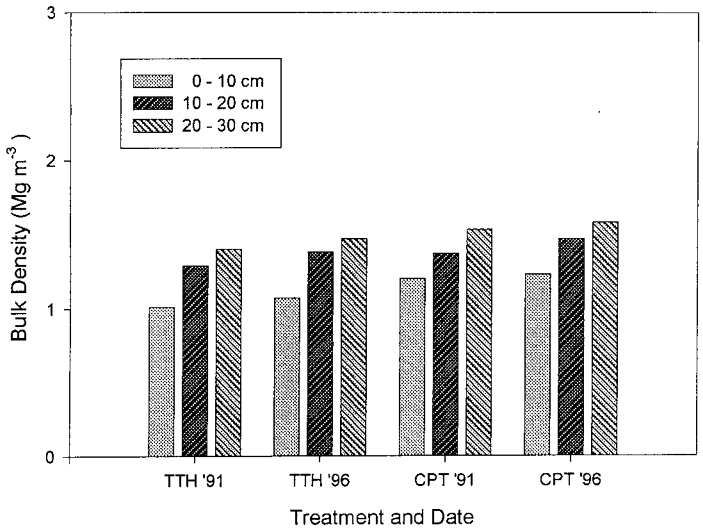

Fig. 2. Bulk density of TTH and CPT plots in May 1991, immediately after compaction and in May 1996, 5 yr after treatment.

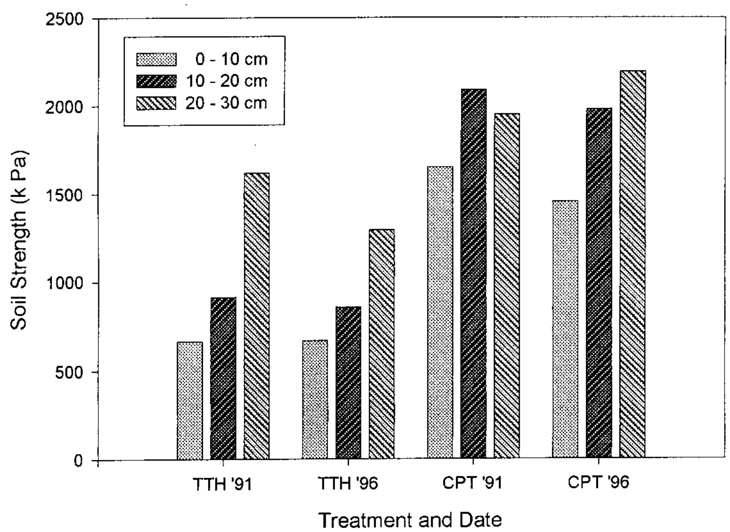

Fig. 3. Soil strength of TTH and CPT plots in May 1991, immediately after compaction and in May 1996, 5 yr after treatment.

Table 2. Depth and dry weight of forest floor materials 5 yr after treatment

Treatment	n^z	Thickness (cm)	Weight (Mg ha^{-1})
Non-cut control (NCC)	2	3.9*b*	106*b*
Total-tree harvest (TTH)	4^y	3.4*b*	89*b*
Forest floor removal (FFR)	3^y	1.9*a*	54*a*

^{z}Number of plots per treatment.
^{y}Two of the plots also were compacted.
a,b Means in columns followed by the same letter do not differ significantly.

have noted substantially greater soil strength values in harvested aspen stands than in adjacent non-cut stands (unpublished data). Secondly, Alban et al. (1994) found that infiltration rates on the NCC plots were significantly higher than on the TTH plots on this site during both the first and

Table 3. Total C and N in forest floor and mineral soil 5 yr after treatment

Treatment	Forest floor	Mineral soil depth (cm) 0 – 10	10 – 20	20 – 30	Total
		Total C (Mg ha^{-1})			
NCC (24)^z	21.1*b*	22.5	11.4	7.6	62.9*b*
TTH (48)^y	19.8*b*	21.7	9.8	7.8	59.1*b*
FFR (36)^y	10.6*a*	21.1	9.6	7.4	48.8*a*
		Total N (Mg ha^{-1})			
NCC	0.77*b*	1.29	0.92	0.77	3.76
TTH	0.79*b*	1.36	0.88	0.87	3.89
FFR	0.47*a*	1.31	0.82	0.80	3.41

^{z}Number of samples per treatment.
^{y}Two of the plots also were compacted.
a,b Treatment means followed by the same letter, or without letters do not differ significantly.

Table 4. Mean density, basal diameter (15 cm), and height of aspen suckers after five growing seasons

Treatment	Number (k ha^{-1})	Diameter (mm)	Height (cm)
NCC (2)[z]	3.6*a*	8.4*a*	112*a*
CPT (2)	19.6*b*	17.5*c*	233*bc*
FFR (1)	40.6*c*	13.7*b*	201b
CPT + FFR (2)	33.8*b*c	14.6*b*	204*b*
TTH (2)	40.4*c*	19.4*c*	271*c*

[z]Number of plots per treatment.
a–c Means in columns followed by the same letter do not differ significantly.

Table 5. Dry weight of aspen sucker components after five growing seasons

Treatment	Foliage	Stems	Total
		(kg ha^{-1})	
NCC (2)[z]	30*a*	126*a*	156*a*
CPT (2)	829*b*	3 521*b*	4 350*b*
FFR (1)	822*b*	3 697*b*	4 520*b*
CPT + FFR (2)	854*b*	3 833*b*	4 687*b*
TTH (2)	2 422*c*	10 470*c*	12 893*c*

[z]Number of plots per treatment.
a–c Means in columns followed by the same letter do not differ significantly.

Table 6. Density, DBH, height, and dry weight of aspen saplings (>2.5 cm DBH)

Treatment	Number (ha^{-1})	DBH (mm)	Height (cm)	Foliage	Stems	Total
					kg ha^{-1}	
CPT	940	28.5	391	230	880	1,110
FFR	420	28.0	390	80	360	440
CPT + FFR	830	27.4	406	170	700	880
TTH	5,000	29.7	446	1,360	5,200	6,560

second year after treatment. Effects of heavy equipment on forest floor characteristics of frozen soils, particularly the forest floor-mineral soil interface, merit additional attention.

COMPACTION. The 17 to 18% increase in bulk density of the surface 10 cm of soil (Table 1) is not large compared with values commonly found on major skid trails and landings (unpublished data), and is close to the 22% increase reported for these plots by Alban et al. (1994). Perhaps of greater significance, in terms of root growth, were the increases in bulk density of the fine fraction and in soil strength on the compacted plots, particularly in the surface 30 cm where mean soil strength was more than doubled by the CPT treatment (Fig. 1).

Treatment impacts depend on both magnitude and duration. The essentially equal bulk density values of samples collected from compacted plots in 1991 and 1996 indicate no change during the 5 yr since treatment (Fig. 2). Likewise, mean soil strength of the surface 30 cm of soil measured in 1991 and 1996 indicate no recovery during this period (Fig. 3). Thus, neither bulk density nor soil strength show any trend toward recovery to pre-treatment conditions. Corns (1988) estimated time for bulk densities to recover from post-logging values to those of non-cut stands to range from 13 to 17 yr, 17 to 21 yr, and 10 to 15 yr for three soil associations in Alberta. The soils on a fourth site were not compacted by the summer logging.

FOREST FLOOR REMOVAL. Alban et al. (1994) reported that the FFR treatment reduced the forest floor thickness from 4.4 cm to 0.9 cm (an 80% reduction), and that forest floor weight was reduced from 99 Mg ha^{-1} to 27 Mg ha^{-1} (a 73% reduction). After 5 yr, both thickness and dry weight of the forest floor on the TTH plots were slightly, but not significantly, lower than the NCC plots. The differences are most likely due to increased decomposition during the first year or two following harvest, and essentially have recovered to pre-harvest conditions. During this period, the forest floor in the FFR treatment has recovered 1.0 cm in thickness, and 27 Mg ha^{-1} dry weight, or about 5 Mg ha^{-1} yr^{-1}. This may be

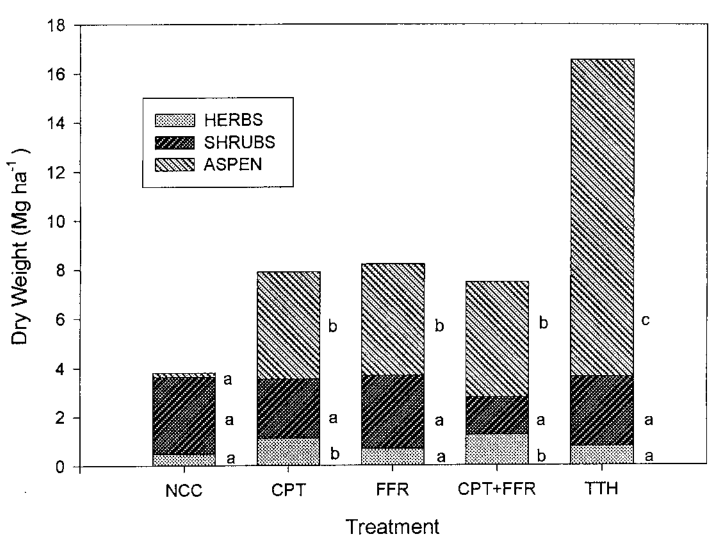

Fig. 4. Distribution of biomass on aspen plots after five growing seasons. For each strata, treatment means followed by the same letter do not differ significantly at $P \leq 0.05$.

an overestimate due to sampling variation, both in the 1991 values (D. H. Alban, personal communication) and in the 5-yr data (Federer 1982; Grigal et al. 1991). However, at this rate of accumulation, the forest floor mass will approach that of the NCC plots in another 10 yr, or 15 growing seasons after treatment.

In May 1991, immediately after forest floor removal, Alban et al. (1994) estimated total C in the forest floor of the FFR treatment at 5.1 Mg ha^{-1}. The 1996 data (Table 3) indicate 10.6 Mg ha^{-1}, an increase of about 1.1 Mg ha^{-1} per year. At this rate of accumulation, these plots will require an additional 10 yr to regain the C lost in the FFR treatment. Data on total N in the forest floor are not available for the 1991 samples. In 1996, the NCC and TTH plots each contained about 800 kg ha^{-1} and those in the FFR treatment averaged about 500 kg ha^{-1}. If the rate of N recovery is proportional to C accumulation, total N in the FFR plots could approximate that of the NCC and TTH treatments at about 15 yr after treatment.

Aspen Development

HARVESTING. Dormant season logging produced abundant regeneration; the 40.4 k suckers ha^{-1} was well within the typical range of 25 to 50 k ha^{-1} at age 5 (Table 6 in Peterson and Peterson [1992]). Basal diameter and height of suckers on the TTH plots was somewhat greater than those of the other treatments (Table 4), and biomass production significantly exceeded that of all other treatments (Table 5). Of greater silvicultural significance is the 5.0 k stems ha^{-1} in the sapling size class on the TTH plots (Table 6); it is noteworthy that the 1360 kg ha^{-1} of foliage produced by the saplings is 300 kg ha^{-1} greater than that produced by the 35.4 k suckers ha^{-1} that were <2.5 cm DBH (data not shown). If photosynthate production is proportional to foliar biomass, the photosynthetic potential of these larger 5.0 k stems ha^{-1} exceeds that of the smaller 35.4 k suckers ha^{-1}. As an index of **net primary productivity** (**NPP**), total aboveground biomass production was nearly double that of the treatments involving soil disturbance (Fig. 4).

COMPACTION. The most direct effect of the CPT treatment was to reduce sucker density (Table 4). CPT reduced aspen suckers from 97 k ha^{-1} to 66 k ha^{-1} the first year, and from 86 k ha^{-1} to 58 k ha^{-1} the second year (Alban et al. 1994), a decrease of about 32% each year. By the fifth year, the difference had increased from 40.4 k ha^{-1} to 19.6 k, more than 51%. Because of the lower sucker density, mean diameter and height of individual stems were similar to those on the TTH plots (Table 4). However, total sucker biomass was only about one-third that of the TTH treatment (Table 5). Variation among stands in biomass accumulation has been referred to as "carrying capacity", "average mass density", and "stockability" (DeBell et al. 1989; Perala et al. 1995). Perala et al. (1995) showed that trembling aspen and its Eurasian counterpart, *P. tremula* L., comprise a circumboreal superspecies from the standpoint of self-thinning and stockability. Lonsdale (1990) and Weller (1990) pointed out that the growing environment as well as genetics can affect both the rate and power parameters of the stockability equations. These data (Table 5) indicate that the CPT treatment has reduced 5-yr aspen biomass production, and temporarily lowered stockability. In Colorado, Shepperd (1993) noted decreased sucker density and growth on disturbed areas up to 12 yr after harvesting.

FOREST FLOOR REMOVAL. The greatest direct effect of the FFR treatment was a large increase in sucker density. Disturbance of aspen root systems and increased soil temperatures are known to stimulate suckering (Schier et al. 1985; Peterson and Peterson 1992). FFR resulted in more than 260 k suckers ha^{-1} the first year following treatment, nearly three times the density of the TTH plots (Alban et al. 1994). By the second year, this had declined to 130 k ha^{-1} about 1.5 times the TTH. Although fifth-year stocking of both treatments was about 40 k ha^{-1}, the early over-stocking resulted in significantly lower mean sucker diameter, height, biomass, number and biomass of saplings, and about 35% of the total aboveground aspen biomass compared with the TTH treatment. Although self-thinning is occurring, the reduced diameter and height and lower biomass may have decreased stockability and perhaps future productivity. Thus, it seems unlikely that stand development following FFR will approach that of the TTH treatment within the next 5 yr.

SITE PRODUCTIVITY. The overall effects of CPT and CPT + FFR were similar in terms of production and distribution of biomass (Fig. 4). Alban et al. (1994) found an increase in the number of ground-flora species on all plots 2 yr following harvest, probably due to increased light and the amount of exposed soil. The increases were related to the degree of disturbance, with six on the TTH plots, 10 with FFR, 11 with CPT, and 17 with CPT + FFR. During the fifth growing season, the TTH and FFR plots each produced about 0.75 Mg ha^{-1} of herbaceous species, comprised largely of large-leaf aster (*Aster macrophyllus* L.), wild sarsaparilla, and bracken fern (*Pteridium aquilinum* var. *latiusculum* Brake). The treatments that included CPT had about 1.2 Mg ha^{-1} of herbaceous materials, including the former species and miscellaneous "weed" species. The significantly greater herbaceous production was accompanied by slightly lower shrub production, although not significantly different from the FFR treatment.

Considering total aboveground biomass as an index of NPP, each of the disturbance treatments significantly decreased NPP of the site. After five growing seasons the NPP indices, relative to the TTH treatment were: FFR = 0.50; CPT = 0.48; and CPT + FFR = 0.45. Thus, the disturbance treatments have significantly reduced 5-yr aspen productivity to about one-third that of the TTH treatment and total biomass to about one-half, retarded development of potential crop trees, delayed early stand development, and temporarily lowered the stockability and productivity of this aspen ecosystem.

CONCLUSIONS

Results of this 5-yr study of site disturbance effects in an aspen ecosystem growing on a loamy sand soil in northern Minnesota can be summarized as follows: (1) Total-tree harvest (TTH) of mature aspen when the soils were frozen had little effect on physical soil properties and produced a fully stocked stand of aspen suckers. (2) The compaction treatment (CPT) increased bulk density of the surface soil by about 20% and doubled soil strength of the surface 30 cm. Neither bulk density nor soil strength have changed during the 5 yr since treatment. (3) The forest floor removal treatment (FFR) resulted in an 80% reduction in forest floor material and an initial increase in sucker density nearly threefold over the TTH treatment. The forest floor mass has increased about 5 Mg ha^{-1} yr^{-1} and could equal that of non-cut plots 15 yr after treatment. Total N in the FFR plots could approximate that of the non-cut control (NCC) and TTH treatments about 15 yr after treatment. (4) Compared with TTH, the CPT, FFR, and CPT + FFR treatments each reduced total aboveground biomass by one-half and aspen biomass by two-thirds, retarded development of potential crop trees, delayed early stand development, and temporarily lowered the stockability and site productivity of the ecosystem.

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APPENDIX

The equations used to estimate biomass of the major shrub species and the aspen saplings follow. For additional species see Perala and Alban (1993). The form of the equations is:

$$\text{Component weight} = \text{Constant} \times \text{D15\^{}b} \times \text{Age\^{}c} \times \text{Soil and other treatment multipliers}$$

where weight, D15 and Age are in grams, millimetres and years, respectively.

Species (shrubs)	Component	Constant	D15	Age
Acer rubrum	Stems	6.242-2	2.486	3.991-1
	Leaves	9.901-2	2.113	NS[z]
Betula papyrifera	Stems	2.373-2	2.687	4.838-1
	Leaves	6.132-2	2.174	NS
Cornus spp.	Stems	4.635-2	3.096	NS
	Leaves	1.004-1	2.476	NS
Corylus cornuta	Stems	4.544-2	2.848	1.594-1
	Leaves	7.188-2	2.244	NS
Populus grandidentata	Stems	1.671-1	2.329	NS
	Leaves	2.266-1	2.068	–5.506-1
P. tremuloides	Stems	7.789-2	2.563	1.107-1
	Leaves	8.338-2	2.248	–4.375-1

Species (saplings)	Component	Constant	DBH	Age
P. grandidentata	Stems[y]	1.857-1	2.520	NS
	Leaves	4.705-1	1.931	–3.563-1
P. tremuloides	Stems	2.484-1	2.322	2.845-1
	Leaves	1.061	2.365	–1.518

[z]NS, not a significant term in the equation.
[y]Also contains a treatment multiplier for full-tree harvested sites; the complete equation is:

weight = 0.1857 × DBH^2.520 × 1.234.