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Snow depth manipulation and its influence on soil frost and water dynamics in a northern hardwood forest

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Abstract. Climate change will likely result in warmer winter temperatures leading to less snowfall in temperate forests. These changes may lead to increases in soil freezing because of lack of an insulating snow cover and changes in soil water dynamics during the important snowmelt period. In this study, we manipulated snow depth by removing snow for two winters, simulating the late development of the snowpack as may occur with global warming, to explore the relationships between snow depth, soil freezing, soil moisture, and infiltration. We established four sites, each with two paired plots, at the Hubbard Brook Experimental Forest (HBEF) in New Hampshire, U.S.A. and instrumented all eight plots with soil and snow thermistors, frost tubes, soil moisture probes, and soil lysimeters. For two winters, we removed snow from the designated treatment plots until February. Snow in the reference plots was undisturbed. The treatment winters (1997/1998 and 1998/1999) were relatively mild, with temperatures above the seasonal norm and snow depths below average. Results show the treated plots accumulated significantly less snow and had more extensive soil frost than reference plots. Snow depth was a strong regulator of soil temperature and frost depth at all sites. Soil moisture measured by time domain reflectometry probes and leaching volumes collected in lysimeters were lower in the treatment plots in March and April compared to the rest of the year. The ratio of leachate volumes collected in the treatment plots to that in the reference plots decreased as the snow ablation seasons progressed. Our data show that even mild winters with low snowfall, simulated by snow removal, will result in increased soil freezing in the forests at the HBEF. Our results suggest that a climate shift toward less snowfall or a shorter duration of snow on the ground will produce increases in soil freezing in northern hardwood forests. Increases in soil freezing will have implications for changes in soil biogeochemical processes.

Introduction

The interactions between snow, soil frost, vegetation, energy exchanges, and climate are of great interest because of concerns about climate change and the realization that biogeochemical processes continue during winter months (Mitchell et al. 1996; Brooks et al. 1998; Groffman et al. 1999). There is concern that climate change that results in warmer winters with less snowfall will lead to extensive soil freezing in temperate forests. Soil freezing can alter the dynamics of water flow and nutrient cycling during snowmelt, a critical period for ecosystem biogeochemistry (Likens & Bormann 1995; Rascher et al. 1987; Williams & Melack 1991; Stottlemyer & Toczydlowski 1996, 1999; Brooks et al. 1999).

The seasonal snowpack in the northern latitudes is well known to reduce soil freezing by insulating the soil surface. As frost depth generally varies inversely with snow depth, a lack of snow, or a late accumulating snowpack, results in soil freezing that is deeper and of longer duration than when the snowpack is established in early winter (Shanley & Chalmers 1999; Stadler et al. 1996). However, the controls on the spatial and temporal variability of the relationship between snow depth and soil freezing, e.g. vegetation, topographic position, and soil characteristics, are less well understood. Shanley and Chalmers (1999) noted that in northern Vermont, frost depth developed more extensively in open land than in forests because of nighttime radiation cooling in open land prior to snow accumulation. They also noted that, because of greater snow accumulation in deciduous and mixed forests, less frozen soil developed compared to coniferous forests where snow accumulation was more variable.

The effects of snow and frost on soil water dynamics are extremely complex. Partitioning of snowmelt into infiltration and surface runoff is influenced by soil drainage characteristics, soil frost conditions, soil water storage capacity, and snowmelt rates (Johnsson & Lundin 1991; Granger et al. 1984). Zhao and Gray (1999) report that numerous studies found that seasonal infiltration is inversely related to the total moisture content of a frozen soil at the time of melt. Concrete frost, partially saturated soil that freezes so pores are filled with ice, has very low permeability that greatly reduces infiltration of snowmelt or rain and promotes overland flow (Johnsson & Lundin 1991; Seyfried et al. 1997; Stähli et al. 1997). Concrete frost is most often found on open areas and sometimes in forested land (Fahey & Lang 1975). Granular frost, which occurs when unsaturated soils freeze, results in a more permeable soil, allowing more infiltration and less overland flow than concrete frost. Stadler et al. (1996) measured snow depth, frost depth, and snowmelt runoff in conifer forests. They found that when snow was present, daily surface discharge of water in forest gaps (i.e. where snow was deepest) was minimal compared to a treed plot with less snow, frozen soil, and variable runoff behavior. Johnsson and Lundin (1991) and Granger et al. (1984) studied the influence of soil freezing and snow on infiltration and drainage in agricultural environments. They found that high water content at the onset of freezing reduced infiltration of snowmelt. The permeability of frozen soils is important because winter and snowmelt periods are critical for solute losses from ecosystems (Likens & Bormann 1995; Mitchell et al. 1996; Brooks et al. 1999). Freezing influences the potential for interaction between snowpack nutrients and soil microbes, which is a critical regulator of nutrient cycling and retention during these periods (Brooks et al. 1998, 1999).

The Hubbard Brook Experimental Forest (HBEF) in New Hampshire has been the site of numerous biogeochemical studies and is the longest continuously operating ecosystem study in the nation. Established in 1955 by the U.S. Forest Service as a major center for hydrologic research, the site encompasses 3,138 hectares of National Forest land. While there is extensive long-term snow data at HBEF, there have been no detailed snow or snow manipulation studies despite the suggestion that winter dynamics are important regulators of variation in solute loss from year to year (Likens & Bormann 1995; Mitchell et al. 1996).

In this study, we manipulated snow depth by manually shoveling snow for two winters, simulating the late development of snowpack as may occur with global warming (Cooley 1990). We explored relationships between subsequent snow depth, soil freezing, soil moisture, and infiltration. The objectives of this paper are to (1) examine quantitative relationships among snow depth, soil freezing, and soil moisture; (2) evaluate these relationships in terms of the potential effects of climate change on soil temperature and meltwater; and (3) interpret the physical processes occurring in the snow and soil that link these relationships. This project was not originally designed to address landscape scale variability between plots. Effects of this snow manipulation experiment on roots (Tierney et al. this issue), soil nitrogen cycle processes (Groffman et al. this issue b), and soil solution chemistry (Fitzhugh et al. this issue) are described elsewhere.

Methods

Site characteristics

The HBEF is located near W. Thornton in central New Hampshire, U.S.A. (lat. 43°56′ N, long. 71°45′ W). The experimental forest covers an area of 3,138 ha and ranges in altitude from 222 to 1,015 m above sea level (Likens & Bormann 1995). Weather data have been collected at the HBEF Headquarters site since 1955. The mean air temperature is 18 °C in July and –9 °C in January. Average annual precipitation at HBEF is 140 cm. A snowpack develops each year to a depth of approximately 1.5-m. Maximum snow water equivalence (SWE) usually occurs mid-March followed by one to two months of snowmelt, depending on aspect and elevation.

The forests of HBEF are a combination of deciduous and coniferous species typical of the northern hardwood forest ecosystem. American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*) and yellow birch (*Betula alleghaniensis*) dominate vegetation at HBEF. The forest was selectively cut in the 1880s and 1910s and some of the older stands were damaged by a hurricane in 1938. The soils at HBEF are characterized as mostly well-drained, acidic (pH 3.9) spodosols (haplorthods) of sandy loam texture developed from unsorted basal tills. Soils are shallow (75–100 cm) with a thick (0.02–0.2-m) organic layer at the surface. The typically continuous snowpack insulates the soils, which usually remain thawed during the overwinter period (Likens & Bormann 1995).

The specific sites for this study included two sites dominated (> 80%) by sugar maple and two dominated (> 80%) by yellow birch. The four sites are referred to as Sugar Maple 1 (SM1), Sugar Maple 2 (SM2), Yellow Birch 1 (YB1), and Yellow Birch 2 (YB2) and vary in elevation, aspect, and slope (Table 1). The variability between sites is important primarily in understanding the different responses to freezing based on unique characteristics of the sites. Two 10- × 10 m paired plots were located in each stand, with one randomly designated as a treatment plot and one designated as a reference plot. In the fall and winter of 1996, we cleared minor amounts of understory vegetation from both treatment and reference plots for plot installations and to facilitate shoveling. Soil properties specific to our study sites were measured both in the field and in the laboratory.

Snow manipulation

From the first autumn snowfall until early February, the designated treatment plots were kept snow-free to simulate the effects of a late accumulating snowpack on the soil temperature regime, soil freezing, and below-ground biogeochemical processes. This treatment was applied during two consecutive winters: 1997/1998 and 1998/1999. As soon as practical after each snowfall, shovels were used to clear the treatment plots of the new snow. We manually compacted 5 to 10 cm of snow from early-winter storms to protect plot installations and the forest floor from shovel damage and to increase

Table 1. Characteristics of the four study sites

	Sugar Maple 1 (SM1)	Sugar Maple 2 (SM2)	Yellow Birch 1 (YB1)	Yellow Birch 2 (YB2)
Elevation (m asl)	648	564	472	640
Aspect	south	south	southeast	north
Slope gradient (%)	19	21	18	27

the albedo of the forest floor to aid in soil freezing. We used the smooth backside of the shovels to carefully compact the snow and protect the soil from disruption prior to its freezing. This compacted snow layer was maintained throughout the entire treatment period and observations of the forest floor each spring confirmed that the protective compact layer of snow was effective at protecting the forest floor from shovel damage. The reference plots accumulated snow at natural rates all winter and the treatment plots accumulated snow at natural rates after shoveling stopped in early February. We continued to monitor all plots for a third year, but did not manipulate the snow on the treatment plots.

Instrumentation, installation and data collection

Data on snow and frost depths, snow and soil temperature, volumetric soil moisture and soil water volume were collected continuously from fall 1997 through spring 2000. This period is referred to as the 'measurement period,' which included two winter seasons of 'treatment' (1997/1998 and 1998/1999) and one winter season of 'recovery' (1999/2000).

Snow depths were measured throughout the winter. We measured snow depths using a metal meter stick at least every other week, but not always at every site. Each measurement represents the mean of between 10 and 100 randomly selected measures of snow depth. We took depth measurements immediately adjacent to the reference plot to avoid disturbing snow in the plot. Snow depths for the reference plots are measured depths throughout the season. Snow depths from the treatment plots assume a 5-cm-thick compacted snow layer was present until the end of the treatment in early February (day 32, 1998, and day 35, 1999). Once the shoveling treatment ended, we estimated snow accumulation in the treatment plots based on relative changes outside the plot to avoid disturbing the snow on the plot. Dampening of measured snow temperatures in the treatment plots confirmed approximate depths of snow accumulation.

Snow water equivalence (SWE) at the time of maximum snow depth was calculated for each plot during both treatment years. Snow pits were dug at two locations to obtain a measure of the snow density profile in 0.03 m increments. To calculate SWE, we used the average snow density of 354 kg m^{-3} ($n = 55$), measured at the time of peak snow accumulation multiplied by the snow depth.

Frost depths were measured throughout the winter. During winter 1997/1998, we calculated frost depths from hourly soil temperature data described below. This technique provided information on when soil temperatures, in 10 cm intervals, dropped below 0 °C. To improve the accuracy and resolution of frost depth measurements, we installed two frost tubes in each plot (16 total) in the fall of 1998 (Ricard et al. 1976). Frost tubes consist of a flexible PVC tube filled with methylene blue dye. The flexible tube is inserted into a polyethylene casing to a soil depth of approximately 0.8 m. To measure frost depth, the flexible, dye-filled tubes were removed from the casing and the length of frozen dye was measured. One useful property of methylene blue is that it turns purple when frozen, easing the distinction between frozen and thawed dye. We measured frost depth using the frost tubes every one to two weeks during the winters of 1998/1999 and 1999/2000. During the thaw period we noted the timing and extent of soil thaw from the surface downward.

In each treatment and each reference plot during the fall of 1996, we dug soil pits approximately one meter wide by 0.6 m deep. The area upslope of the vertical pit wall was left undisturbed. In each pit we installed five thermistor probes and four soil water lysimeters prior to backfilling the pit with the soil. This early installation of instruments allowed soil disturbance effects to subside prior to the sampling period in fall 1997. A Campbell Scientific CR10X datalogger sampled soil temperatures and moisture content every minute and stored hourly averages on a storage module.

Thermistor probes were installed horizontally into the vertical, upslope pit wall of both treatment and reference plots. This single series of thermistors measured temperatures every 0.1 m depth in the soil to a depth of 0.5 m and every 0.2 m height in the snowpack to a height of 0.8 m (Table 2) (10 thermistors per plot). Above ground, snow thermistors were attached to a white plastic rod, which was inserted horizontally through holes in a 5 cm diameter PVC post. Thermistor tips were approximately 25 cm from the vertical post and positioned such that no thermistor rod was directly above another. We installed snow thermistor strings prior to snow accumulation, within 1 m of the soil thermistor profile.

To measure the unfrozen volumetric water content of porous soil, we installed TDR probes (rod length of 0.3 m) horizontally at two depths in

Table 2. Measured soil and snow parameters at each plot

Parameters measured	Height (m)	Accuracy	Sensor
Soil temperature	0, –0.1, –0.2, –0.3, –0.4, –0.5 m	+/–0.1 °C	BetaTHERM Thermistor Probe
Soil moisture	–0.05 and –0.15 m	+/–2.0% *	Campbell Scientific CS615 Water Content Reflectometer (TDR)
Soil water flux	Approx. –0.05 and –0.15 m		Zero Tension Lysimeters
Snow temperature	0.2, 0.4, 0.6, 0.8	+/–0.1 °C	BetaTHERM Thermistor Probe
Snow depth and density	variable	+/–0.01 m	Meter stick; 100-cc density cutter
Frost depth	4 per site	0.005 m	Frost tube (Ricard et al. 1976)

*See discussion on soil moisture sensor accuracy in text.

all reference and treatment plots – two each in the Oa and Bh horizons (approximately 0.05 and 0.15 m deep, respectively). Sensors were installed in intact faces of the pits. Each plot therefore had four measures of soil moisture, two in each horizon, which were averaged to represent the moisture of each horizon. We converted the TDR output frequency to volumetric soil moisture using the manufacturer's recommended calibration for soils with low electrical conductivity (< 1 dS/m).

$$\theta_v(\tau) = -0.187 + 0.037^{*}\tau + 0.335^{*}\tau^2 \quad (1)$$

where θ_v is the fractional volumetric water content and τ is the CS615 output period (milliseconds). Because the HBEF Oa horizon soils have relatively high organic matter content, they are different from the soils used to calibrate the CS615 by Campbell Scientific (J. Bilskie, personal communication). We therefore used data from these probes and calibration with caution. Similarly, as these probes are intended for unfrozen soil, we did not use data when soils were frozen. These data are most valuable for providing relative moisture contents and may not accurately represent absolute values.

Duplicate zero-tension (gravity) lysimeters, similar to the design of Driscoll et al. (1988), were installed below the Oa and within the Bs soil horizons at each plot during the autumn of 1996 (four lysimeters per plot). Gravity lysimeters are believed to largely sample macropore flow during hydrological events and while the soil is draining to field capacity (Litaor 1988) and thus provide a sample of water exported from the ecosystem. The primary purpose of the lysimeters was to collect water for chemical analysis (Fitzhugh et al. this issue); however, we also measured collected volumes for comparison between reference and treatment plots. Lysimeters were constructed with sample cups that drained into two-liter collection vessels. The lysimeter cups were made from PVC piping, while the tubing and collection vessels were made of polyethylene. Lysimeters were installed carefully beneath undisturbed soil profiles to minimize soil mixing and disturbance. An additional set of lysimeters was installed at the treatment plot of YB1 during the summer of 1998. We collected soil solutions on 37 dates at weekly to monthly intervals from December 1997 through November 1999. The more frequent weekly sampling occurred during spring snowmelt. The volume of the soil solution collected from each duplicate lysimeter was summed on each sampling date so that each plot – horizon – treatment combination (16 total combinations) had one observation of soil solution volume for each sampling date.

Statistical analysis

Relationships between snow depth and soil frost were explored with Pearson Product Moment Correlation coefficients (r). To test the effects of snow removal treatment on the response of soil temperature, mean daily values at 10, 20, and 30 cm depth were compared between reference and treatment plots using repeated measures of ANOVA for each plot (SM1, SM2, YB1, YB2) and for all plots combined. Similarly, ANOVA tests investigated the hypothesis that means of soil moisture and lysimeter volume were the same between all treated plots and all reference plots and among individual plots. All statistical analyses were performed using the alpha = 0.05 level of significance. STATGRAPHICS Plus 5.0 software was used for the statistical analysis.

Results and discussion

Comparison with historical records and plot variability

Although summer temperatures in 1998 and 1999 were comparable to the 30 year average, both treatment snow seasons (1997/1998 and 1998/1999) were relatively mild, with temperatures above the seasonal norm for HBEF and snow depths below average (Table 3). The freezing index, a measure of the combined duration and magnitude of below-freezing temperatures occurring during a given freezing season (Berg & Johnson 1983), provides a sensitive index of winter severity. The higher the freezing index, the colder

Table 3. Summary of air temperatures, calculated freezing indices, maximum snow depth (not cumulative snowfall), and duration of snow cover for the two treatment (1997/1998, 1998/1999) years, one non-treatment year (1999/2000), and the 30 year average (1968–1998). Temperature data are from the HBEF Headquarters station, where winter temperatures include data from December through March and summer temperatures include data from April through November. Average snow depth and snow cover data are from watershed 2 within the HBEF. The snow data only are the average of 42 years (1956–1998)

Parameter	1997–1998	1998–1999	1999–2000	30 (42)–Year Average
Winter temperature (°C)	–2.1	–3.2	–3.2	–4.7
Summer temperature (°C)	12.7	13.3	11.7	12.1
Freezing index	365	500	513	589
Maximum snow depth (cm)	61	57	64	74
Duration of snow cover (days)	135	105	92	165

and/or longer the freezing season. This index is calculated by determining the number of degree-days between the highest and lowest points of a curve that depicts cumulative degree-days (Figure 1). Figure 1 compares cumulative degree-days for the 1997 through 2000 freezing seasons with the 30 year average. The maximum of the curve represents the onset of freezing, and the minimum represents the beginning of thaw. Despite an earlier than average start (11 November) and later than average end (25 March) of the freezing season for 1997/1998, the freezing index was significantly lower than average. For 1998/1999, the freezing season was shorter and warmer than average, resulting in a smaller freezing index compared to the 30 year average. Maximum snow depths and duration of snow cover for the measurement and recovery period were also below the seasonal 30 year norm for HBEF (Table 3). In general, both treatment years were warmer with less snowfall than the average. The recovery year was also warmer with less snowfall than average.

In assessing all data on snow depth, frost depths, soil temperature and moisture and lysimeter volumes, it is critical to keep perspective on the inherent variability of processes in natural systems. The HBEF is characterized by both landscape and plot scale variability. On a landscape scale, our four study sites ranged in elevation from 475 to 630 m asl. While all sites had similar forest canopy densities, they varied in aspect, elevation, and slope (Table 1). Because of the landscape scale variability, freezing events affected each site differently. In all years the YB2 site was the first to freeze due to

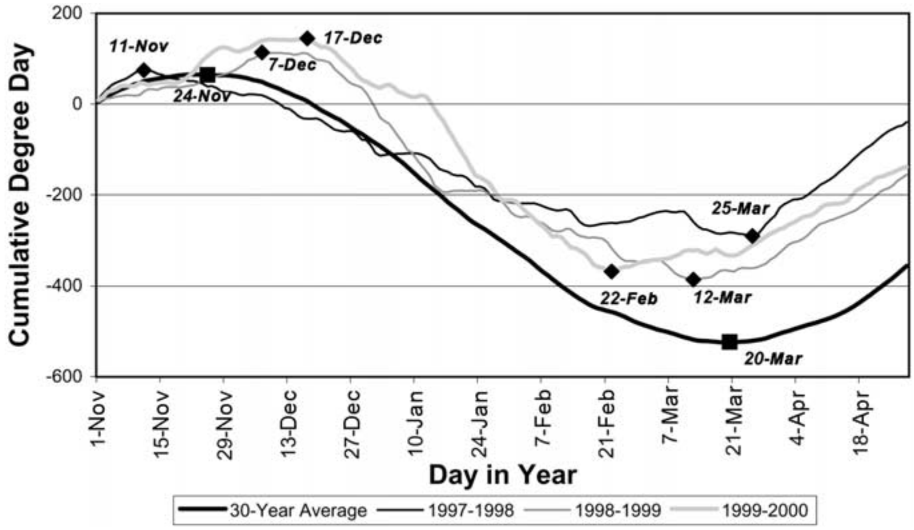

Figure 1. Cumulative Degree-Days for the 30 year average compared with the two treatment years (1997/1998, 1998/1999) and one recovery year (1999/2000) for November 1 to May 1. The dates associated with each line represent the start and end of each freezing season.

its location at a relatively high elevation and its northerly aspect. The last site to freeze, SM2, froze to 10 cm depth between 19 (1999/2000) and 63 (1997/1998) days later than the YB2 site froze to the same depth. SM2 is located on a flat bench at the base of a slope and has the highest soil moisture of the plots. Soils at HBEF are rocky, which leads to high variability of soil thermal properties within plots. Each plot had only a single thermistor profile and a single 0.5- $\times$ 0.5-m square area containing all lysimeters and TDR probes. The addition of two frost tubes per plot was partially intended to help reduce the uncertainty inherent with these single point measures. It is also important to note that the intent of our soil temperature monitoring was not to address landscape scale variability in soil freezing events but rather to provide data to support investigation of the effects of soil freezing on biogeochemical processes.

Snow and frost depths, snow water equivalence (SWE)

Snow depth was a strong regulator of frost depth (Figure 2). Maximum snow accumulation occurred approximately March 16 in 1998 and March 8 in 1999. Maximum snow depths in the treatment plots ranged from 18 (YB1 1999) to 45 cm (YB2 1998) while maximum snow depth in reference plots ranged from 60 (YB1 1999) to 102 cm (YB2 1998). YB2 with its northern

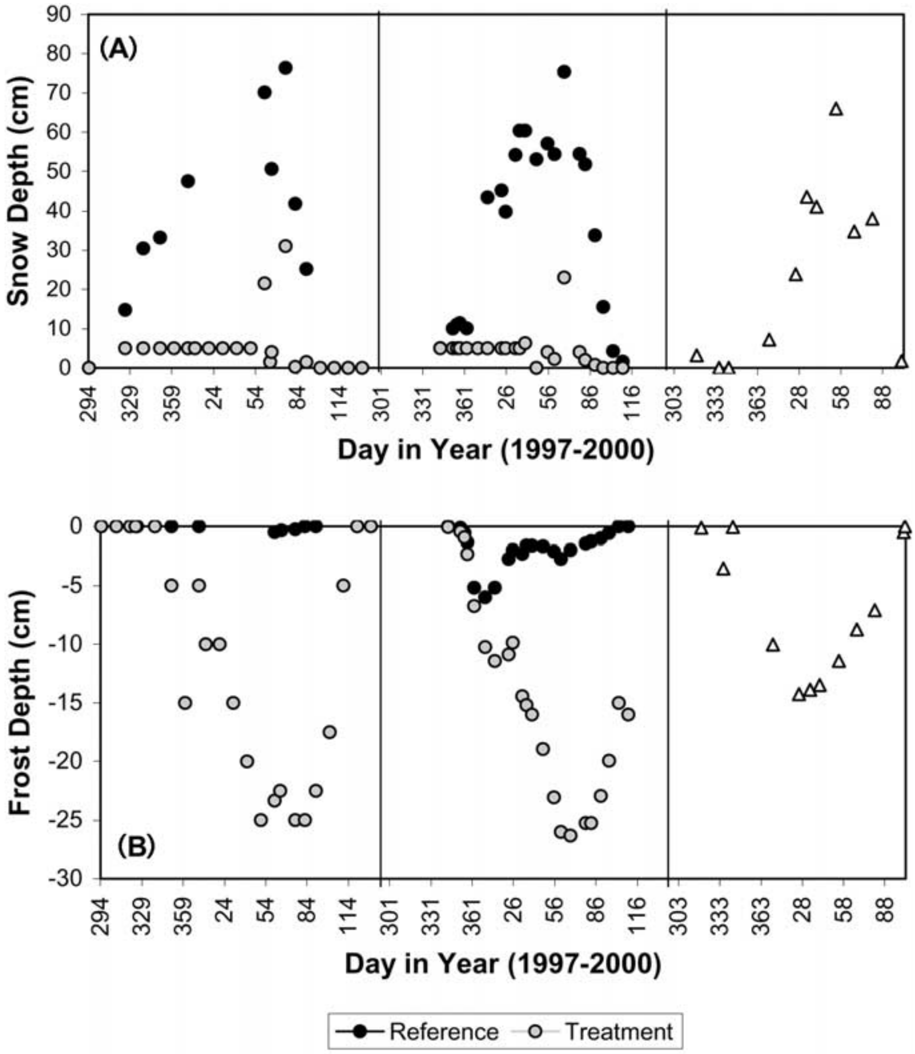

Figure 2. Snow (A) and frost (B) depths for the entire measurement period with reference (●) and treatment (◉) plots considered separately. The recovery year (1999/2000) is distinguished with a (Δ). Each data point is the average measurement from all four sites

aspect and higher elevation consistently received more snow and retained it longer than other plots.

The soil froze significantly ($p < 0.00$) deeper when data from all treated plots were combined, compared to the reference plots during November to May of two treatment years, confirming the importance of the insulating properties of a snow cover (Figure 2). Frost depths for 1997/98 were inferred from thermistors measuring temperatures below 0 °C. The frost depths for 1998/1999 and 1999/2000 were based on frost tube data. The inferred frost depth based on temperature measurements and the frost depths measured with frost tubes compared well during the 1998/1999 and 1999/2000 seasons. Mean soil freezing depths were slightly more severe in both treatment and reference plots during the winter of 1998/1999 than 1997/1998, likely due to colder winter temperatures and later arriving snowpack (Table 3).

Just as the snow cover protected the soil in reference plots from extensive freezing, accumulating snow after the treatment ended in February insulated the frozen ground in the treatment plots and delayed its thaw. Once frozen soil developed in the treated plots, it lasted into March and April even after snow on the plots was gone. Any frozen soil in the reference plots slowly thawed as the insulating snow cover developed. Although the non-treatment season of 1999/2000 was intended as a 'recovery' season, the late arriving snowpack resulted in natural and extensive freezing in all plots (Figure 2). During this natural freezing event, all soils remained frozen until early April despite the accumulation of an average 66 cm snowpack.

The relationship between maximum snow depth and maximum frost depth highlights the significance of the insulating effect of snow on frost depths (Figure 3). There was significant variability in the snow/frost relationships across the landscape, but strong consistency among sites. The strength of the overall, inverse relationship (Pearson product moment correlation) between snow depth and soil frost was not strong ($r = -0.67$, $p = 0.00$) when all points on Figure 3 were considered together ($n = 20$). However, when each site was considered separately for all three years ($n = 5$), the inverse relationships showed strong negative correlations between snow depth and soil frost (SM1, $r = -0.99$, $p = 0.00$; SM2, $r = -0.89$, $p = 0.04$; YB1, $r = -0.87$, $p = 0.06$; YB2, $r = -0.93$, $p = 0.02$). Only the YB1 correlation failed to be statistically significant. As expected, YB2 had the deepest snow and frost of all sites, while SM2 had the least soil freezing and moderate snow depths. The average maximum SWE in the reference plots was 270 mm in both 1998 and 1999. The average maximum SWE in the treatment plots was 110 mm in 1998 and 80 mm in 1999. In 1998, the snow removal treatment reduced available SWE for infiltration or runoff in the treated plots to approximately 41% of that available in the reference plots [(110/270) = 41%]. In 1999, the treatment reduced SWE to approximately 30% of that available to reference plots. The snow removal treatment thus reduced *annual* water input to the plots by 13% in 1998 (annual precipitation = 1252 mm) and 16% in 1999 (annual precipitation = 1218 mm).

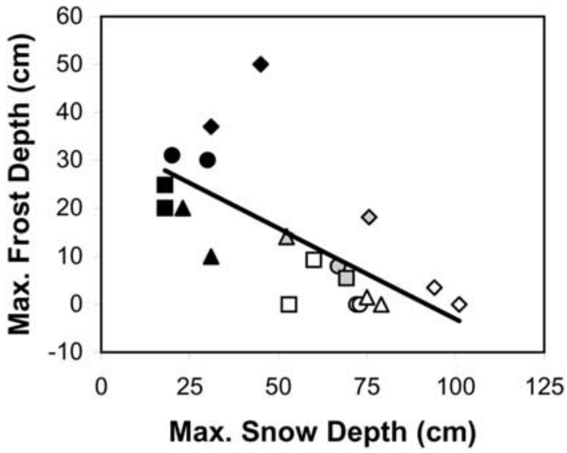

Figure 3. Relationship between maximum snow depth and maximum frost depth for all eight plots: SMI (circle), SM2 (triangle), YB1 (square), and YB2 (diamond). White data points are from the reference plots during treatment years (1997/1998 and 1998/1999). Black data points are from the treatment plots during treatment years (1997/1998 and 1998/1999). Grey data points are from the post-treatment year (1999/2000)

Soil temperature and moisture

The shoveling treatment applied to the treatment plots resulted in colder soil temperatures than reference plots (Figure 4). This time series of average daily soil temperature at each measurement depth presented in Figure 4 was normalized to day 295, 1997, in order to compensate for the variability in soil temperatures between sites. At all depths, winter soil temperatures in the treatment plots were colder than in the reference plots. Recall that in 1999/2000 no treatment was applied to the plots and therefore differences between plots were minimal. During this recovery year all plots froze to –10 or –20 cm depth. To better assess the magnitude of the temperature changes induced by shoveling, we plotted the average difference between the treatment and reference plots for the three years (minus summer months) at each of the six soil depths (Figure 5). Values less than zero occurred when temperatures in the treatment plots were colder than reference plots.

On a plot-by-plot basis, temperatures at 10, 20, and 30 cm depth were significantly colder ($p < 0.01$) in all treatment plots compared to reference plots during the winter months of treatment (December through February) (Table 4). While temperatures were consistently colder in all treatment plots at all depths and at all sites, there were some consistent variations among plots. As expected, the north-facing YB2 temperatures were the coldest at all depths in both reference and treatment plots, followed by the high

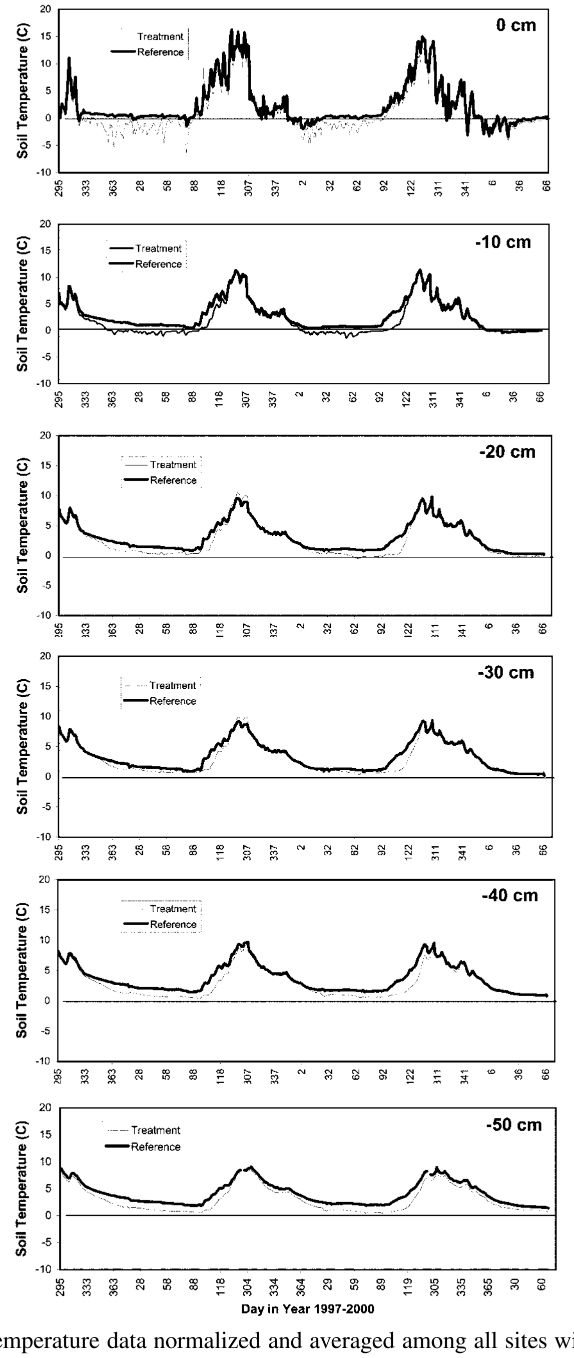

Figure 4. Soil temperature data normalized and averaged among all sites with reference and treatment plots considered separately. The data were normalized to day 295, 1997, in order to compensate for the variability in soil temperatures among sites. Thermistor depth is indicated on each plot.

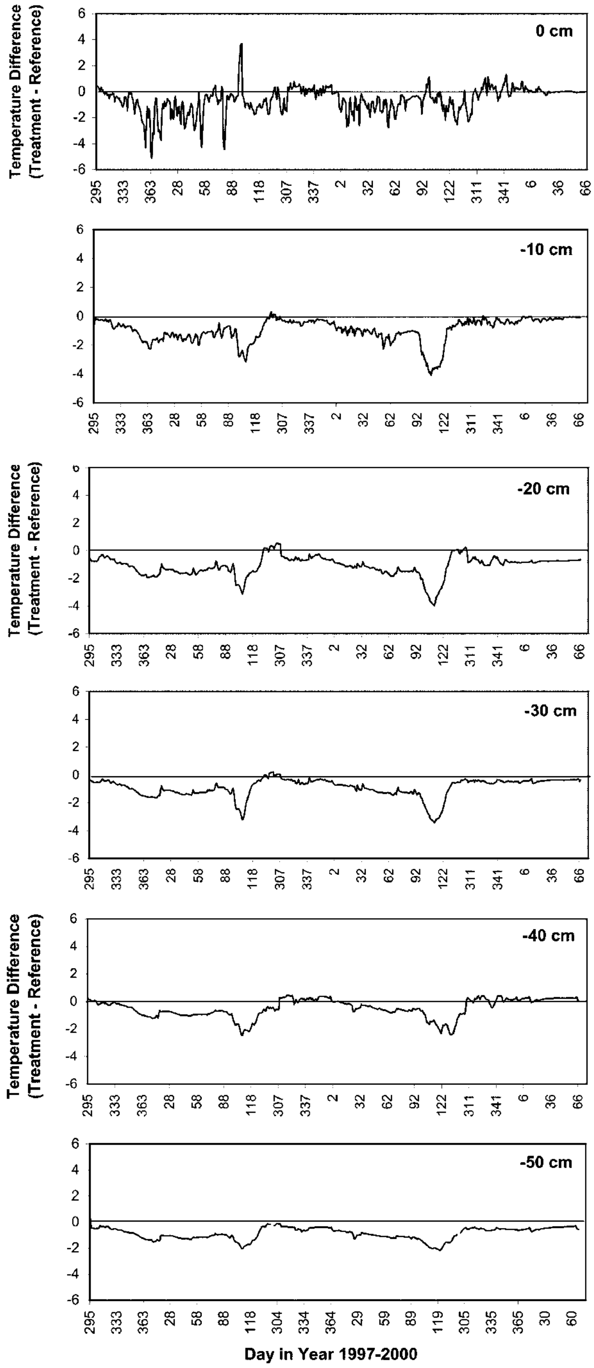

Figure 5. Mean soil temperature differences between treated and reference plots for the three measurement years (November–May). Negative values of temperature difference indicate that treated plots were colder than reference plots. Thermistor depth is indicated on each plot.

Table 4. Mean soil temperature in reference and treatment plots at 10-, 20-, and 30-cm depth for December through February for both treatment years. Statistical significance is indicated by the ANOVA *p*-value

Plot	**Depth**	**Reference**	**Treatment**	***p*-value**
SM1	10 cm	1.3	–0.1	0.000
SM2	10 cm	1.4	1.0	0.000
YB1	10 cm	2.1	0.6	0.000
YB2	10 cm	1.0	–0.2	0.000
All Plots	**10 cm**	**1.4**	**0.3**	**0.000**
SM1	20 cm	3.4	2.1	0.000
SM2	20 cm	4.3	3.0	0.000
YB1	20 cm	3.4	2.5	0.000
YB2	20 cm	2.3	1.5	0.000
All Plots	**20 cm**	**3.4**	**2.3**	**0.000**
SM1	30 cm	3.7	2.3	0.000
SM2	30 cm	4.0	3.4	0.000
YB1	30 cm	3.7	2.9	0.000
YB2	30 cm	NA	NA	NA
All Plots	**30 cm**	**3.8**	**2.9**	**0.000**

elevation south-facing SM1 site (Table 1). Generally, soil temperatures at the YB1 site were colder than the higher elevation and wetter SM2 site. As noted above, SM2 soils were the last to freeze in response to the shoveling treatment. Because SM2 soils have the highest moisture content (data presented below) of all plots, these soils have increased heat capacity and therefore a reduced soil thermal sensitivity. For all plots, temperatures at 20 cm depth were approximately 2 °C warmer than at 10 cm depth.

Soil moisture data collected from the TDR probes are considered separately for spring (March and April) and summer (May through November) months (Figure 6). During March and April, soils in the treatment plots were thawing, with all plots frost-free by the end of April in 1998 and two plots frost-free by late April 1999. Valid (non-frozen soil) TDR data points during these months were determined from positive soil temperatures at the depths of the TDR probes. The number of March–April days with valid data ranged from 7 (YB2 1999) to 60 (SM2 1998). For both treatment years, reference plots were significantly ($p < 0.015$) wetter than treatment plots during the March–April period (Figure 6). The wetter soils may result from a combination of more SWE available for infiltration in the

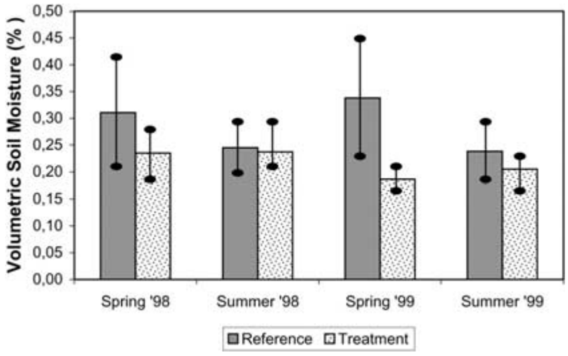

Figure 6. Volumetric soil moisture data from TDR probes for spring (March and April) and summer (May through November) of both treatment years. Data include average volumetric soil moisture in both horizons for each plot, with reference and treatment plots considered separately. Error bars show +/– one standard deviation. There were significant differences between treatment and reference plots in spring ($p < 0.015$) but not in summer ($p = 0.39$).

reference plots *and* from frozen soil inhibiting infiltration in the treatment plots (see discussion below). There was no significant difference in mean soil moisture between reference and treatment plots during the summer months (Figure 6).

An analysis of soil moisture on a plot-by-plot basis illustrates some variability across the landscape. Spring and summer data combined for both treatment years were considered separately for each plot (Table 5). As expected, the SM2 reference plot had the highest mean soil moisture of all plots during both spring and summer periods, while data from the other three plots showed no trend. During spring months the mean soil moisture was consistently higher in reference plots compared to treatment plots; however, for the YB1 site the differences were not significant. For the other sites, this does suggest that the unfrozen forest soils in reference plots permitted increased meltwater infiltration. During summer months, mean soil moisture in reference plots was the same as (SM1), higher than (SM2 and YB2), and less than (YB1) measured soil moisture in the treatment plots. The difference in means was significant in all but the SM1 site. This lack of a consistent relationship between summer soil moisture measurements suggest the effects of the treatment did not last into summer months. At all reference plots the soil moisture was higher in the spring than in the summer due to the expected contribution from snowmelt infiltration. However, at all treatment plots except YB2, which was equal, the spring soil moisture measurements were less than summer measurements. If reference plots represent the undisturbed soil moisture condition, these data confirm that increases in soil freezing inhibit soil moisture recharge during the critical snowmelt period

Table 5. Mean soil moisture in reference and treatment plots in spring (March–April) and summer (May–November) of 1998 and 1999 combined. Statistical significance is indicated by the ANOVA *p*-value

Test Plot	Season	Soil moisture (%)		*p*-value
		Reference	Treatment	
SM1	Spring	0.25	0.17	0.00
	Summer	0.22	0.22	0.82
SM2	Spring	0.49	0.23	0.00
	Summer	0.32	0.25	0.00
YB1	Spring	0.26	0.25	0.18
	Summer	0.23	0.29	0.00
YB2	Spring	0.29	0.19	0.00
	Summer	0.21	0.19	0.00

in the northeastern United States. Snowmelt not infiltrating the frozen soils then contributes to overland flow.

Lysimeter volumes

Soil infiltration is controlled by several factors, such as available SWE, the presence of air-filled macropores in the soil, soil water storage capacity, and the presence of ice lenses on the soil surface or at shallow soil depths. Our lysimeter volume data provide information on the effects of treatment on soil infiltration during spring and summer months (Figure 7). These data should be viewed as *relative* measures of volume for two reasons: (1) the maximum water capacity of the lysimeter collection vessels is two liters and in some cases the capacity was met prior to collection (confirmed from SM2 field notes), and (2) there were periods at some sites where frozen water in the lysimeter tube blocked sample collection. However, the data show that there was significantly ($p < 0.02$) reduced leaching in treated plots during March and April of both treatment years and that differences in leaching were not significant during the summer ($p = 0.92$). Lysimeters in treated plots collected approximately 54% (spring 1998) and 44% (spring 1999) of the water collected in the reference plot lysimeters. These spring reductions are approximately proportional to reductions in SWE caused by our snow removal treatment. The overall lack of differences in leachate volumes between treated and reference plots during the summer months suggests complete recovery from the effects of snow removal treatment and more extensive soil freezing.

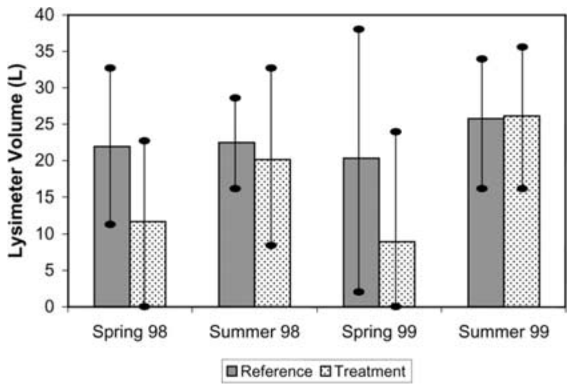

Figure 7. Volume of water collected in lysimeters during spring (March and April) and summer (May through November) of both treatment years. Each of the eight data points is the average volume from 16 lysimeters (four lysimeters at four plots) for each period, with reference and treatment plots considered separately. Error bars show +/– one standard deviation. There were significant differences between treatment and reference plots in spring ($p < 0.02$) but not in summer months ($p = 0.92$).

When soil lysimeter volume data are considered on a plot-by-plot basis, the data show less soil water collected in all treated plots than reference plots during spring months (Table 6). The YB1 treatment means consider data from 1999 only. Although SM2 was the only site where this difference was statistically significant at the 95% confidence level, the data show less infiltration in treated plots relative to reference plots. During the summer months of collection, the lysimeters in the SM1, YB1, and YB2 reference plots collected less water than in the treatment plots while the SM2 reference plot collected more water than the treated plot. On a plot-by-plot basis, summer soil water collected by the lysimeters in reference plots was not statistically different ($p > 0.05$) from soil water collected by the treatment plots, suggesting recovery from treatment effects. Recall that SM2 is the wettest site positioned on a flat bench, which is reflected in the high water volumes collected at this site in both seasons. Soils in this plot were last to freeze and first to thaw, allowing greater opportunity for soil water collection.

The ratio of leachate volumes collected in the treatment plots to that in the reference plots decreased as the snow ablation seasons progressed (Figure 8). The first March measurements of leachate volume occurred near peak snow accumulation in both years (11 March 1998 and 8 March 1999) and show that the treatment lysimeters collected 78 to 88% of the water collected by the reference lysimeters. During these first March measurements of both years, all plots were 100% snow covered and soils in the treated plots were frozen to average depths of 25 cm in 1998 and 26 cm in 1999 with no measured surface

Table 6. Mean lysimeter volumes collected in reference and treatment plots in spring (March–April) and summer (May–November) of 1998 and 1999 combined. Statistical significance is indicated by the ANOVA *p*-value. *The treatment means and *p*-values for YB1 used 1999 data only

Test Plot	Season	Lysimeter volumes (L) Reference	Treatment	*p*-value
SM1	Spring	37.4	10.3	0.06
	Summer	35.1	45.7	0.07
SM2	Spring	66.5	51.5	0.00
	Summer	52.6	49.8	0.06
YB1	Spring	12.7	0.62*	0.2*
	Summer	24.2	16.9*	0.7*
YB2	Spring	24.8	7.7	0.15
	Summer	35.8	45.6	0.57

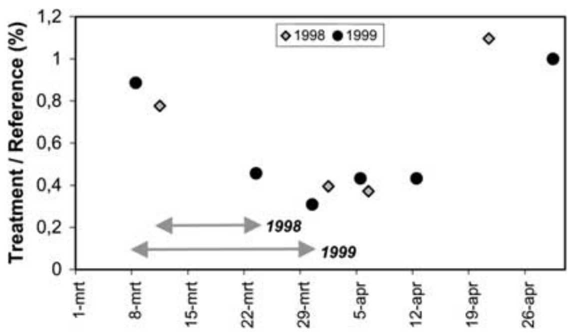

Figure 8. The ratio of leachate volumes in the treated plots to that in the reference plots for 1998 (◇) and 1999 (●). The horizontal lines show the approximate period from maximum snow accumulation to complete ablation in the treated plots.

thaw. This reduced infiltration in the treated plots in early March suggests that the frozen ground reduced snowmelt infiltration in the treated plots by 12 to 22%. The remaining measurements during most of the spring melt period show the treatment plots collected 31 to 46% of the melt in the reference plots. The relatively low infiltration ratios as the ablation season progressed relates to the absence of snow on the treatment plots by the end of March in both years, depleting the source available for snowmelt infiltration. Between late March (SM2) and mid-April (YB2) soils in all treated plots at the lysimeter depths thawed. Thus, we conclude that the snow removal treatment affected spring leaching volumes by (1) reducing infiltration through the frozen soils early in the ablation season and (2) reducing available SWE for snowmelt as the ablation season progressed. Snow cover in the reference plots remained into mid-April. Infiltration in the treatment and reference plots was nearly identical by late April (Figure 8) and during summer months, suggesting full recovery from treatment effects on infiltration.

During natural freezing events as occurred during our recovery year (1999/2000), and similar to what may be expected with certain climate change scenarios, reduced leaching of snowmelt is likely compared to normal years. During the 1999/2000 season, all plots froze to at least 10 cm depth (mean = 14.5 cm) before enough snow accumulated to insulate the soil. Frozen soil was still present in two plots on 11 April 2000 while the snow in all but one plot was gone. Given the results for our treatment years, we estimate there was 12 to 22% less infiltration in spring 2000 than would be expected in a normal winter when forest soils were protected from extensive freezing. Reduced leaching should result in increased surface runoff and higher stream flow. Monthly stream flow data from HBEF Watershed 3 during the 2000 snowmelt period (March, April and May) indeed showed 20 to 80% higher runoff than the 42 year mean (Hornbeck & Bailey 2001). Most significantly, weirs at Watershed 3 recorded 80% more runoff in March 2000 than the 42 year mean.

Conclusions

1. Snow depth was a strong regulator of soil freezing in the northern hardwood forest at HBEF at all locations. Our data show that even mild winters with low snowfall resulted in increased soil freezing in these forests. Our results suggest that a climate shift toward less snowfall or a shorter duration of snow on the ground will produce increases in soil freezing in northern hardwood forests.
2. Our experimental plots encompassed a range of landscape positions. While all plots had similar responses (soil freezing, soil moisture, soil water volume) to the snow removal treatment, the timing and extent of the response varied between plots.
3. Soil freezing did not have dramatic effects on soil water dynamics during snowmelt in these forests; however, treated plots recorded less soil moisture and soil water in spring months compared to reference plots. Reductions in soil leachate volume were approximately proportional to reductions in SWE caused by shoveling. However, during early spring when all plots were snow covered, leachate volumes were reduced 12 to 22% in the treatment plots, suggesting inhibition of infiltration by frozen soil. The effects of soil freezing on infiltration were also shown

by our non-treatment year (1999/2000), when natural freezing occurred, and higher runoff relative to the long-term mean was observed in one of the gaged watersheds at HBEF.

4. It is likely that the highly organic surface soil horizons in these forests are not conducive to the development of concrete frost that can greatly reduce infiltration. Temperate forests with less well-developed organic horizons, e.g. those with earthworms or with past agricultural land use, may be more susceptible to freezing disruption of soil water dynamics during snowmelt.

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