Paper 5 (draft)

Short term changes in soil bulk density following skidding in the boreal forest of west-central Alberta

A. D. Startsev and D. H. McNabb

Abstract

Soil bulk density was monitored at 9 sites in the boreal forest of west-central Alberta during 2-year period following 3, 7, and 12 skidding cycles. Four identical blocks of skidding treatments were established at each site. Bulk density was measured immediatelly after skidding at an average depth of 5, 10, and 20 cm in four random locations in each treatment. Measurements of bulk density were repeated one and two years after skidding at points within 0.5 m of each of the previous location. The soil temperature, water potential, snow depth, rain, and air-temperature were monitored at the sites to identify possible microclimatic factors affecting changes in bulk density. Bulk density increased significantly by about 0.05 Mg m^{-3} across all treatments after one year; probably as a result of natural compression following the termination of root growth. After two years, bulk density of soil in the compacted treatments decreased slightly, and the decrease was greater in the higher trafficked soil. However, bulk density of compacted soil remained significantly higher than in untrafficked soil regardless of the number of skidding cycles. The failure of soil to decompact rapidly is attributed to heavy snowpacks that prevented the soil from freezing.

Soil compaction, measured as an increase in soil bulk density, is one of the most common soil disturbances that occur during mechanized forest harvesting operations (Froehlich and McNabb 1984). The direct consequence is a complex modification of pore space that affects mass and energy transfer within the soil-plant continuum and leads to a decrease in quality of the root environment. The impacts have been recognized worldwide, including in boreal forests (Lull 1959, Greasen and Sands 1980, Froehlich and McNabb 1984, Corns 1988, McNabb 1994).

After harvesting, soil bulk density remains significantly higher than in uncut forest for up to several decades, which is commonly considered as a factor reducing tree growth (Wert and Thomas 1981, Froehlich et al. 1985). Swelling-shrinking, freezing-thawing, root activity and organic matter were identified as the natural factors that can ameliorate soil compaction (Larson and Allmaras 1971). Freezing-thawing is the major factor in boreal forest soils because these soils generally lack inputs of other ameliorating factors. The estimates of bulk density recovery rate in seasonally frozen soils vary from rapid to slow (Philips and Kirkham 1962, Mace 1971, Voorhees, 1983). Corns (1988) estimated that complete natural recovery of compacted soil in Alberta boreal forests would require at least a decade. However, the surface layers of these soils recover more rapidly and tillage can accelerate the process in deeper layers (McNabb 1994).

The level of soil disturbance itself can affect the frost penetration and soil recovery rate due to the relationship between thermal properties and soil bulk density (Willis and Raney 1971). The increased water content in compacted soil may also affect both the heat capacity and thermal diffusivity of soil. In forest soils, compression and/or scalping of forest floor by skidder tires and dragged tree crowns may have a considerable effect as the litter removal was shown to increase the soil freezing depth (Thorud and Duncan 1972, Sartz 1973). The presence of snow cover was identified as the major factor determining the soil freezing depth and reducing individual effects of litter removal and compaction (Thorud and Duncan 1972).

The long-term persistence of high soil bulk density following forest harvesting is commonly thought to be entirely a residual effect of machinery-induced compaction. However, an increase in soil bulk density may also be due to a structural collapse induced by wetting and drying, which is often referred to as natural compaction or hardsetting (Bresson and Moran 1995, Barber 1995). In fact, the cyclic freezing and thawing in a loose soil may also lead to its consolidation (Eigenbrod 1996).

The changes in soil physical environment during the first few years after harvesting are important because they determine the rate and type of natural revegetation, growth and survival of seedlings that are commonly planted in 2-3 years after harvesting (ref). Objective of this study is to evaluate changes in soil bulk density as affected by natural factors and by the level of soil disturbance during mechanized clearcut harvesting in boreal forest.

MATERIALS AND METHODS

A total of 9 sites were selected in mature conifer stands across west central Alberta where substantial amounts of forest operations occur in summer (Table 1). Most sites are located in the Southern Alberta Uplands ecodistricts of the Lower and Upper Boreal Cordilleran ecoregions (Strong 1992). The Lower ecoregion is dominated by lodgepole pine or white spruce with some aspen on well-drained soils while the Upper ecoregion is dominated by lodgepole pine with a small component of white or black spruce depending on the soil wetness (Corns and Annas 1986). Soils are predominantly Gray Luvisols that vary in degree of gleying and depth to mottles (Table 1).

The sites were skidded in 1994 as part of normal harvesting operations using equipment listed by site in Table 1. At every site, four identical blocks were established in felled timber prior to skidding. Each block contained four levels of skidding activity: a control with 0 skidding cycles, 3, 7, and 12 skidding cycles. A skidding cycle is one empty and one loaded pass of a skidder over a corridor approximately 6 m wide and 40 m long. A control area, 10 m wide, separates each level of skidding activity.

Bulk density was measured on undisturbed cores, 7.6 cm in diameter and 3 cm in height, collected in several days after skidding at an average depth of 5, 10, and 20 cm in four random locations in each treatment. The cores were then oven-dried in the laboratory to determine bulk density and gravimetric water content (Blake 1965). The measurements were repeated in one and two years following skidding in the points within 0.5 m of each of the previous location. The year of 1994, when sites were skidded and soil bulk density measured first time, and the two consequent years 1995 and 1996, when bulk density was remeasured, will be further referred to as years 0, 1, and 2, respectively.

One block of each of 8 sites was instrumented with a multiplexed CR10 data logger (Campbell Scientific Inc.) to measure soil temperature and water potential in the control and adjacent 7-cycle compaction treatment, air temperature and precipitation. The weather station was not installed at site 6 because it is closely located to site 5. Thermocouples were inserted horizontally at the interface between LFH layer and mineral soil, further referred to as 0-cm depth, and at 5-, 10-, and 20-cm depths in mineral soil. Water potential was estimated from electrical resistance measured with Watermark-200 soil moisture sensors, which were calibrated in the lab and then inserted horizontally at 5-, 10-, and 20-cm depths in the mineral soil. Rain was measured with TE525 tipping bucket rain gauge (Texas Electronics, Inc.) Snow depth was measured with UDGO1 ultrasonic sensor (Campbell Scientific, Inc.) mounted to a metal pole at 2-m height above the ground level; air temperature and rain were measured at the same height. Temperature and water potential were recorded every second hour, snow depth – at noon and midnight.

The analysis of bulk density data was performed using SAS 6.11 doubly repeated mixed model with time and depth as repeated factors (Little et al. 1996). It was followed by analyses of effects sliced by the interacting factor and differences among least square means for significant effects. Analysis of effects was conducted starting from higher order interactions according to Milliken and Johnson (1994). The effects of 7-cycle skidding treatment and depth on soil temperature for the period from November 1, 1995 to April 15, 1996 were analyzed using SAS 6.11 PROC ARIMA for time series regression (SAS Institute Inc. 1991).

RESULTS

The bulk density means and standard errors are listed in Table 2 by site, depth and treatment. The analysis of bulk density data shows a significant effect of skidding treatment (Table 3). The first 3 skidding cycles caused an increase in bulk density (Fig.1). Bulk density continued to increase after additional 4 skidding cycles. However, a further trafficking to 12 skidding cycles did not cause a significant increase. These changes apply to every site and every depth because interactions of skidding treatment with site and depth are not significant. Interaction of treatment with year is also not significant, which is an indication that the effect of skidding did not depend on time during the study period. Differences among least square mean bulk densities of 3-, 7-, and 12-cycle treatments become less significant in 2 years after skidding but they remain significantly different from the control (Fig. 1).

The year effect is significant, which applies to every level of treatment and to every depth because interactions of year with treatment and depth are not significant (Table 3). Analysis of differences among least square means indicates an increase in bulk density first year after skidding across all treatments including control (Fig. 1). In the second year, the effect is variable across the treatments. The general tendency of the second year bulk density is to decrease more significantly in more heavily trafficked treatments while control bulk density remains at the level. Interaction between year and site is significant, which is an indication that the effect of time was not uniform across the sites. Analysis of the time effect sliced by site indicates that it is significant at sites 1, 5, 7, 8 and not significant at sites 2, 3, 6, 9, and marginally at site 4 (p=0.0577). At the sites 1 and 5, least square mean bulk density increased in one year after skidding and then decreased in the following year. At the sites 7 and 8, it also increased in one year after skidding but did not change in the following year.

Site effect is significant and it does not depend on the level of skidding treatment (Table 3). The effect reflects differences of sites in inherent soil properties. In general, bulk densities at the sites 1, 2, 7, and 9 were significantly higher than that at sites 5 and 6 but significantly lower than at sites 4 and 8. Site 3 belongs to two groups of sites, with medium and highest bulk densities. Although interactions of site with depth and time are significant, the effect of site is significant at every depth and every year. Obviously, the interactions are significant because the effects of depth and time are site-specific.

Effect of depth is significant and does not depend on the level of skidding treatment and year but it depends on the site (Table 3). In fact, the effect of depth was significant at all sites except only one, site 2. At the majority of sites, least square mean bulk densities at all three depths were significantly different from each other. At the sites 4 and 8, least square mean bulk density at 10- and 20-cm depths was not significantly different.

The air temperature pattern was similar across the sites during winter, which is indicated by the narrow confidence interval for this period (Fig. 2). The major periods of warm and cold weather were observed at all sites simultaneously. The snow depth fluctuations were also similar at the sites indicating a simultaneous occurrence of the major periods of snow accumulation.

The relative uniformity in daily air temperature and snow accumulation patterns in the study area predetermined little variation in daily soil temperatures across the sites. The confidence interval of soil temperature shows a certain dependence on the air temperature. It was largest during cold periods, which is most obvious at 0- and 5-cm depths. The larger differences among sites during cold weather could be associated with soil water content. The soil temperature at drier sites was more responsive to decreases in air temperature.

Although subzero temperature was observed to 20-cm depth, the average temperature did not drop below –0.5°C in the mineral soil and –1°C at 0-cm depth (Fig. 2). The time series regression indicated no significant effect of treatment and depth on the soil temperatures within 0-20 cm layer. However, the average daily temperature of mineral soil at 10- and 20-cm depths was consistently lower in the treatment during fall and winter, before and after the snow cover was established, and higher – in the spring, when snow melted down. Under the snow, the effect was less pronounced at 5-cm depth and was not present at all at the interface between forest floor and mineral soil.

The 1996 water regime varied across the sites as indicated by dynamics of water potential (Fig 3). No effect of skidding treatment on soil water potential could be identified obviously due to rapid equilibration of potentials in moist soil over the short distance between sampling points in the control and 7-cycle treatment. Sites 1, 5, 7, and, to a lesser extent, site 8 are characterized by a more contrast water regime. The typical features of such regime are several weeks of saturation in the spring and a period in the end of summer when water potential could decrease to less than –300 kPa after several days without rain and increase again to near-saturation values after a significant rainfall. Sites 2, 3, 4, and 9 are characterized by a conservative hydric regime with water potential between near 0 and –20 kPa throughout the season. The differences are likely due to specifics of site hydrology, particularly soil drainage and dynamics of groundwater and perched water tables, rather than amount and distribution of precipitation that were relatively uniform across the sites.

DISCUSSION

The immediate effect of skidder traffic on soil bulk density occurred to at least 22.5-cm depth after the first few skidding cycles with progressively decreasing amount of compaction produced by additional trafficking (Fig. 1). This result is in agreement with single repeated factor analysis conducted in the study area on the same sites with addition of five other sites (McNabb and Startsev 1988) and with earlier reports for different areas and soils (Froehlich et al. 1980).

The analysis of effects of time on soil bulk density, which was originally focused on soil decompaction, is complicated by a concurrent increase in bulk density that occurred in one year after skidding uniformly across skidding treatments including control (Fig. 1). In the following year, bulk density decreased in the skidding treatments while control bulk density stabilized at some level, significantly higher than initial. These fluctuations resulted in significant main effect of time, which did not interact with treatment effect. Bulk density increase over the first years following clearcut harvesting were observed earlier (Corns 1988 and personal communication with J. A. Burger, 1995, M. Osberg and M. Kranabetter, 1996, I. G. W. Corns, 1997). The common feature of the sites where the time-related bulk density changes were significant is a contrast post-harvest water regime (Fig. 3) that was obviously moderated in uncut forest by the effects of canopy and draining role of trees. Pre-harvest assessment indicated that these sites were generally better drained and more productive. Aust et al. (1992) found that post-harvest groundwater table rise was larger in the moderately well-drained sites as compared to poorly drained sites. The change in water regime could contribute to a structural collapse due to repeated wetting and drying, a process similar to the natural compaction reported elsewhere (Barber 1995, Bresson and Moran 1995). The removal of canopy and dying out of moss layers protecting weak structure of boreal forest soil from direct impact of rain, runoff and other factors, may have also resulted in some consolidation of soil. Loss of organic matter due to accelerated decomposition and shifting of humus formation towards mobile forms contributed to the process (Startsev et al. 1998). Similar increases in bulk density may be possible after natural disturbances as widespread windfall and wildfire, though no relevant information was found in existing literature.

Although least square mean bulk density of heavier trafficked treatments somewhat decreased while control bulk density remained significantly higher than initial level (Fig. 1), no significant decrease in bulk density of compacted soil relative to control occurred in two years after skidding. There are two possible explanations for the low contribution of freezing to soil decompaction. The deformed frozen soil matrix could reconsolidate during thawing and/or early spring precipitation with no apparent lasting change in bulk density (Unger 1991, Voorhees and Sharratt 1997). Creation of permanent structure by freezing and thawing is an evolving process that requires multiple freeze-thaw cycles. The diurnal freezing and thawing could take place during several days in the fall and spring (Pikul et al. 1989) but, according to our data, this process could occur at only the very surface of soil. An alternative explanation is that subzero soil temperature was not low enough for efficient frost heaving. Despite the low air temperatures observed during 1995/96 winter, freezing of soil was only superficial and temperature remained near freezing point due to early establishment of insulating thick snow before the soil froze and relatively high soil water contents and ground water tables in the fall enabling "zero-curtain" effect during the first winter months (Outcalt et al. 1990). According to this theory, the persistence of nearly isothermal region with very small temperature gradient could be associated with water advection and internal distillation within the unfrozen zone preventing conductive heat transfer. The "zero-curtain" effect is also believed to be linked to the rapid propagation of thermal disturbances across the isothermal region. Such phenomenon occurred at majority of sites in the beginning of January when average air temperature decreased by more than 30°C during several days and soil temperature responded by one-degree decrease almost simultaneously at all depths, particularly in the 7-cycle treatment (Fig 2). The rapid soil warming observed at depth almost immediately after the snow melted was also reported by Hinkel and Outcalt (1994) in connection with "zero-curtain" effect and is an obvious indication that soil freezing was not deep if present at all. At the temperatures of mineral soil observed in this study, only a portion of water stored in large pores could freeze (Spaans and Baker 1996).

The non-significant effect of skidding on winter soil temperature supports the Thorud and Duncan (1972) conclusion about dominant role of snow cover and suppression of individual effects of compaction and forest floor disturbance. The non-significant but still consistent differences between soil temperatures of skidding treatment and control depended on the presence of snow cover (Fig. 2). With no snow on the soil surface, the compression and/or partial scalping of forest floor by skidder tires and tree crowns caused a reduction in its insulating capacity and determined the rate of cooling down in the fall and warming up in the spring. Under the snow cover, the difference in insulating effects of disturbed and undisturbed forest floor is negligible comparing to that of snow, which is indicated by small differences between control and treatment at 0- and 5-cm depths. The larger differences between control and treatment at 10- and 20-cm depths and a more distinct propagation of thermal disturbances observed in the treatment may be due to a nonconductive heat transfer across the isothermal region (Outcalt et al. 1990). Lower temperature in compacted soil can be responsible for decrease in bulk density of heavily trafficked treatments (Fig. 1). There is a potential for accumulation of this effect over several years; then it will become more signifiant. Results of this study and earlier reports (Thorud and Duncan 1972) suggest that minimizing the insulating effect of snow cover by its removal or packing down will increase the effect of soil compaction on frost penetration and accelerate soil decompaction.

Attempting to forecast further changes, the control bulk density is expected to remain at present level for a number of years until the reestablishing ecosystem recreates the soil structure. Bulk density in compacted treatments will be decreasing asymptotically to control level and, possibly, at a rate proportional to the level of disturbance, such that a complete soil recovery can be achieved regardless of number of skidding cycles (to 12).

SUMMARY AND CONCLUSION

Analysis of changes in soil bulk density of skid trails indicated no significant decrease relative to untrafficked control in two years after harvesting. The early establishment of thick snow cover was the major factor prevented effective freezing and decompaction of soil. It also diminished the individual effect of compaction on soil freezing. However, compacted mineral soil tended to be colder that can be associated with larger decrease in bulk density of heavily trafficked treatments. If this effect accumulates over time, the number of skidding cycles may become less important in terms of time required for complete soil recovery. Removal or packing snow in cutblocks has a potential to accelerate soil decompaction.

The natural compaction, non-machinery-induced increase in bulk density, was more significant at the sites with substantial transformation of soil water regime following harvesting and with increased fluctuation in soil water content during warm period. Soil bulk density recovery rates could be underestimated when comparisons are made with uncut forest and the natural compaction is not taken into account.

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Table 1. Site locations, soil type and texture, and skidding equipment.

Site	Longitude	Latitude	Soil type	Soil texture	Equipment	Tire width
						m
1	53o22’	117o00’	Orthic/Gleyed Gray Luvisol	Loam	John Deere 648E	0.8/1.1[†]
2	54o32’	119o05’	Gleyed Gray Luvisol	Silt Loam	Valmet 540	0.7
3	53o57’	116o58’	Orthic Gray Luvisol	Silt Loam	Timberjack 480B	1.1
4	54o52’	115o15’	Orthic Gray Luvisol	Loam	John Deere 648E	0.8/1.1
5	53o00’	116o00’	Brunisolic Gray Luvisol	Loam	CAT D4H TSK	0.6
6	53o00’	116o00’	Brunisolic Gray Luvisol	Loam	John Deere 648E	1.1
7	52o10’	115o20’	Eluviated Dystric Brunisol	Silt Loam	Timberjack 450C	0.8
8	54o30’	119o00’	Orthic/Gleyed Gray Luvisol	Clay Loam	John Deere 748E	1.1
9	54o00’	117o50’	Orthic Gray Luvisol	Silt Loam	John Deere 648E	1.1
10	53o41’	117o50’	Orthic/Gleyed Gray Luvisol	Silt Loam	John Deere 648E	0.8/1.1
11	51o45’	115o05’	Eluviated Dystric Brunisol	Loam	John Deere 748E	0.8
12	54o54’	119o57’	Orthic/Brunisolic Gray Luvisol	Clay Loam	John Deere 748E	1.1/1.2
13	53o22’	117o00’	Gleyed Gray Luvisol	Clay Loam	Timberjack 520A	1.1
14	54o00’	117o50’	Orthic Gray Luvisol	Silt Loam	Timberjack 450C	1.1

[†] Front/rear if tires are different.

Table 2. Soil bulk density means and standard errors by site, skidding treatment, year and depth.

Site	Skidding cycles	Year 0			Year 1			Year 2		
		5 cm	10 cm	20 cm	5 cm	10 cm	20 cm	5 cm	10 cm	20 cm
		$Mg\ m^{-3}$								
1	0	1.13±0.02	1.34±0.04	1.46±0.02	1.20±0.03	1.37±0.02	1.48±0.04	1.12±0.05	1.28±0.05	1.39±0.03
	3	1.30±0.02	1.47±0.04	1.46±0.03	1.24±0.02	1.52±0.05	1.61±0.03	1.07±0.06	1.30±0.05	1.39±0.03
	7	1.31±0.04	1.44±0.04	1.39±0.06	1.35±0.04	1.51±0.05	1.58±0.02	1.14±0.02	1.36±0.07	1.38±0.06
	12	1.28±0.01	1.45±0.03	1.48±0.03	1.36±0.03	1.49±0.02	1.58±0.01	1.19±0.05	1.34±0.06	1.36±0.04
2	0	1.29±0.04	1.37±0.07	1.29±0.09	1.20±0.06	1.23±0.04	1.30±0.07	1.18±0.07	1.30±0.05	1.33±0.04
	3	1.34±0.08	1.38±0.03	1.40±0.05	1.39±0.06	1.41±0.05	1.35±0.07	1.26±0.10	1.38±0.05	1.40±0.08
	7	1.40±0.06	1.41±0.04	1.38±0.03	1.34±0.06	1.43±0.03	1.43±0.02	1.33±0.04	1.45±0.01	1.42±0.03
	12	1.46±0.04	1.42±0.06	1.41±0.05	1.42±0.05	1.38±0.05	1.42±0.03	1.35±0.05	1.40±0.03	1.44±0.06
3	0	1.19±0.07	1.31±0.03	1.35±0.04	1.28±0.06	1.33±0.03	1.40±0.04	1.22±0.07	1.36±0.03	1.47±0.04
	3	1.27±0.07	1.42±0.04	1.47±0.03	1.27±0.08	1.37±0.04	1.44±0.04	1.34±0.06	1.46±0.04	1.49±0.01
	7	1.39±0.05	1.47±0.04	1.50±0.05	1.27±0.08	1.39±0.08	1.45±0.06	1.31±0.11	1.45±0.02	1.53±0.03
	12	1.37±0.05	1.48±0.03	1.51±0.03	1.35±0.03	1.45±0.03	1.54±0.03	1.39±0.09	1.49±0.05	1.57±0.04
4	0	1.21±0.04	1.39±0.03	1.38±0.05	1.27±0.01	1.39±0.04	1.39±0.03	1.30±0.03	1.35±0.05	1.41±0.03
	3	1.38±0.02	1.39±0.06	1.43±0.06	1.33±0.01	1.49±0.01	1.46±0.01	1.30±0.03	1.40±0.01	1.42±0.03
	7	1.39±0.03	1.46±0.05	1.46±0.04	1.46±0.05	1.49±0.05	1.51±0.03	1.36±0.06	1.43±0.05	1.54±0.07
	12	1.42±0.06	1.47±0.04	1.50±0.02	1.41±0.02	1.57±0.04	1.57±0.02	1.27±0.04	1.54±0.01	1.54±0.03
5	0	1.09±0.06	1.16±0.03	1.21±0.07	1.17±0.02	1.30±0.03	1.38±0.04	1.06±0.05	1.24±0.06	1.41±0.01
	3	1.13±0.06	1.20±0.05	1.29±0.04	1.19±0.07	1.29±0.05	1.38±0.06	1.23±0.06	1.31±0.01	1.36±0.03
	7	1.18±0.04	1.28±0.08	1.30±0.07	1.29±0.03	1.41±0.04	1.44±0.03	1.13±0.05	1.29±0.04	1.42±0.02
	12	1.18±0.06	1.30±0.04	1.33±0.04	1.33±0.04	1.44±0.02	1.45±0.02	1.18±0.10	1.26±0.06	1.40±0.04
6	0	1.08±0.05	1.22±0.02	1.31±0.02	1.05±0.05	1.31±0.03	1.34±0.04	1.22±0.06	1.35±0.02	1.37±0.02
	3	1.16±0.09	1.34±0.08	1.43±0.05	1.20±0.03	1.35±0.03	1.42±0.02	1.17±0.08	1.29±0.04	1.37±0.04
	7	1.31±0.07	1.30±0.10	1.45±0.04	1.13±0.03	1.33±0.09	1.47±0.03	1.28±0.08	1.42±0.05	1.39±0.06
	12	1.14±0.05	1.32±0.07	1.41±0.07	1.17±0.04	1.36±0.06	1.45±0.04	1.23±0.04	1.30±0.02	1.31±0.03
7	0	1.00±0.07	1.25±0.08	1.43±0.04	1.05±0.05	1.30±0.08	1.43±0.05	1.14±0.03	1.33±0.04	1.48±0.04
	3	1.12±0.05	1.23±0.05	1.45±0.07	1.20±0.09	1.35±0.05	1.49±0.03	1.27±0.05	1.39±0.05	1.53±0.04
	7	1.18±0.07	1.28±0.05	1.44±0.05	1.21±0.08	1.42±0.08	1.56±0.04	1.23±0.14	1.39±0.11	1.51±0.03
	12	1.22±0.09	1.36±0.06	1.47±0.05	1.30±0.11	1.43±0.05	1.50±0.05	1.32±0.10	1.45±0.08	1.57±0.06
8	0	1.15±0.05	1.33±0.07	1.39±0.03	1.41±0.03	1.55±0.00	1.53±0.00	1.38±0.06	1.52±0.01	1.58±0.03
	3	1.15±0.06	1.36±0.02	1.43±0.05	1.37±0.02	1.51±0.04	1.49±0.02	1.37±0.01	1.55±0.06	1.56±0.04
	7	1.31±0.04	1.45±0.06	1.45±0.02	1.49±0.05	1.55±0.03	1.49±0.02	1.50±0.02	1.59±0.01	1.58±0.02
	12	1.28±0.04	1.38±0.03	1.37±0.02	1.39±0.05	1.51±0.04	1.47±0.02	1.40±0.04	1.54±0.04	1.54±0.01
9	0	1.18±0.09	1.33±0.07	1.38±0.05	1.21±0.08	1.27±0.07	1.32±0.02	1.23±0.07	1.24±0.08	1.27±0.06
	3	1.26±0.04	1.30±0.01	1.35±0.05	1.27±0.06	1.34±0.03	1.39±0.02	1.37±0.02	1.39±0.06	1.42±0.05
	7	1.29±0.03	1.38±0.05	1.42±0.04	1.32±0.05	1.44±0.02	1.47±0.05	1.36±0.06	1.41±0.04	1.46±0.05
	12	1.30±0.12	1.38±0.04	1.47±0.06	1.27±0.11	1.33±0.08	1.45±0.05	1.41±0.04	1.41±0.03	1.49±0.05

Table 3. Three-year analysis of variance for bulk density at 9 sites with depth and time as repeated factors.

Source of variation	NDF[†]	Type III F	Pr>F
Site	8	12.19	0.0000
Treatment	3	20.46	0.0000
Site x Treatment	24	0.56	0.9463
Depth	2	218.05	0.0000
Site x Depth	16	6.79	0.0000
Treatment x Depth	6	0.99	0.4334
Site x Treatment x Depth	48	0.69	0.9276
Year	2	18.39	0.0000
Depth x Year	4	0.80	0.5259
Treatment x Year	6	0.56	0.7647
Site x Year	16	8.87	0.0000
Site x Treatment x Year	48	1.02	0.4542
Site x Depth x Year	32	2.78	0.0000
Treatment x Depth x Year	12	1.04	0.4181

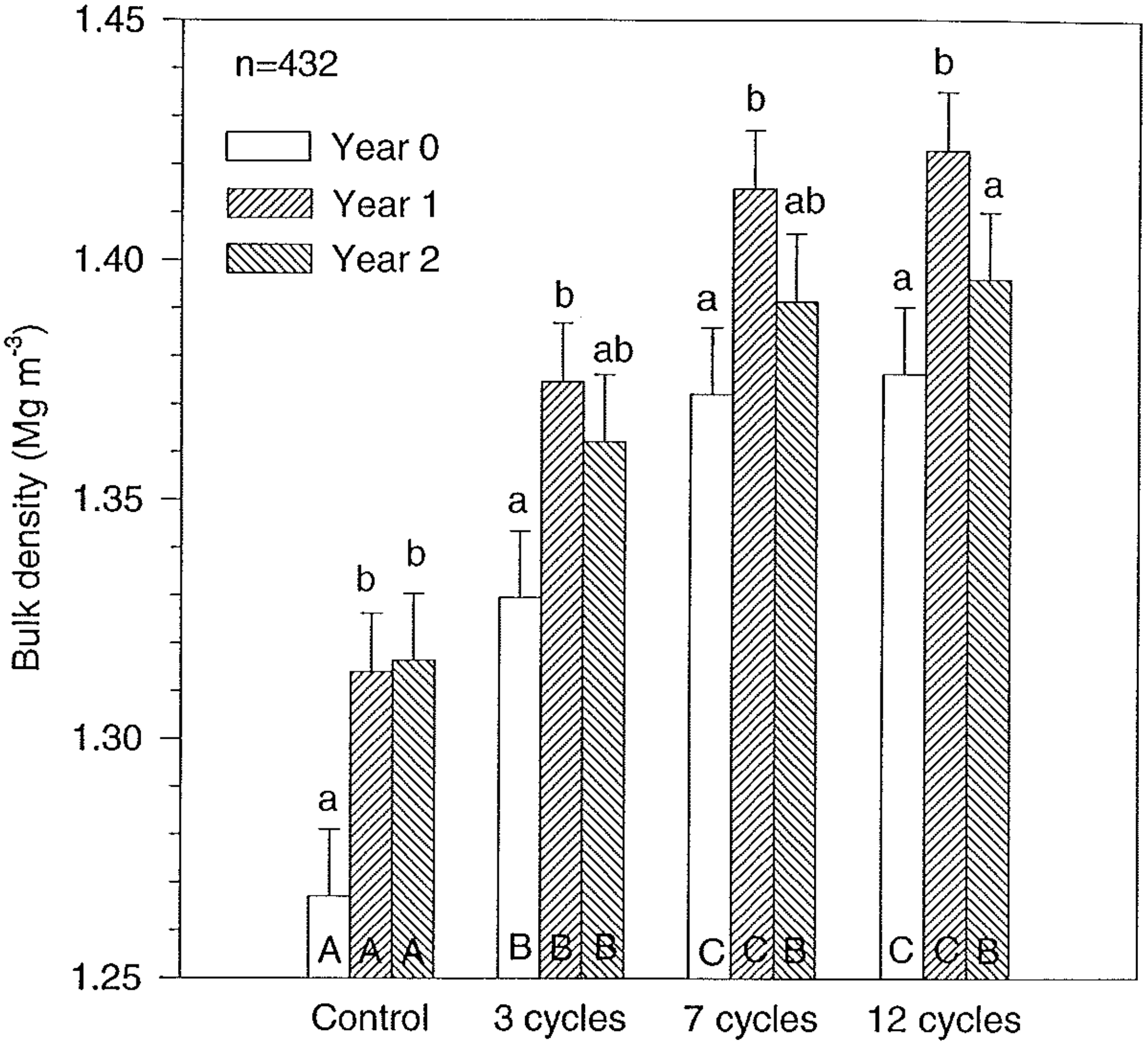
[†] NDF-numerator degrees of freedom in SAS 6.11 PROC MIXED output; denominator degrees of freedom (DDF) is 108 in all cases.

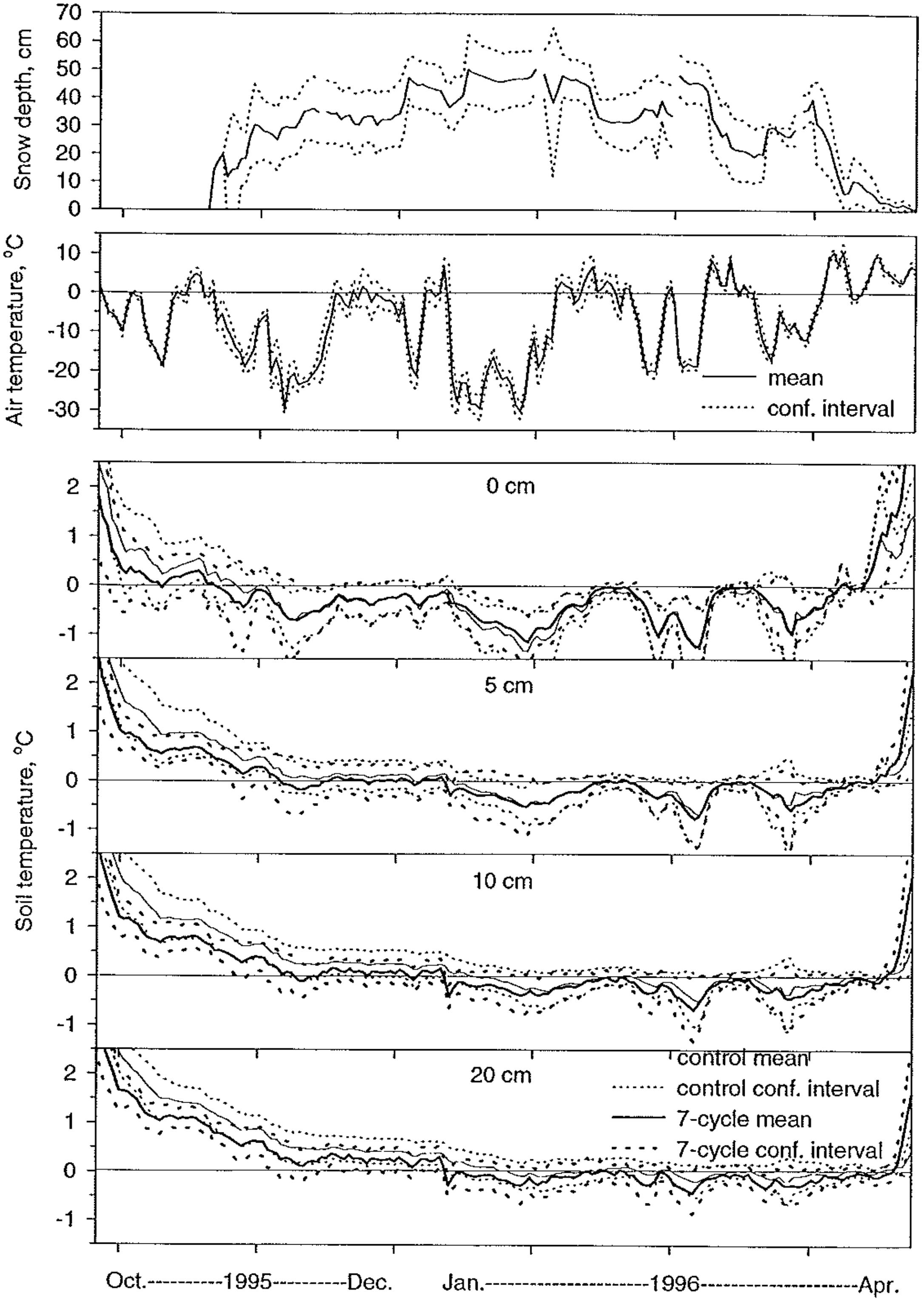
List of Figures

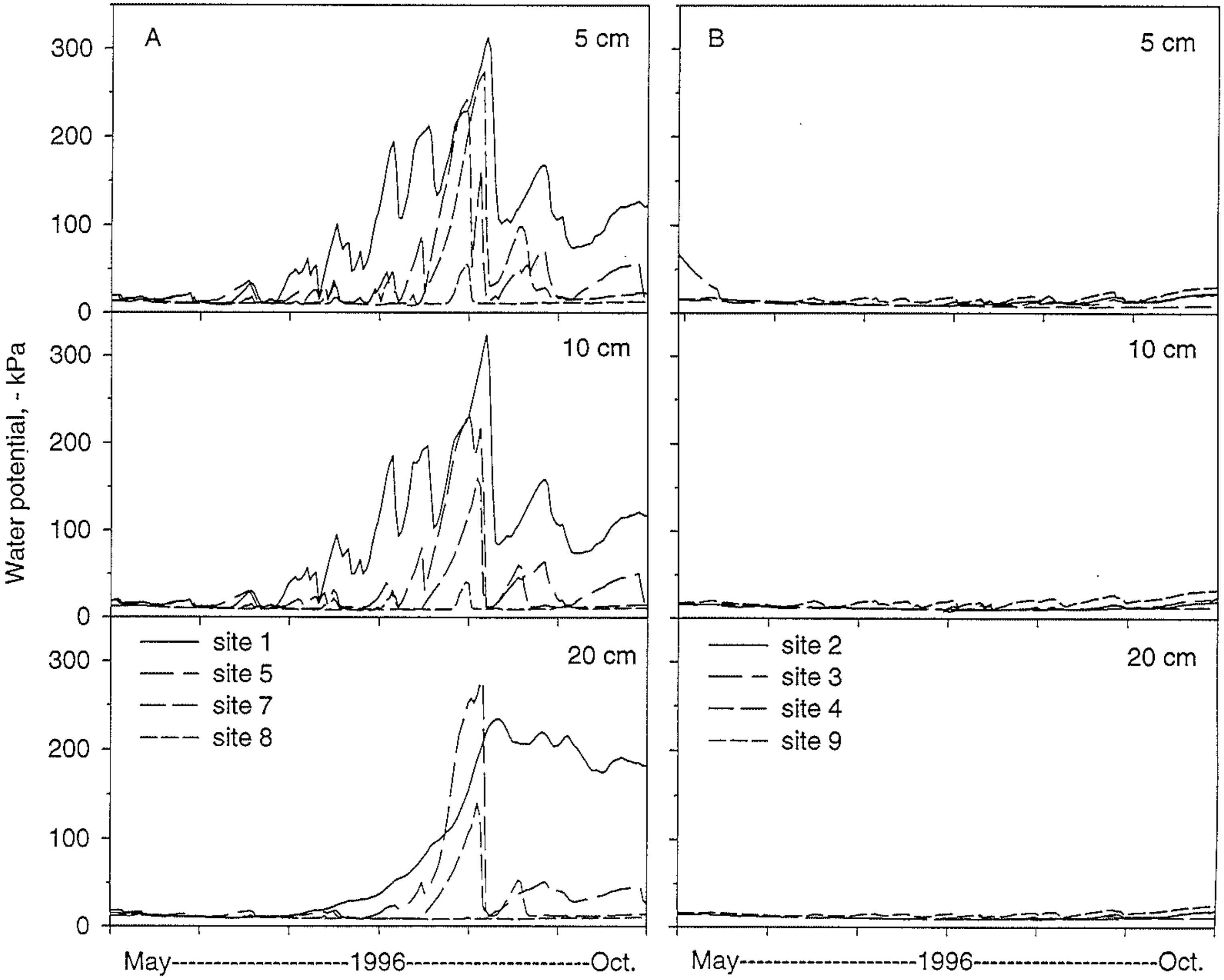
Figure 1. Bulk density least square means and standard errors in doubly repeated measure ANOVA by treatment and year. Different low case letters indicate significant at 0.05 level differences among years within a treatment; different capital letters indicate significant differences among treatments within a year.

Figure 2. Daily average snow depth, air temperature, and soil temperature.

Figure 3. Dynamics of soil water potential in the control soil. Sites are grouped by significance of time-related change in bulk density: significant (A) and not significant at 0.05 level (B).


n=432
Year 0
Year 1
Year 2
Bulk density (Mg m^{-3})
1.45
1.40
1.35
1.30
1.25
Control
3 cycles
7 cycles
12 cycles
a
b
b
A A A
a
b
ab
B B B
a
b
ab
C C B
a
b
a
C C B


Snow depth, cm
70
60
50
40
30
20
10
0
Air temperature, °C
10
0
-10
-20
-30
mean
conf. interval
Soil temperature, °C
0 cm
5 cm
10 cm
20 cm
2
1
0
-1
control mean
control conf. interval
7-cycle mean
7-cycle conf. interval
Oct.----------1995----------Dec.
Jan.--------------------1996--------------------Apr.


A
B
5 cm
10 cm
20 cm
Water potential, - kPa
300
200
100
0
site 1
site 5
site 7
site 8
site 2
site 3
site 4
site 9
May--------------------1996----------------------Oct.