The long-term effects of silvicultural thinning and partial cutting on soil compaction in red pine (*Pinus resinosa* Ait.) and northern hardwood stands in the northern Great Lakes Region of the United States

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Tarpey, R. A., Jurgensen, M. F., Palik, B. J. and Kolka, R. K. 2008. **The long-term effects of silvicultural thinning and partial cutting on soil compaction in red pine (*Pinus resinosa* Ait.) and northern hardwood stands in the northern Great Lakes Region of the United States.** Can. J. Soil Sci. **88**: 849–857. Periodic silvicultural thinnings (23.0, 27.6, 32.1 m^2 ha^{-1} residual basal area) in a red pine stand growing on a sandy soil in north-central Minnesota over a 57-yr period increased soil compaction as the intensity of the thinning treatment increased. Of the three different methods used to measure soil compaction (bulk density, penetration resistance, and saturated hydraulic conductivity), saturated hydraulic conductivity was the most sensitive, decreasing by 60% in the 23.0 m^2 ha^{-1} basal area thinning treatment, as compared with the uncut control. Soil bulk density measurements were more variable, but generally increased with increased thinning intensity. Few differences in soil penetration resistance were found among the three thinning treatments. In contrast, no evidence of soil compaction was detected in a northern hardwoods stand growing on a rocky loam soil in north-central Wisconsin that had three thinning treatments (13.8, 17.2, 20.6 m^2 ha^{-1} residual basal area), a two- stage shelterwood harvest, and a 20-cm-diameter limit cut over a 50-yr period. With the increased demand for forest products, fuel reduction operations in high fire-risk stands, and biomass removal for energy production, more information is needed on the impact of multiple stand entries on soil compaction, and if compaction occurs, whether it will affect long-term soil productivity.

Key words: Soil physical properties, bulk density, soil penetration resistance, hydraulic conductivity

Tarpey, R. A., Jurgensen, M. F., Palik, B. J. et Kolka, R. K. 2008. **Incidence à long terme des éclaircies et des coupes partielles sur le compactage du sol dans les peuplements de pin rouge (*Pinus resinosa* Ait.) et de bois dur du nord de la région des Grands Lacs, aux États-Unis.** Can. J. Soil Sci. **88**: 849–857. L'éclaircie périodique (23,0, 27,6, 32,1 m^2 par hectare de zone de base résiduelle) d'un peuplement de pin rouge poussant sur un sol sablonneux dans le centre-nord du Minnesota pendant 57 ans s'est soldée par une hausse du compactage proportionnelle à l'intensité du traitement. Parmi les trois méthodes employées pour mesurer le compactage du sol (masse volumique apparente, résistance à la pénétration et conductivité hydraulique à saturation), la troisième est la plus sensible, puisqu'elle indique une baisse de 60 % avec l'éclaircie de 23,0 m^2 par hectare de surface de base résiduelle, comparativement à la parcelle témoin non traitée. Les relevés obtenus avec la masse volumique apparente varient davantage, mais en général, ils progressent avec l'intensité du traitement. Les trois traitements varient peu au niveau de la résistance à la pénétration. Par comparaison, on n'a décelé aucun signe de compactage dans un peuplement de bois dur poussant sur un loam rocheux dans le centre-nord du Wisconsin après trois éclaircies (13,8, 17,2 et 20,6 m^2 par hectare de surface de base résiduelle), une coupe d'abri en deux étapes et l'interdiction de récolter les arbres de moins de 20 cm de diamètre sur 50 ans. Face à la demande croissante de produits forestiers, à la diminution de l'usage du carburant aux endroits à risque élevé d'incendie et à la récupération de la biomasse pour la production d'énergie, il faudrait en savoir davantage au sujet de l'impact des peuplements multiples sur le compactage du sol et déterminer si le compactage, quand il existe, affectera la productivité du sol à long terme.

Mots clés: Propriétés physiques du sol, masse volumique apparente, résistance à la pénétration du sol, conductivité hydraulique

Silvicultural prescriptions that include selective harvests and extended rotations are assumed to be more ecological or "natural" than other management systems because they more closely mimic natural disturbance regimes and increase biological diversity (Seymour and Hunter 1999). These management practices also increase the quality and quantity of merchantable timber, improve nutrient availability, alter stand structure, and reduce damage from disease and fire (Zeide 2001; Franklin et al. 2002; Frey et al. 2003; Skov et al. 2004; Gilmore and Palik 2006; Ostaff et al. 2006). However, soil compaction from multiple stand entries (e.g., thinnings) to change stand structure or maximize volume production could reduce long-term soil productivity. The negative consequences

Abbreviations: PR, penetration resistance of soil compaction due to clear-cut harvesting activities are well documented, and have been shown to impact long-term site productivity and forest ecosystem function (Graecen and Sands 1980, Powers et al. 1998, Powers et al. 2006).

The severity of soil compaction is site-specific and influenced by slope, season of harvest, soil texture, and soil moisture, which can exacerbate or confound the impacts of heavy equipment on soil properties (Arikian et al. 1999, Block et al. 2002, Shaw and Carte 2002, Berger et al. 2003). In a review of soil compaction studies, Graecen and Sands (1980) concluded that both thinning and clear-cut harvesting are forest management practices most likely to cause soil compaction, although quantitative data on the impact of thinning on soil compaction were not given. Compaction decreases soil porosity and reduces the movement of air, water and nutrients through the soil, which can reduce tree rooting space and tree growth, and negatively impact microbial populations, nutrient availability and organic matter decomposition (Brussaard and van Faassen 1994; Thibodeau et al. 2000; Bulmer and Simpson 2005; von Wilpert and Schäffer 2006).

Bulk density, or the mass of soil per unit volume, is the most commonly accepted measure of soil compaction, and is a soil variable that indirectly measures water and nutrient availability, gas exchange and root activity (Miller et al. 2001; Powers 2006). However, bulk density alone may not be an accurate metric in some soils, and soil penetration resistance (PR) tests are often used, either alone or in conjunction with bulk density measurements, to estimate soil compaction (Fritton 1990; Powers et al. 1998). Penetrometer measurements are used as an index of soil resistance to root penetration, and are inversely related to pore volume. In some soils penetrometer tests can indicate compaction has occurred when no difference in soil bulk density is found (Sands et al. 1979; Alban et al. 1994; Miller et al. 2001). Hydraulic conductivity, which measures the rate of saturated water flow, is also an indirect measure of total soil pore space and pore size. Higher rates of hydraulic conductivity indicate less resistance to water moving through the soil, and from soil to roots. This parameter is used in soil water, nutrient, and productivity studies (Siegel-Issem et al. 2005; Powers 2006). Thus, a combination of bulk density, soil PR, and hydraulic conductivity information would provide a more comprehensive assessment of thinning effects on soil physical properties and long-term stand growth.

Many studies have found increased soil bulk densities, greater soil PR, and reduced water infiltration rates after a single-cohort (clear-cut) timber harvest (e.g., Mace 1970; Miller et al. 1996; Block et al. 2002; Shaw and Carte 2002; Scott et al. 2004). In contrast, few studies have addressed the effects of stand thinnings or partial cuts on soil compaction, and these have focused mostly on skid trails after one thinning (King and Haines 1979; Landsberg et al. 2003). We could find little information on the impact of repeated stand thinnings, which would increase the number of equipment passes over a specific soil area (Froehlich 1973). Since more ‘‘ecological’’ silvicultural prescriptions, such as extended rotations and selective cutting systems, are being used in forest management (Seymour and Hunter 1999; Franklin et al. 2002), the impacts of long-term thinning operations on forest soil properties needs to be known. Consequently, the objective of our study was to determine the long-term effects of multiple thinnings on soil compaction in two common forest types of the North American Great Lakes Region – red pine (*Pinus resinosa* L.) and northern hardwoods. We tested a range of thinning/ cutting treatments in red pine and the northern hardwood stands (ranging from heavily thinned to unthinned), and hypothesized that the degree of soil compaction would increase with increased cutting intensity.

MATERIALS AND METHODS

Study Location and Description

The red pine stand is located in the Cutfoot Experimental Forest in north-central Minnesota (lat. 47°32′00″N, long. 94°05′00″W), and was established after a wildfire in 1867. The overstory is red pine with a shrub layer comprised mainly of beaked hazelnut (*Corylus cornuta* Marsh.) and balsam fir [*Abies balsamea* (L.) P. Mill.], white spruce [*Picea glauca* (Moench.) Voss], white pine (*Pinus strobus* L.), and red oak (*Quercus rubra* L.) regeneration. Soil is a Menahga loamy sand occurring on a nearly level glacial outwash plain (Table 1).

The northern hardwood stand is on the USFS Argonne Experimental Forest in north-central Wisconsin (lat. 45°45′00″N, long. 89°03′00″W), and was selectively cut in 1905. The overstory is predominately sugar maple (*Acer saccharum* Marsh.) with a white ash (*Fraxinus americana* L.), basswood (*Tilia americana* L.), yellow birch (*Betula alleghaniensis* Britt.), and eastern hemlock [*Tsuga canadensis* (L.) Carr.]. Soil is a Argonne sandy loam, which was formed on a glacial till plain with a high rock content and a moderately deep (50–100 cm) fragipan (Table 1).

Study Histories and Experimental Design

Both the red pine and northern hardwood stands have three blocks (replicates) of four and six cutting treatments, respectively. Each treatment consists of a different thinning intensity or partial cutting treatment occurring periodically for at least 50 yr. Both stands were bole-only harvested during the winter when snow depths were 40–100 cm, and all logging slash was left on site. Permanent log landings created in both stands were used with successive harvests to minimize the affected stand area.

The red pine stand has three residual basal area (BA) treatments of 23.0, 27.6, and 32.1 m^2 ha^{-1} applied seven

Table 1. Study stands in the USFS Cutfoot Experimental Forest in north-central Minnesota, and the Argonne Experimental Forest in north-central Wisconsin

Location	Cutfoot Experimental Forest		Argonne Experimental Forest	
National Forest	Chippewa		Nicolet	
Soil series	Menahga loamy sand		Argonne sandy loam	
Acidity and drainage	Strongly acid, excessively drained		Moderately acid, moderately well-drained	
Taxonomic description	Mixed, frigid Typic Udipsamments		Mixed, superactive, frigid Alfic Oxyaquic Fragiorthods	
Rock fragment content (30cm)	2% gravel		12% gravel; 1% cobbles;	
Annual precipitation (cm)	66		76.2	
Mean annual air temperature (C)	5.5		4.4	
Current stand age	139		104	
Study initiation	1949		1951	
Stand age at study initiation	82		50	
Dominant vegetation		% basal area		% basal area
Trees	*Pinus resinosa* Ait.	96.4	*Acer saccharum* Marsh.	63.3
	Abies balsamea (L.) P. Mill	.28	*Fraxinus americana* L.	15.5
	Picea glauca (Moench.) Voss	.14	*Tilia americana* L.	18.6
	Quercus rubra L.	.31	*Betula alleghaniensis* Britt.	11.5
	Pinus banksiana Lamb.	.93	*Tsuga canadensis* (L.) Carr.	15.6
	Pinus strobus L.	1.9		
Shrubs	*Corylus corunata* Marsh.		*Rubus idaeus* L.	
	Vaccinium angustifolium Ait.		*Sambucus racemosa* L.	
Forbs	*Pteridium aquilinum* (L.) Kuhn.		*Osmorhiza claytonii* (Michx.) C.B. Clarke	
	Maianthemum canadense Desf.		*Athyrium filix-femina* (L.) Roth	
	Aquilegia canadensis L.		*Polygonatum pubescens* (Willd.) Pursh.	

times to 1–2 ha plots (Table 2). Hand-felling and horse-skidding were used from 1949–1965 (four thinnings), and conventional bole-only logging with hand-felling and tractor or grapple skidding was used after 1974 (three thinnings) until the last harvest in 1995. An uncut control of three 1–2 ha plots was located in an adjacent uncut area having no known history of timber removal or any kind of management since the stand's establishment.

The northern hardwood study has six 1-ha thinning/partial cutting treatments: three residual BA treatments of 20.6, 17.2, and 13.8 m^2 ha^{-1} cut six times since 1951, a diameter-limit harvest (removed all trees $>$20 cm dbh in 1951 and 1991), a shelterwood (removed 40% crown cover in 1957 and the remaining overstory in 1964), and a control with no history of timber removal since being selectively cut in 1905. Boles were removed by horses in the first harvest (1951), and mechanical logging equipment (tractors, tracked Iron Mule, rubber tire forwarders) was used in subsequent cuttings until the last harvest in 2001. All logging slash was left in each treatment plot.

Sampling

A series of 20 grid points, approximately 20 m apart and at least 20 m from the plot perimeter, was established in each stand treatment plot during June 2003 (red pine) and June 2004 (northern hardwoods). There were some well-defined skid trails in both the red pine and hardwood stands, which were likely used in repeated thinning operations. However, the occurrence and distribution of these skid trails were not related to the intensity of the thinning treatments, but to the location of log landings or yarding areas off the study sites. Since we wanted to determine the effect of thinning intensity on soil compaction in the treatment plots, the few grid points that landed on skid trails were not used, and another point established within 5 m. At each grid point, a bulk density sample was taken to a 30-cm mineral soil depth with a 5-cm-diameter soil core sampler with plastic inserts. The inserts were sealed immediately after sampling and transported to the US Forest Service Laboratory in Grand Rapids, MN, for processing.

In the laboratory all plastic insert cores were cut into separate A horizon and B horizon (all soil below the A horizon to a 30 cm depth) sections, and then dried at 110°C for a minimum of 24 h and weighed. Total bulk density of the A and B horizons was determined from the dry weight and horizon volume in each plastic soil core section. Soil PR was measured in 10 cm increments to a soil depth of 40 cm with a Rimik CP-20 cone penetrometer (Agrdry Rimik Pty Ltd Towoomba Australia). Three random penetrometer readings were taken 5 m from each grid point for a total of 60 PR readings per plot and 180 for each cutting treatment.

Hydraulic conductivity was measured with an Amoozemeter (constant head borehole permeameter) in five random holes (5 cm diameter by 30 cm deep) in each plot. The Amoozemeter determines the steady-state rate

Table 2. History of thinning/cutting treatments: (A) red pine – Cutfoot Experimental Forest, Minnesota, and (B) northern hardwoods – Argonne Experimental Forest, Wisconsin

A.

Treatment[z]	Date of thinning									
	1949	1951	1954	1956	1959	1960	1965	1975	1985	1995
					Replicates[y]					
23.0	2	1	2	1	2	1	All	All	All	All
27.5	2	1	2	1	2	1	All	All	All	All
32.1	2	1	2	1	2	1	All	All	All	All
Uncut					None					

B.

Treatments [x]	Date of thinning							
	1951	1957	1961	1964	1971	1981	1991	2001
				Replicates[w]				
20-cm-diameter limit	All						All	
Shelterwood[v]		1		2				
Basal area residual								
13.8	All		All		All	All	All	All
17.2	All		All		All	All	All	All
20.7	All		All		All	All	All	All
Uncut				None				

[z]Residual basal area remaining after thinning in m^2 ha^{-1}.
[y]Number of treatment replicates ($n = 3$) that were thinned that year. Horse-logging occurred between 1949 and 1965.
[x]Treatments: 20-cm-diameter limit – all trees above 20 cm dbh cut; shelterwood – 60% of canopy was removed from one replicate in 1957, from the other two replicates in 1964, and the remaining canopy was removed in 1964 and 1971, respectively; basal area residual – residual basal area (m^2 ha^{-1}) remaining after thinning; uncut – no history of timber management since the area was selectively cut in 1905.
[w]Numbers of treatment replicates ($n = 3$) that were harvested that year.
[v]In 1964 overstory removal occurred in one replicate, and initial cuts occurred in the other two replicates. Overstory was removed from these two replicates in 1971.

of water recharge into the 5 cm cylindrical borehole, which is assumed to measure hydraulic conductivity into an unbounded soil volume extending radially from the ponded water in the hole (Amoozegar 2002). Since all boreholes were located in the fine soil fraction at both sites, we assumed that the water infiltration rate on the loamy-textured till soil in the hardwood stand was influenced by fine soil pore-size distribution and the flow rate around rock-fragments. Water infiltration (mL min^{-1}) was measured until rates stabilized, usually within 1 h.

Data Analysis

Analysis of variance was used to test for differences in soil physical properties (bulk density, soil PR, and hydraulic conductivity) means among treatments in each stand. The least significant difference (LSD) test of significance was used to assess differences of means among the thinning/partial cutting treatments at $P < 0.10$.

RESULTS

Bulk Density and Soil Penetration Resistance

We found no significant difference in A and B horizon bulk density among the three residual BA thinnings in the red pine stand (Table 3, Fig. 1A). Contrary to our hypothesis, soil bulk density of the A horizon in the heaviest thinning (23 m^2 ha^{-1} BA remaining after treatment) was significantly lower (25.6%) than the uncut control. The A horizon carbon concentration in the 23 BA residual plots was higher (8.3%), but not significantly different than in the control plots (6.7%, unpublished data), and likely does not account for the bulk density difference. In contrast, bulk densities of the B horizon in the 23 BA and 32.1 BA plots were 17.0 and 10.3% higher than in the than the uncut control. Soil penetration resistance was not significantly different in any treatment at the 0- to 10-cm depth, but the 23 BA plot was significantly higher (17.6%) than the control at the 10- to 20-cm soil depth (Table 4A).

There were no significant bulk density differences in the surface A horizon or the B horizon in any thinning and partial cutting treatments in the northern hardwood stand (Table 3, Fig. 1B). The high rock-fragment content of the Argonne soil may have protected it from compaction, but it may also have reduced our ability to measure if any soil compaction had occurred. We were only able to obtain bulk density values where our 5-cm-diameter soil corer could penetrate to a 30-cm depth between rocks. Similar problems were encountered with penetrometer measurements, which gave significantly higher soil PR values at the 10- to 20-cm depth in the diameter-limit and 17.2 m^2 ha^{-1} residual BA cutting treatments than the uncut control (Table 4B).

Table 3. Analysis of variance (ANOVA) for soil bulk density, penetration resistance, and hydraulic conductivity by thinning treatments in: (A) red pine of the Cutfoot Experimental Forest, MN; and (B) northern hardwood of Argonne Experimental Forest, WI

Effect by thinning (y = . . .)	df	R-square	Root MSE	*F* ratio	*P* value
A					
Bulk density					
A horizon	11	0.52	0.10	2.86	0.10
B horizon	11	0.53	0.10	2.97	0.09
Penetration resistance					
0–10 cm	11	0.55	44.9	2.07	0.22
10–20 cm	11	0.92	23.2	18.36	0.004
20–30 cm	11	0.23	66.8	0.50	0.70
30–40 cm	11	0.42	111.4	1.19	0.40
Hydraulic conductivity (0–30 cm)	11	0.85	198.4	15.39	0.001
B					
Bulk density					
A horizon	17	0.11	0.23	0.30	0.91
B horizon	17	0.25	0.34	0.80	0.57
Penetration resistance					
0–10 cm	17	0.22	50.2	0.69	0.64
10–20 cm	17	0.56	46.3	3.02	0.05
20–30 cm	17	0.30	57.6	1.05	0.43
30–40 cm	17	0.11	79.9	0.29	0.91
Hydraulic conductivity (0–30 cm)	17	0.15	162.5	0.43	0.82

Hydraulic Conductivity

The relationship of thinning intensity to soil-saturated hydraulic conductivity was clearly shown in the red pine stand (Fig. 2A). Water infiltration rates were highest in the uncut stand, and decreased significantly with increasing BA removal. Hydraulic conductivity was also highest in the uncut northern hardwood control plots, but no significant differences were found among cutting treatments (Fig. 2B). However, it is possible that high within plot variability in this rocky soil may have masked compaction in some treatments. Overall, hydraulic conductivity was more sensitive to increased thinning intensity than bulk density or soil PR.

DISCUSSION

Thinning Effects on Soil Compaction

Many studies have shown that soil bulk density and PR increased at various soil depths after clearcut timber harvesting (e.g., Mace 1970, Alban et al. 1994, Brais and Camiré 1998, Arikian et al. 1999, Block et al. 2002, Shaw and Carte 2002). Page-Dumroese et al. (2006) documented a corresponding increase in PR in half of the soils they measured when soil bulk density increased due to harvesting activities. Alban et al. (1994) found that the proportional increase of soil PR in a loamy sand was much greater than bulk density after a timber harvest, especially at the 0- to 10-cm soil depth. However, PR values decreased significantly 13 mo after harvest, while bulk density did not change.

In contrast, much less is known on the effects of thinning or partial cutting on soil bulk density and PR. Mace (1970) found that full-tree red pine thinning in northern Minnesota significantly increased bulk density at the 0- to 5-cm soil depth, but not when only tree boles were removed. However, significant bulk density increases were found at 5- to 10-cm and 10- to 15-cm soil depths with both thinning methods. This lack of surface soil compaction in tree-length skidding was attributed to the protective layer of slash from the thinned tree branches. A similar surface soil protection could have occurred in our 23 BA residual plots, which would have had the highest slash inputs to the forest floor. In a study on sessile oak [*Quercus petraea* (Matlusch) Lieb.] stands in Turkey, Makineci (2005) found that surface soil bulk density (0–6 cm depth) was significantly lower in both 22 and 64% BA removal treatments, but was significantly higher at 6- to 17-cm soil depth than in unthinned stands. The lack of compaction in the surface soil was attributed to mixing of the forest floor into the mineral soil during thinning operations. However, soil samples were taken 8 yr after the last thinning, which could be enough time for amelioration of compaction in the surface soil. All stands in this study were manually thinned, and no information was given about the equipment used for skidding or hauling thinned trees. King and Haines (1979) found that mechanically removing 36% of the BA with a harvester and forwarders from an 8-yr-old slash pine (*Pinus elliottii* Engelm.) plantation in Alabama had no effect on bulk density at 5- and 10-cm soil depths. In northeastern Washington, Landsberg et al. (2003) showed that thinning an overstocked mixed-conifer stand with harvesters and feller-bunchers increased soil bulk density and PR on skid trails, but not in the surrounding stand. All of these studies focused on the short-term impact of

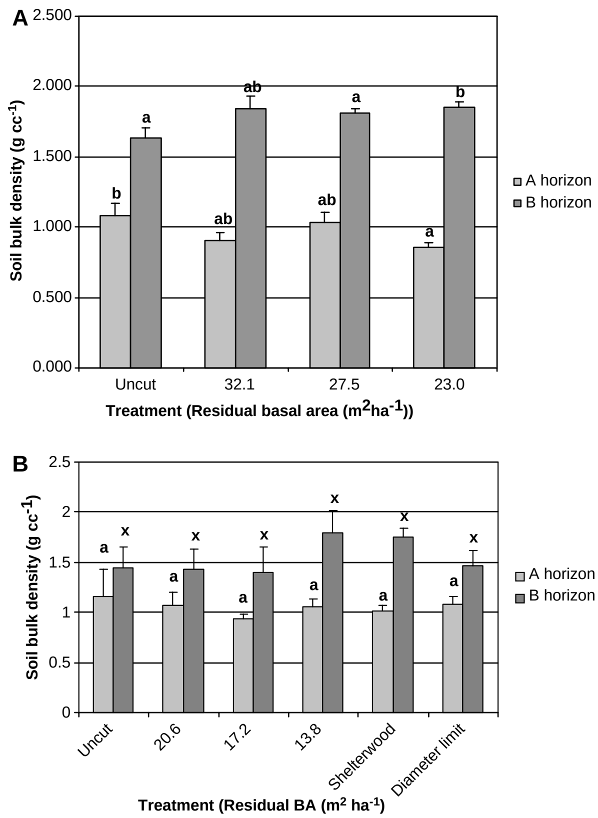

Fig. 1. Soil bulk density of the A and B horizon among different thinning treatments in: (A) a red pine stand located in Cutfoot Experimental Forest, MN; and (B) a northern hardwood stand located in Argonne Experimental Forest, WI. Values with different letters are statistically different when $P < 0.10$. Bars indicate standard error of the mean.

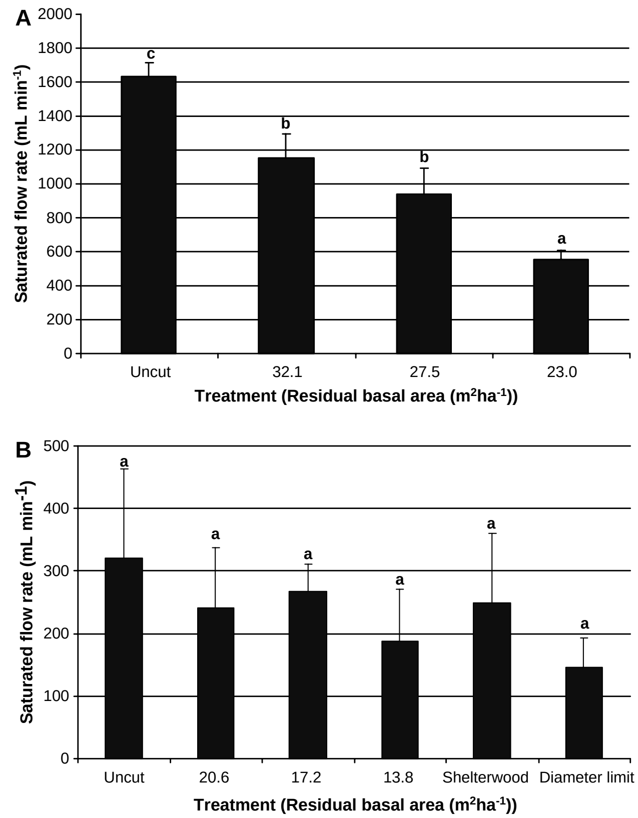

Fig. 2. Saturated flow rate (0- to 30-cm soil depth) among different thinning/cutting treatments in: (A) a red pine stand located in Cutfoot Experimental Forest, MN; and (B) a northern hardwood stand located in Argonne Experimental Forest, WI. Values with different letters are statistically different when $P < 0.10$. Bars indicate standard error of the mean.

Table 4. Soil penetration resistance in different thinning/cutting treatments in: (A) red pine in the Cutfoot Experimental Forest, MN, and (B) northern hardwood in the Argonne Experimental Forest, WI

Treatment	Soil penetration resistance (kPa)			
	0–10 cm	10–20 cm	20–30 cm	30–40 cm
A				
Basal area residual (m^2 ha^{-1})				
23.0	531*a* (68.1)	920*m* (22.8)	1027*r* (58.8)	1377*x* (71.5)
27.5	555*a* (1.0)	864*mn* (9.0)	1063*r* (52.8)	1524*x* (20.6)
32.1	543*a* (12.2)	906*mn* (5.8)	1076*r* (48.3)	1586*x* (120.5)
Uncut	456*a* (8.9)	758*n* (15.4)	1012*r* (29.2)	1302*x* (60.4)
B				
Diameter limit −20 cm	493*a* (18.9)	635*mn* (12.4)	777*r* (34.2)	1130*x* (61.4)
Shelterwood	472*a* (7.2)	575*no* (33.5)	749*r* (34.2)	1138*x* (58.5)
Basal area residual (m^2 ha^{-1})				
13.8	468*a* (18.4)	577*no* (25.2)	692*r* (23.6)	1095*x* (60.6)
17.2	502*a* (22.1)	671*m* (24.2)	783*r* (16.8)	1164*x* (64.5)
20.7	472*a* (21.1)	623*mno* (18.8)	773*r* (30.5)	1160*x* (55.4)
Uncut	433*a* (20.8)	545*o* (5.5)	740*r* (33.3)	1142*x* (21.3)

Values with different letters within columns are statistically different when $P < 0.10$. Standard error values are in parentheses.

one thinning operation on soil compaction. We could find no information on the effect of repeated thinnings over a longer time period.

Our hydraulic conductivity results generally follow similar trends of decreased water infiltration and/or hydraulic conductivity reported in short-term timber harvesting studies (Steinbrenner 1955, Steinbrenner and Gessel 1955, Sands et al. 1979). Alban et al. (1994) found water infiltration was reduced by nearly 50% after clear-cutting an aspen stand in northern Minnesota. Similar to the results of our study, they found that hydraulic conductivity was a more sensitive metric of compaction than bulk density or PR in their loamy sand soil. We could not find any study that measured the effect of thinning on hydraulic conductivity.

Soil pore size distribution can be significantly affected by timber harvesting, even when total pore space and bulk densities are not (Page-Dumroese et al. 2006). Smaller soil macropore size, as indicated by decreased water flow, seems to be a more sensitive response variable to compaction than a reduction in total pore space. While saturated hydraulic conductivity may be a more sensitive indicator of soil compaction than bulk density or PR, this does not mean it is the best method to use in compaction studies. For example, bulk densities values may be needed to convert soil nutrient concentrations to area estimates of soil nutrient pools. Other factors, such as cost, sampling design, and study objectives, would also enter into the determination of which method to use.

Soil type is an important factor in any soil compaction study (e.g., Smith et al. 1997). Sandy soils, such as the Menahga sand in the red pine stand, are typically not compacted as easily as a finer-textured soil (King and Haines 1979, Page-Dumroese et al. 2006). But our results show evidence of compaction in the sand, and none in the loamy Argonne soil. The high rock content in this glacial till could have limited the impact of logging equipment on this soil. Page-Dumroese et al. (2006) did not directly relate rock content to soil bulk density changes in their compaction study, but indicated that variables, such as rock-fragment content and freeze-thaw frost cycles, may help ameliorate the effects of compaction.

Management Implications

The repeated impact of any timber harvesting operation on soil compaction is a function of harvesting method and equipment used, harvest intensity, the number and length of the harvest cycle, season of harvest, and the time interval after the harvest when soil compaction is measured. The spatial variability of these harvesting variables is also large, and can confound any evidence of soil compaction (Graecen and Sands 1980, Block et al. 2002). Hand felling and horse-logging was used early in both stands we studied, and they likely had much less soil impact than the mobile harvesting equipment used in later harvests (Zastocki 2003, Suwaa 2004). All harvests were also conducted in the winter, when the effects of compaction would be less on frozen soil protected by a layer of snow (Arikian et al. 1999, Berger et al. 2003). High soil moisture contents during our late spring sampling period would also reduce the sensitivity of soil PR measurements to differences in soil compaction (Sands et al. 1979), and may have masked treatment effects. Soil PR values inherently have high variability (Fritton 1990, Miller et al. 2001), and this would be compounded by the rock-fragment content of the hardwood soil.

Designated skid trails were reused during successive harvests, which would greatly reduce the area affected by harvesting equipment (Froehlich and McNabb 1984). In addition, we sampled the red pine thinning plots 9 yr and the hardwood thinning plots 4 yr after the last cutting cycle, which may have been enough time for some amelioration of compaction effects to occur. However, Powers et al. (2006) observed that stands with the lowest rates of recovery from compaction were in regions with frigid soil temperature regimes (e.g., Minnesota). Freeze-thaw cycles in these soils are not particularly effective at remediating compaction below 10 cm soil depths.

In summary, the results of our study indicate that repeated thinning of a red pine stand growing on a sand soil caused some soil compaction, but compaction was not evident after thinning or partial cutting a northern hardwood stand growing on a rocky till soil. Many studies on clear-cut harvesting have shown that soil compaction can reduce tree growth and stand productivity (Greacen and Sands 1980, Page-Dumroese et al. 2006, Powers et al. 2006). In contrast, King and Haines (1979) suggested that decreased hydraulic conductivity rates from compacted coarse-textured soils could increase stand productivity by decreasing leaching losses of soil nutrients. Powers et al. (2006) reported that compacting sandy soils in California reduced average pore diameter, and increased both water availability and tree growth. However, measuring the effect of soil compaction on the productivity of thinned stands is more difficult, since thinning reduces total stand biomass production but increases the growth of individual trees (Liechty et al. 1986, Zeide 2001, Karlsson 2006). If the response of stand productivity to thinning is only measured on the residual trees, the negative effects of soil compaction could be masked by increased growth on the remaining trees. We could not find any studies that attempted to separate the impact of soil compaction and increased tree growth from thinning on stand productivity. With the increased demand for forest products, the emphasis on more intensive forestry practices in plantation management, fuel reduction in high fire-risk stands, and biomass removal for energy production (Liechty et al. 1986, Gilmore and Palik 2006, Kenefie et al. 2006), repeated thinning and other management practices will likely increase. Much more information is needed on the impact of multiple stand entries on soil compaction, and if compaction occurs, whether it will affect long-term soil productivity.

ACKNOWLEDGEMENTS

The following people are recognized for their diligent work that made this research possible: John Elioff, Christel Kern, Terry Strong, and two anonymous reviewers for their helpful comments. This research was funded by the American Forest and Paper Association under Agenda 2020.

Alban, D. H., Host, G. E., Elioff, J. D. and Shadis, D. 1994. Soil and vegetation response to soil compaction and forest floor removal after aspen harvesting. USDA Forest Service Research Paper NC-31: 1–8.

Amoozegar, A. 2002. Models for field determination of saturated hydraulic conductivity. Pages 45–54 *in* C. Stokes, ed. Proceedings of the forty-fifth annual meeting of the soil science society of North Carolina. North Carolina State University, Raleigh, NC.

Arikian, M. J., Puettmann, K. J., Davis, A. L., Host, G. E. and Zasada, J. C. 1999. Harvesting impacts on soil properties and tree regeneration in pure and mixed aspen stands. Pages 329–331 *in* A. Ek and B. ZumBahlen, eds. Improving forest productivity for timber: A key to sustainability. University of Minnesota, St. Paul, MN.

Berger, A. L., Puettmann, K. J. and Host, G. E. 2003. Harvesting impacts on soil and understory vegetation: the influence of season of harvest and within-site disturbance patterns on clear-cut aspen stands in Minnesota. Can. J. For. Res. **34**: 2159–2168.

Block, R., Van Rees, C. J. and Pennock, D. J. 2002. Quantifying harvesting impacts using soil compaction and disturbance regimes at a landscape scale. Soil Sci. Soc. Am. J. **66**: 1669–1676.

Brais, S. and Camiré C. 1998. Soil compaction induced by careful logging in the claybelt region of northwestern Quebec (Canada). Can. J. Soil Sci. **78**: 197–206.

Bulmer, C. E. and Simpson, D. G. 2005. Soil compaction and water content as factors affecting the growth of lodgepole pine seedlings on sandy clay loam soil. Can. J. Soil Sci. **85**: 667–679.

Brussaard, L. and van Faassen, H. G. 1994. Effects of compaction on soil biota and soil biological processes. Pages 215–235 *in* B. D. Soane and C. van Ouwerkerk, eds. Soil compaction in crop production. Elsevier, Amsterdam, the Netherlands.

Franklin, J. F., Spies, T. A., Van Pelt, R., Carey, A. B., Thornburgh, D. A., Berg, D. R., Lindenmayer, D. B., Harmon, M. E., Keeton, W. S., Shaw, D. C., Bible, K. and Chen, J. 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. For. Ecol. Manage. 155: 399–423.

Frey, B. R., Lieffers, V. J., Munson, A. D. and Blenis, P. V. 2003. The influence of partial harvesting and forest floor disturbance on nutrient availability and understory vegetation in boreal mixedwoods. Can. J. For. Res. **33**: 1180–1188.

Fritton, D. D. 1990. A standard for interpreting soil penetrometer measurements. Geoderma **150**: 543–551.

Froehlich, H. A. 1973. The impact of even-age forest management on physical properties of soils. Pages 190–220 *in* R. Hermann and D. Lavender, eds. Even-age Management. Oregon State University, Corvallis, OR.

Froehlich, H. A. and McNabb, D. H. 1984. Minimizing soil compaction in Pacific northwest forest. Pages 159–192 *in* E. L. Stone, ed. Forest and treatment impacts. Proceedings of the 6th North American Forest Soil Conference. Soil Science Society of America, Knoxville, TN.

Gilmore, D. W. and Palik, B. J. 2006. A revised managers handbook for red pine in the North Central Region. USDA Forest Service General Technical Report NC–2**64**: 1–55.

Graecen, E. L. and Sands, R. 1980. Compaction of forest soils, a review. Aust. J. Soil Res. **18**: 163–189.

Karlsson, K. 2006. Impact of thinning regime on the mean diameter of the largest stems by diameter at breast height in even-aged *Picea abies* stands. Scand. J. For. Res. **21**: 20–31.

Kenefic, L. S., Sendak, P. E. and Brissette, J. C. 2006. Comparison of fixed diameter-limit and selection cutting in northern conifers. Norw. J. Appl. For. **22**: 77–84.

King, T. and Haines, S. 1979. Soil compaction absent in plantations thinning. US Department of Agriculture, Forest Service, Research Note SRS-SO–251: 1–4.

Landsberg, J. D., Miller, R. E., Anderson, H. W. and Tepp, J. S. 2003. Bulk density and soil resistance to penetration as affected by commercial thinning in northeastern Washington. US Department of Agriculture, Forest Service, Research Paper PNW-RP-551: 1–35.

Liechty, H. O., Mroz, G. D. and Reed, D. D. 1986. The growth and yield responses of a high site quality red pine plantation to seven thinning treatments and two thinning intervals. Can. J. For. Res. **16**: 513–520.

Mace, A. C. 1970. Soil compaction due to tree length and full tree skidding with rubbertired skidders. Minn. For. Res. Notes **214**: 1–4.

Makineci, E. 2005. Long term effects of thinning on soil and forest floor in a sessile oak (*Quercus petraea* (Matlusch) Lieb.) forest in Turkey. J. Environ. Biol. **26**: 257–263.

Miller, R. E., Hazard, J. and Howes, S. 2001. Precision, accuracy, and efficiency of four tools for measuring soil bulk density or strength. USDA Forest Service Research Paper PNW-RP-S32: 1–16.

Miller, R. E., Scott, W. and Hazard, J. W. 1996. Soil compaction and conifer growth after tractor yarding at three coastal Washington locations. Can. J. For. Res. **26**: 225–236.

Ostaff, D. P., Piene, H., Quiring, D. T., Moreau, G., Farrell, J. C. G. and Scarr, T. 2006. Influence of pre-commercial thinning on balsam fir defoliation by the balsam fir sawfly. For. Ecol. Manage. **223**: 342–348.

Page-Dumroese, D. S., Jurgensen, M. F., Tiarks, A. E., Ponder, F., Sanchez, F. G., Fleming, R. L., Kranabetter, J. M., Powers, R. F., Stone, D. M., Elioff, J. D. and Scott, D. A. 2006. Soil physical property changes at the North American Long-Term Soil Productivity study sites: 1 and 5 years after compaction. Can. J. For. Res. 36: 551–564.

Powers, R. F. 2006. Long term site productivity: genesis of the concept and principles behind the program. Can. J. For. Res. **36**: 519–528.

Powers, R. F., Scott, A. D., Sanchez, F. G., Voldseth, R. A., Page-Dumroese, D., Elioff, J. D. and Stone, D. M. 2006. The North American long-term soil productivity experiment: Findings from the first decade of research. For. Ecol. Manage. **220**: 31–50.

Powers, R. F., Tiarks, A. E. and Boyle, J. R. 1998. Assessing soil quality; practicable standards for sustainable forest productivity in the United States. Pages 53–71 *in* M. B. Adams, K. Ramakrishna, and E. A. Davidson, eds. The contribution of soil science to the development and implementation of criteria and indicators of sustainable forest management. SSSA, Madison, WI.

Sands, R., Greacen, E. L. and Gerard C. J. 1979. Compaction of sandy soils in radiata pine forests. Aust. J. Soil Res. **17**: 101–113.

Scott, A. D., Tiarks, A. E., Sanchez, F. G., Elliot-Smith, M. and Stagg, R. 2004. Forest soil productivity on the southern long-term soil productivity sites at age 5. Pages 372–377 *in* K. F. Connor, ed. Proceedings of the 12th Biannual Southern Silviculture Research Conference. United States Department of Agriculture, Asheville, NC.

Seymour, R. S. and Hunter, Jr., M. L. 1999. Principles of ecological forestry. Pages 22–61 *in* M. L. Hunter, Jr., ed. Composition in managing forests for biodiversity. Cambridge University Press, New York, NY.

Shaw, J. N. and Carte, E. A. 2002. Timber harvesting effects on spatial variability of southeastern U. S. Piedmont soil properties. Soil Sci. **167**: 288–302.

Siegel-Issem, C. M., Burger, J. A., Powers, R. F., Ponder, F. and Patterson, S. C. 2005. Seedling root growth as a function of soil density and water content. Soil Sci. Soc. Am. J. **69**: 215–226.

Skov, K. R., Kolb, T. E. and Wallin, K. F. 2004. Tree size and drought affect ponderosa pine physiological response to thinning and burning treatments. For. Sci. **50**: 81–91.

Smith, C. W., Johnston, M. A. and Lorentz, S. 1997. The effect of soil compaction and soil physical properties on the mechanical resistance of South African forestry soils. Geoderma **78**: 93–111.

Steinbrenner, E. C. 1955. The effect of repeated tractor trips on the physical properties of forest soils. Northwest Sci. **29**: 155–159.

Steinbrenner, E. C. and Gessel, S. P. 1955. The effect of tractor logging on physical properties of some forest soils in southwestern Washington. Soil Sci. Soc. Am. Proc. **19**: 372–376.

Suwaa, M. 2004. Soil disturbances during wood harvesting in pine stands in forestry practice. Lesne Prace Badawcze **1**: 87–101.

Thibodeau, L., Raymond, P., Camire, C. and Munson, A. D. 2000. Impact of precommercial thinning in balsam fir stands on soil nitrogen dynamics, microbial biomass, decomposition, and foliar nutrition. Can. J. For. Res. **30**: 229–238.

von Wilpert, K. and Schäffer, J. 2006. Ecological effects of soil compaction and initial recovery dynamics: a preliminary study. Eur. J. For. Res. **125**: 129–138.

Zastocki, D. 2003. The effect of means used in timber extraction by Forest Service Companies on soil disturbance and tree damage in premature pine stands. Sylwan **147**: 52–58.

Zeide, B. 2001. Thinning and growth: a full turnaround. J. For. **99**: 20–25.