Snow Removal and Ambient Air Temperature Effects on Forest Soil Temperatures in Northern Vermont

K. L. M. Decker,* D. Wang, C. Waite, and T. Scherbatskoy

ABSTRACT

We measured deciduous forest soil temperatures under control (unmanipulated) and snow-free (where snow is manually removed) conditions for four winters (at three soil depths) to determine effects of a snow cover reduction such as may occur as a result of climate change on Vermont forest soils. The four winters we studied were characterized as: 'cold and snowy', 'warm with low snow', 'cold with low snow', and 'cool with low snow'. Snow-free soils were colder than controls at 5- and 15-cm depth for all years, and at all depths in the two cold winters. Soil thermal variability generally decreased with both increased snow cover and soil depth. The effect of snow cover on soil freeze-thaw events was highly dependent on both the depth of snow and the soil temperature. Snow kept the soil warm and reduced soil temperature variability, but often this caused soil to remain near 0°C, resulting in more freeze–thaw events under snow at one or more soil depths. During the 'cold snowy' winter, soils under snow had daily averages consistently >0°C, whereas snow-free soil temperatures commonly dropped below −3°C. During the 'warm' year, temperatures of soil under snow were often lower than those of snow-free soils. The warmer winter resulted in less snow cover to insulate soil from freezing in the biologically active top 30 cm. The possible consequences of increased soil freezing include more root mortality and nutrient loss, which would potentially alter ecosystem dynamics, decrease productivity of some tree species, and increase sugar maple (*Acer saccharum* Marshall) mortality in northern hardwood forests.

Ongoing and future climate changes have the potential to substantially alter the structure and function of northeastern forests. The Intergovernmental Panel on Climate Change (IPCC) estimates that global average surface temperatures have increased by 0.6 (±0.2°C) over the past century (Houghton et al., 2001; IPCC, 2001). The amount and form of precipitation has also changed over the past century. The IPCC estimates that there has been a 0.5 to 1% per decade increase in northern hemisphere precipitation at mid to high latitudes over the past century; and that globally there has been a 10% reduction in the extent of snow cover over the past 40 yr (Houghton et al., 2001; IPCC, 2001). Current climate change models predict that these trends will continue this century (Houghton et al., 2001; IPCC, 2001). These models predict a 1.4 to 5.8°C rise in average global temperatures by 2100, with mid to high latitude, northern hemisphere land masses experiencing above average increases in temperature, especially during the winter (Houghton et al., 2001; IPCC, 2001). Winter precipitation at these same latitudes is projected to increase, but snow cover will decrease. In this paper, we examine potential effects of a reduction in snow cover on northeastern forests by examining soil temperatures under control and snow-free (where snow is manually removed) conditions for four consecutive years between 1 December and 30 April.

In cold temperate mixed deciduous-evergreen forests, where there is a persistent insulating snow layer through much of the winter, a slight rise in average ambient temperature can change thermal dynamics in the biologically active top 30 cm of soil in different ways. The effects of warmer air on soil temperature depend on the extent that the insulating snow layer is reduced (Yin and Arp 1993; DeGaetano et al., 1996). If the elevated ambient temperatures are coupled with an increase in precipitation this will further alter the effects of climate warming on the soil (Pikul et al., 1989; Lehrsch et al., 1991).

Although the average soil temperature may change very little as a consequence of higher ambient temperature and a reduced snow cover, the variation in daily soil temperature may be greater. This may increase the number of freeze–thaw cycles, affecting root mortality, soil aggregate stability, and nutrient loss (Auclair et al., 1996; Edwards 1991; Lehrsch et al.1991; Ron Vaz et al., 1994; Stottlemeyer and Toczydlowski 1991). Additionally, an increase in root-zone soil freezing and thawing events causing increased root desiccation has been implicated in dieback events in northern hardwood forests (Auclair et al., 1996).

Whatever the direct effect of climate change on soil temperature, the long-term indirect effects of increased soil freezing because of reduced snow on northern forest ecosystem health is potentially profound (Auclair et al., 1996; Groffman et al., 2001a; Robitaille et al., 1995; Bertrand et al., 1994). Several studies in the northeastern mixed-deciduous forests have linked prolonged mild soil freezing (caused by winter snow drought) to increases in soil nitrate, (Groffman et al., 2001b), to increases in soil N, P, and C losses (Fitzhugh et al., 2001), and to increased root mortality (Groffman et al. 1999; Tierney et al., 2001).

Together, these studies suggest that a reduction or removal of a snow layer resulting in a loss of thermal buffering can cause an early disruption of the winter soil nutrient storage. This can lead to ecosystem leaching losses during winter when plant and microbial demand is likely to be low. Soil freezing can also reduce quality and quantity of sap of sugar maples (Robitaille et al., 1995). Thus information about the freezing behavior of soil under different winter conditions can be useful to forest managers interested in both maple syrup production and ecosystem health.

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Abbreviations: IPCC, Intergovernmental Panel on Climate Change.

To evaluate the interaction between snow depth, air temperature, and soil temperature, we monitored soil temperatures at three depths within the upper rooting zone for four consecutive years in control and snow-free plots. The four study years differed in ambient temperature, timing and duration of the coldest part of the winter, and the amount and persistence of the snow cover. This allowed us to examine the temperature differences in soil exposed to cold and warm winters under different amounts of snow (control) and with snow removed (snow-free). Our goal was to improve our understanding of the complexity of interactive climate factors that determine soil temperature and freezing using empirical data from a mature northeastern mixed-hardwood forest that is typically blanketed in snow for the duration of the winter.

MATERIALS AND METHODS

Study Site

The study occurred in a northeastern mixed-hardwood forest at the University of Vermont Proctor Maple Research Center located in Underhill, VT (44° 31′ 42″ N Lat., 72° 52′12″ W long.). The soil is a typic Fragiorthod, a frigid Marlow series extremely stony loam that occurs on 5 to 20% convex slopes (Allen, 1973). It consists of a 36- to 45-cm layer of very rocky loam that tops slowly permeable fragipan. Soil above the fragipan is easily saturated by rain, and has a low shrink–swell potential. After saturation, water is rapidly lost to the upper soil zone through surface runoff (Allen 1973). Because of this soil structure and the small size of our ‘snow-free’ plots (1 m^2), it is likely that any snowmelts that occurred around the snow-free plots increased soil moisture within the plots. On top of the soil there is a discontinuous 3-cm duff layer of maple and other hardwood leaf litter.

The Proctor Maple Research Center is located at an elevation of 400 m, in a climate that is cool-temperate and continental. Dominant hardwood species in the area include sugar maple, red maple (*A. rubrum* L.), yellow birch (*Betula alleghaniensis* Britton), black cherry (*Prunus serotina* Ehrh.), and hop hornbeam [*Ostrya virginiana* (Mill) K. Koch]. Average snowfall during the period of 1 December through 30 April in nearby South Burlington is 186 cm. This time period represents the dates when snowfall is likely, and will be used as the effective ‘winter’ for this investigation. The average temperature of the effective winter in South Burlington is −2.9°C (data from the National Climatic Data Center; available online at www.ncdc.noaa.gov).

Experimental Design and Execution

The experiment was originally designed to consist of paired treatments (‘snow free’ and an unmanipulated ‘control’) and three soil depths with two replicate sites. Because of data logging malfunctions, one replicate site had incomplete temperature records. Because of this, the inferential statistics we performed were limited to months where >80% of the data were available. For this reason, much of the results we show are descriptive rather than inferential.

Treatments were designed to examine the effect of snow removal on soil temperature dynamics at three depths. One of a pair of 1-m^2 plots was randomly designated as a non-manipulated control. The second plot was maintained as a snow-free plot. During the period 1 December through 30 April, we measured average snow depths on all control plots, and shoveled snow from snow-free plots within 2 d following a precipitation event. Soil temperatures were measured at three depths for four consecutive years beginning with the 1993 through 1994 winter.

In January 1993, we installed averaging soil thermocouples 5, 15, and 30 cm below the soil surface in each plot. (Averaging is achieved using four leads joined in parallel into a single lead.) One additional thermocouple at each plot was used to measure air temperature 2 cm above the soil. Thermocouples were fabricated from Teflon-coated type-T thermocouple wire and patterned after commercially available models. Thermocouple junctions were waterproofed using a combination of heat shrink tubing covered with plasti-dip (PDI, Inc., St. Paul, MN). We installed subsurface thermocouples in the approximate center of each plot by excavating small 40 cm deep soil pits with smooth vertical faces and inserting the four ends of each thermocouple horizontally into the vertical face approximately 10 cm apart and 7 cm into the face. Thermocouples were individually calibrated and referenced to National Institute of Standards and Technology traceable thermometers. Data were recorded as 15 min averages to a Campbell Scientific, Inc. 21X data logger (Logan, UT 84321-1784; Replicate 1) and to an analog-to-digital converter (ADC bluebox; Remote Measurement Systems, Inc., Seattle, WA) attached to a personal computer (Replicate 2). Ambient air temperatures were also collected by the 21X data logger using a CSI 107-L temperature sensor located 7.5 m above the ground.

Data Analysis

For each soil depth, *t* tests were conducted to compare snow-free and control treatments averaged over all months where data from both replicates were available. Because of the intermittent failures of the ADC-PC system, the data available for analysis were from the 1993 to 1994 season (excluding January), the 1994 to 1995 season (excluding January), and from 1996 to 1997 (February and April only).

We used the average February soil temperature for each of the 3 yr where data from both replicates were available to perform an analysis of variance comparing temperatures from the 3 yr (1993-1994, 1994-1995, and 1996-1997) and from the soil depths during the coldest portion of the winter. The Ryan-Einot-Gabriel-Welsch modified F-test was used to test the differences among means.

For each soil depth, temperature was averaged by day, month, and winter. Because freezes and thaws are implicated in the desiccation of fine roots, we tabulated the number of times the daily average ambient and soil temperature crossed 0°C for each year (and for each winter month for soil at the 5-cm depth). For each soil depth × treatment (control and snow-free) combination, we ran regressions comparing the number of frozen soil days with the number of days the ambient temperature was at or below freezing. Additionally, for each winter, and for each soil depth × treatment combination, we calculated the winter day-to-day variation in temperature by taking the average winter differences in mean daily temperatures for each pair of consecutive days within each winter.

RESULTS

Characterization of Winters

The four winters of interest were characterized by the amount of snow and the average seasonal temperature (Table 1). The winters of 1993 to 1994 and 1995 to 1996 were both cold. However 1993 to 1994 was continuously cold and had deep snow, whereas average 1995 to 1996

Table 1. Comparison of air temperatures and snow fall among four winters in a Vermont mixed-hardwood forest. Temperatures are based on data collected from 1 December to 30 April each year whereas snow data was collected from 1 December to 11 April. Numbers are means with standard errors in parentheses.

Winter		Air temperature, °C			Snow depth, cm	
Year	Characterization	Seasonal average	Average change in day-to-day temp	Days with average temp ≤0	Average seasonal depth	Days with snow
				%		%
1993-1994	cold, snowy	−4.7 (9.3)	4.4 (0.29)	66	41 (20.0)	100
1994-1995	warm, low snow	−1.9 (7.8)	4.1 (0.28)	57	10 (12.5)	56
1995-1996	cold, low snow	−4.8 (8.0)	4.1 (0.30)	77	18 (14.9)	93
1996-1997	cool, low snow	−2.5 (7.3)	4.7 (0.34)	74	11 (12.9)	94

snow depths were only 48% of those of the 1993 to 1994 winter. The two remaining winters were warmer on average and had shallower snow cover. Of these warmer years, 1994 to 1995 was the mildest, with only 56% of its winter days covered in snow. Over the four winters, average air temperature fluctuations ranged from 4.1 to 4.7°C.

Each winter there was a single cooling trend (at the temporal scale of one month) that generally corresponded to an increase in snow depth (Fig. 1). The two cold years 1993 to 1994 and 1995 to 1996 can be characterized differently by examining the monthly data. The winter of 1993 to 1994 was initially warm but cooled in January to an average of −15°C. Thereafter the temperature rose consistently with each month. In contrast, the winter of 1995 to 1996 had average monthly temperatures of −7°C for 3 mo before temperatures began to rise. To compare the two warmer years, 1994 to 1995 had a late-season cold snap whereas 1996 to 1997 was coldest in mid-winter (January).

The number of air freezes and thaws per year also characterized winters (Fig. 1). The winter of 1993 to 1994 had 21 freeze–thaw events. In contrast, the next three winters had consecutively 27, 29, and 29 freeze–thaw events.

When climate variables of each of these years are placed in a historical context, they may improve understanding of how future changes in winter temperature and precipitation will alter soil thermal dynamics in northeastern hardwood forests. Data from a nearby airport weather station in South Burlington were compiled for December through April and used to determine the 50-yr average snowfall and temperature (National Climatic Data Center; data available at www.ncdc.noaa.gov; Fig. 2). The 50-yr average winter air temperature at the South Burlington airport was −2.9°C, and the standard error was 0.20°C. Of the four winters we studied, 1993-1994 and 1995-1996 were colder than average and 1994-1995 and 1996-1997 were warmer (Fig. 2a). The 50-yr average winter snowfall at the South Burlington airport was 185.7 cm., and the standard error was 7.10 cm. Three of the four winters we studied had more snow than average (Fig. 2b). The warmest winter of our study period (1994-1995) also had approximately 50 cm less snow than the long-term average. Thus the soil temperature behavior in 1994-1995 is the most informative when anticipating effects of global warming that would include effects because of combined changes in temperature, snowfall, and snow accumulation.

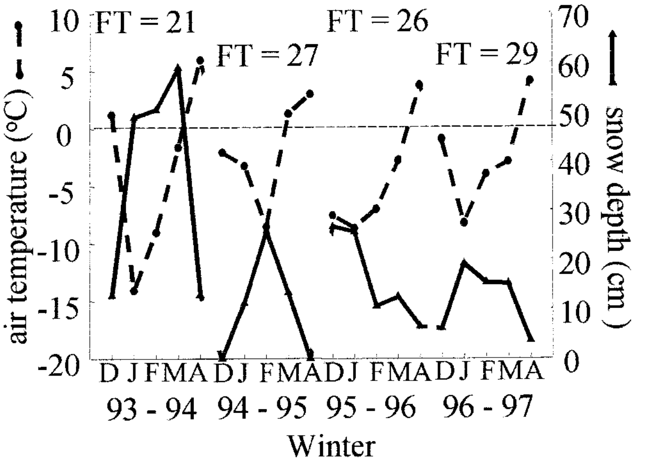

Fig. 1. Average monthly air temperature and snow depth for four winters (1 December–30 April) in a Vermont mixed-hardwood forest. Also shown are the number of times the average daily air temperature crosses the threshold between freezing and thawing.

Soil Temperatures (Monthly Temporal Scale)

There was a significant difference between snow-cover treatments at all soil depths for average winter temperatures where data from both replicates were available (Table 2). At all three depths, control plots were warmer than snow-free plots.

The insulating effect of snow cover (differences between paired snow-free and control plots; control-snow-free temperature = IE) was analyzed for 1993 to 1994, 1994 to 1995, and 1996 to 1997. We conducted this analysis to determine whether year and soil depth were significant sources of variation in the insulating effect of snow during midwinter. Of the three Februarys analyzed, the insulating effect of snow was greatest in 1993 to 1994 (Table 3). In contrast, the insulating effect was lower and did not differ significantly between the two winters with <20-cm average snow depth (1994-1995, and 1996-1997; Table 3). Averaged over the 3 yr, the insulating effect of snow was greatest at a soil depth of 5 cm., intermediate at a depth of 15 cm., and lowest at a depth of 30 cm.

The descriptive statistics we present are based on mean monthly values from one ‘snow-free’ and one ‘control’ paired plot (Fig. 3). However, trends in monthly soil temperatures at all depths for available data from the second replicates (over three of the four winters) indicate that the two replicate sites had similar thermal dynamics. To illustrate this, we present data for a 5-cm soil depth for Replicate 2, which was established 10 m from Replicate 1 (Fig. 3a).

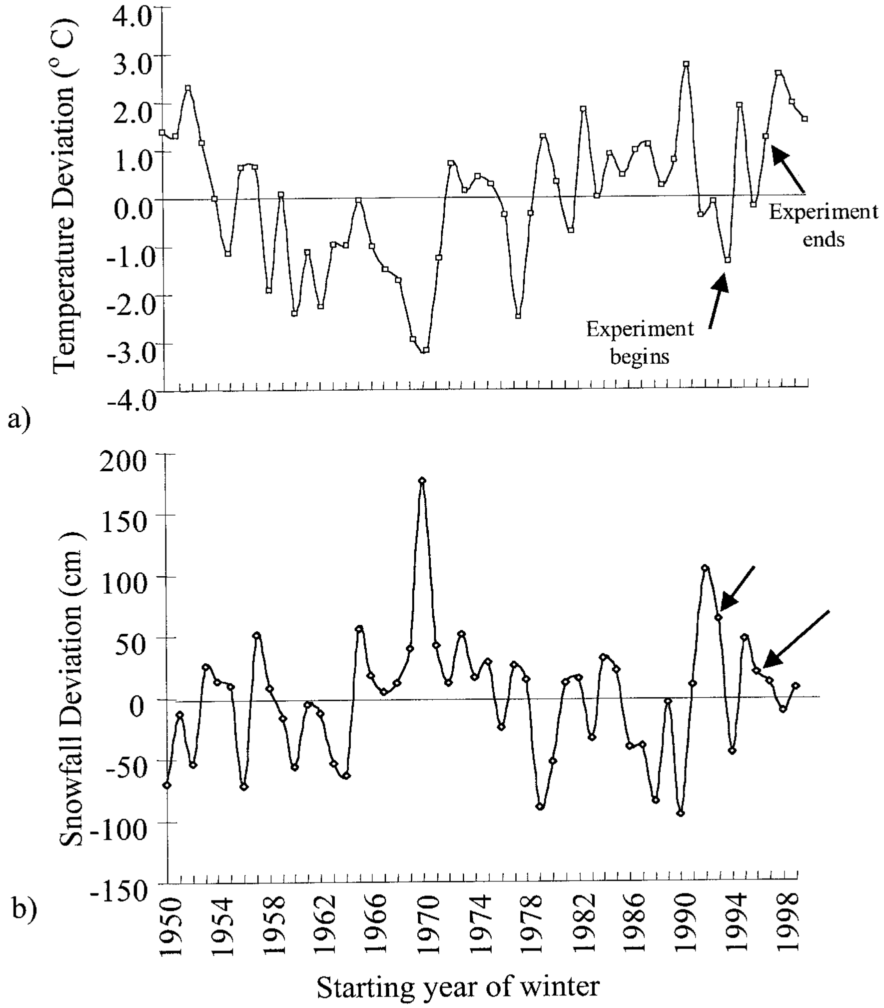

Fig. 2. Deviation from normal average winter (a) temperature and (b) snowfall for the South Burlington Airport (VT) for the past 50 yr. Winters are defined as 1 December through 30 April. (Data compiled from the National Climatic Data Center; www.ncdc.noaa.gov)

Based on descriptive results of both plot pairs (5 cm; Fig. 3a,b) and on one plot pair (15 cm and 30 cm; Fig. 3c,d), snow removal effects on soil temperature depended on year and soil depth. At depths of 5 and 15 cm, soils were consistently cooler in the snow-free plot(s) than in the control plot(s) (Fig. 3 a–c). This difference was greater in the two colder winters (1993-1994; 1995-1996). Average monthly soil temperature during the snowier of these cold winters never went below freezing in the control plot. In contrast, 1994 to 1995 and 1996 to 1997, the years with average seasonal snow depth of only 10 and 11 cm, respectively, had smaller differences between snow-free and control plots at all soil depths. This was apparently the situation even in January of both years when the snow depth was greatest in both years and averaged from near 20 cm (1996-1997) to near 30 cm (1994-1995) (Fig. 1). At a

Table 2. Mean soil temperatures (with standard errors in parentheses) and results of t-tests ($\alpha = 0.05$) comparing snow-free and control plots in a Vermont mixed-hardwood forest. Analysis is based on available replicates for three years (December–April of 1993-1994 and 1994-1995 and February and April of 1996-1997).

	Treatment				
Soil depth	Snow-free	Control	*N*	*t*	*p*<
cm	°C				
5	0.35 (0.01)	1.38 (0.16)	2	−39.40	0.02
15	0.80 (0.14)	1.66 (0.23)	2	−123.95	0.01
30	1.42 (0.23)	1.93 (0.23)	2	−26 708.80	0.001

Table 3. Differences in soil temperature between paired control (C) and snow-free (SF) plots during February in a Vermont mixed-hardwood forest. Insulating efect, $IE_{feb} = C - SF$. Shown are means with standard errors in parentheses of years and soil depths. Means that were significantly different are indicated with diffferent lower case letters.

Source of variation	IE_{feb}
	°C
Year†	
1993–1994	3.12 (0.47) b
1994–1995	0.74 (0.23) a
1996–1997	0.39 (0.11) a
Soil Depth, cm‡	
5	1.94 (0.75) b
15	1.46 (0.49) ab
30	0.84 (0.49) a

† $N = 6$; $F = 34.95$; $p < 0.001$.
‡ $N = 6$; $F = 4.45$; $p < 0.05$.

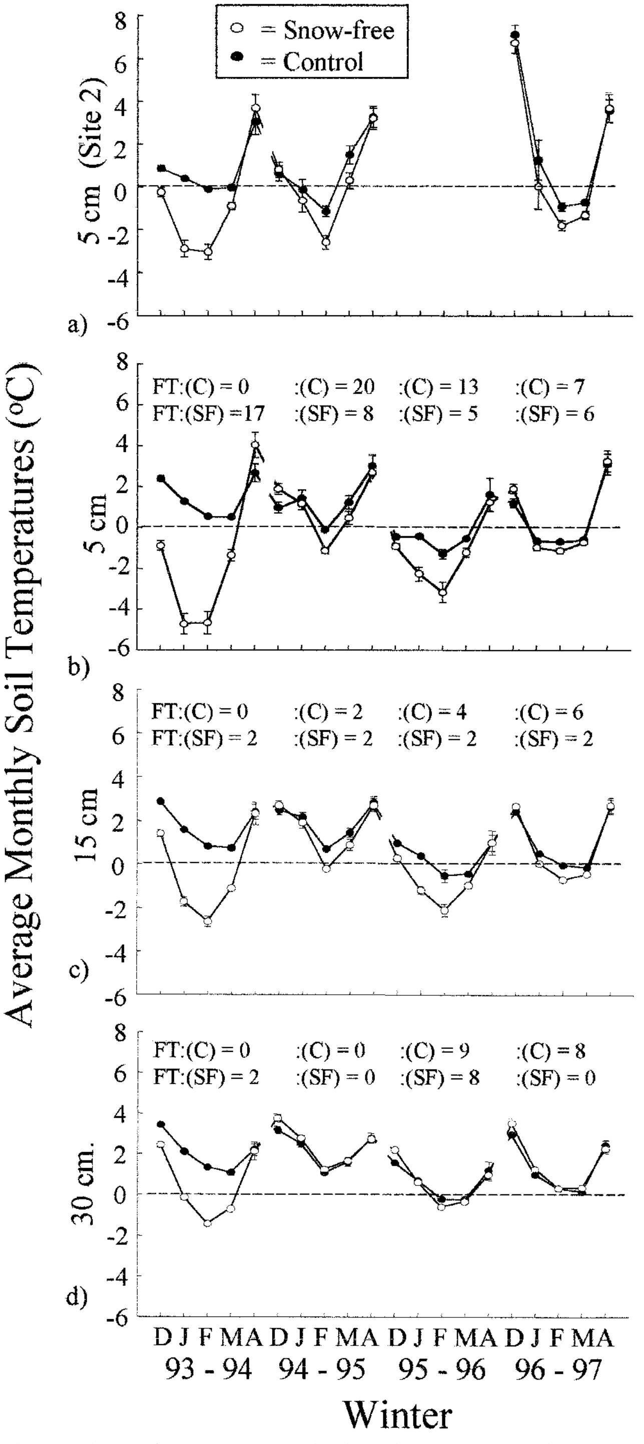

Fig. 3. Winter (1 December–30 April) soil temperatures in control (unmanipulated) and snow-free plots in a Vermont mixed-hardwood forest. Graphs show average monthly soil temperatures (with standard errors) over three winters for Site 2 at the 5-cm depth (Fig. 3a) and over four winters at Site 1 at three soil depths (Fig. 3b–d). Data from replicate Site 2 are included to indicate that the observed patterns in Site 1 were not atypical. Graphs from Site 1 also show the number of times the average daily soil temperature crosses the threshold between freezing and thawing (FT) for each winter for control (C) and snow-free (SF) plots.

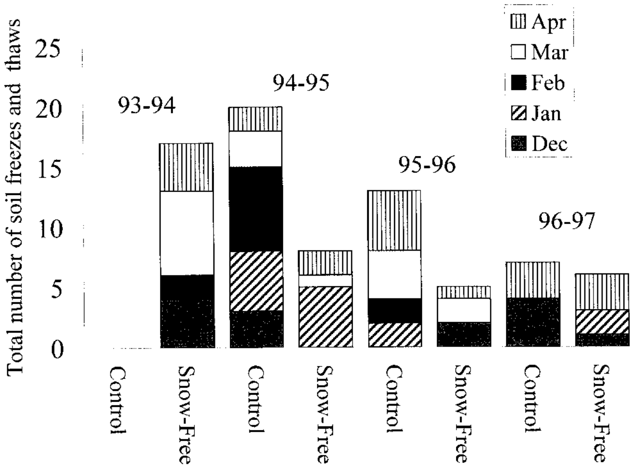

Fig. 4. Monthly tabulations of the number of times the soil temperature crosses 0°C at the 5-cm depth for four consecutive winters (defined as 1 December–30 April) in a Vermont mixed-hardwood forest.

soil depth of 30 cm, there was only an effect of snow removal in the 'cold snowy' winter (1993-1994; Fig. 3d). During this year, the snow-free plot had a subzero average monthly temperature at all soil depths for 3 mo, whereas the control soil was consistently above zero.

Snow removal had an apparent but inconsistent effect on soil freeze–thaw events (as tabulated by daily average soil temperature) (Fig. 3b–d; Fig. 4). If the soil temperature was just above zero, snow removal generally caused more freeze–thaw events due to soil cooling. In contrast, if the soil temperature was just below zero, snow cover brought the temperature up enough so that there were more freeze–thaw events. During the winter of 1993 to 1994, the snow-free plot had consistently more freeze–thaw events than the control plot at all three soil depths (Fig. 3). In this 'cold, snowy' winter the top 5 cm of soil were affected the most, and the snow-free plot had most freeze–thaw events in December, March, and April (Fig. 4). In the 'warm, low snow' year (1994-1995), the effect of snow removal on freeze–thaw events was the opposite of that in the winter of 1993 to 1994, and was the most pronounced in the top 5 cm (Fig. 3). During this winter, control soil at a 5-cm depth experienced more freeze–thaw events than snow-free soils, especially in December, February, and March (Fig. 4). In the winters of 1995 to 1996 and 1996 to 1997 control soils had more freeze–thaw events than snow-free soils at all three depths (Fig. 3). In the winter of 1995 to 1996, control soil at 5 cm had all but two of its freeze–thaw events after the snow layer decreased from an average of 27 cm to under a 15-cm depth between January and February (Fig. 4; Fig. 1). In contrast, snow-free soil at a 5-cm depth had all of its freeze–thaw events during early and late winter (Fig. 4). Winter of 1996 to 1997 control soils in the top 5 cm experienced freeze–thaw events only in December and April, when average snow depths were below 10 cm (Fig. 4; Fig. 1). In contrast, 1996 to 1997 snow-free soils at the 5-cm depth experienced two freeze–thaws in January in addition to December and April freeze–thaws.

Table 4. Average day-to-day change in temperature (°C) of a Vermont mixed-hardwood forest soil. Shown are means (with standard errors in parentheses) of daily variations in soil temperatures for control and snow-free plots at three depths for each winter (1 December–30 April).

	Soil depth					
	5 cm		15 cm		30 cm	
Year	**Control**	**Snow-free**	**Control**	**Snow-free**	**Control**	**Snow-free**
1993-1994	**0.15 (0.09)**	**1.35 (0.12)**	**0.11 (0.02)**	**0.46 (0.05)**	**0.09 (0.02)**	**0.22 (0.10)**
1994-1995	**0.60 (0.08)**	**0.57 (0.06)**	**0.31 (0.05)**	**0.31 (0.04)**	**0.24 (0.04)**	**0.19 (0.03)**
1995-1996	**0.33 (0.06)**	**0.70 (0.07)**	**0.13 (0.03)**	**0.38 (0.04)**	**0.13 (0.27)**	**0.12 (0.01)**
1996-1997	**0.47 (0.07)**	**0.64 (0.06)**	**0.23 (0.03)**	**0.29 (0.03)**	**0.19 (0.03)**	**0.15 (0.02)**

For each winter, we calculated the variation in average day-to-day temperature (winter average of difference between temperatures of consecutive days) to describe the effect of snow insulation on thermal variability in the shallow rooting zone (0–30 cm) of the soil (Table 4). For all four winters day-to-day temperature variation generally decreased with soil depth in both control and snow-free plots. Thus there was a thermal buffering gradient from shallow to deep soil. This thermal buffering gradient within the soil was less steep in the control plot in years where there was a continuous snow layer throughout the winter (1993-1994; 1995-1996, 1996-1997). Overall, snow cover reduced thermal variability in the soil. In 1993 to 1994, the winter with the most snow, soil from the control plot had the least amount of variability. However, variability in soil temperature was increased 244 to 900% by removing snow. In the other two winters with continuous but thin snow layers, snow removal increased soil temperature variation at a 5-cm depth 136 to 212% over that of the control plot. Comparing control plots of the four winters, 1994 to 1995 had the highest day-to-day variation in soil temperature at all three soil depths. In this warm year, the 56% of days that were snow-covered did not reduce average daily winter variability in control soil temperatures compared with those from the snow-free plot.

Soil Temperature (Daily Temporal Scale)

To understand the fine-scale effects of snow cover on soil temperature, we contrasted daily averages of the two most distinct winters (Fig. 5). In 1993 to 1994, snow was deep and snow cover was continuous throughout most of the winter (Fig. 5a). During this winter average daily temperatures of the control soil were consistently above zero (Fig. 5b). However, snow-free soil had long freezing periods throughout mid-winter that decreased in severity and length with soil depth (Fig. 5c). In contrast to 1993 to 1994, the winter of 1994 to 1995 was the mildest, and had the least snow (Fig. 5d). In spite of the mildness, in the control plot there were several periods when the average temperature was below freezing at a soil depth of 5 cm (Fig. 5e). These mild soil freeze events coincided with the presence of snow in late December and from late January through late February. Thus, in contrast to 1993 to 1994, snow did not prevent soil freezing in this warmer winter, possibly because of a shallower snow cover. However, as might be expected, soil in the snow-free plot was colder, and freezing was deeper than controls during the coldest weeks of 1994 to 1995 (Fig. 5f).

The insulating effect, or the difference in temperature between the control and the snow-free soil, differed between 1993 to 1994 (Fig. 6a) and 1994 to 1995 (Fig. 6b). In 1993 to 1994, snow insulated the soil against cooling until the ambient air temperature began to rise above 0°C in early April (Fig. 6a). At this point the insulating snow prevented the soil temperatures from warming as ambient air temperature increased. In 1994 to 1995 when snow was present, control soils were warmer than snow-free soils to a depth of 15 cm, but control and snow-free soils had similar temperatures in deeper soil (Fig. 6b). In fact, in many cases in 1994 to 1995, soil under snow was colder than soil in the snow-free plot.

Ambient Temperature and Soil Freezing

We ran regressions to determine the relationship between average winter ambient temperature and the number of days or winter where the average daily soil temperature was ≤0°C (Fig. 7). In the snow-free plot, there was a significant negative relationship between average ambient temperature and the number of days the soil was frozen at all three soil depths (Fig. 7a). In contrast, in the control plot there was no significant relationship between ambient temperature and the number of frozen soil days at any depth (Fig. 7b). This relationship in the control plot was strongly affected by the data from 1993 to 1994, when there was a deep layer of snow relative to the other three years. Insulation from this deep persistent snow layer resulted in average daily soil temperatures that were never <0°C. When we removed the data points from the winter of 1993 to 1994, ambient air temperature accounted for 83 to 98% of the variation in the number of frozen soil days (Fig. 7c). As with the snow-free plots, this relationship was significant and the correlation was negative at all three soil depths.

DISCUSSION

This investigation is useful because it is a complete time-series record of soil temperature over four winters. We examined the top 30 cm of soil to determine how air temperature and snow cover affect temperatures in the most biologically active portion of the mineral soil. This soil fraction holds much of the roots because the

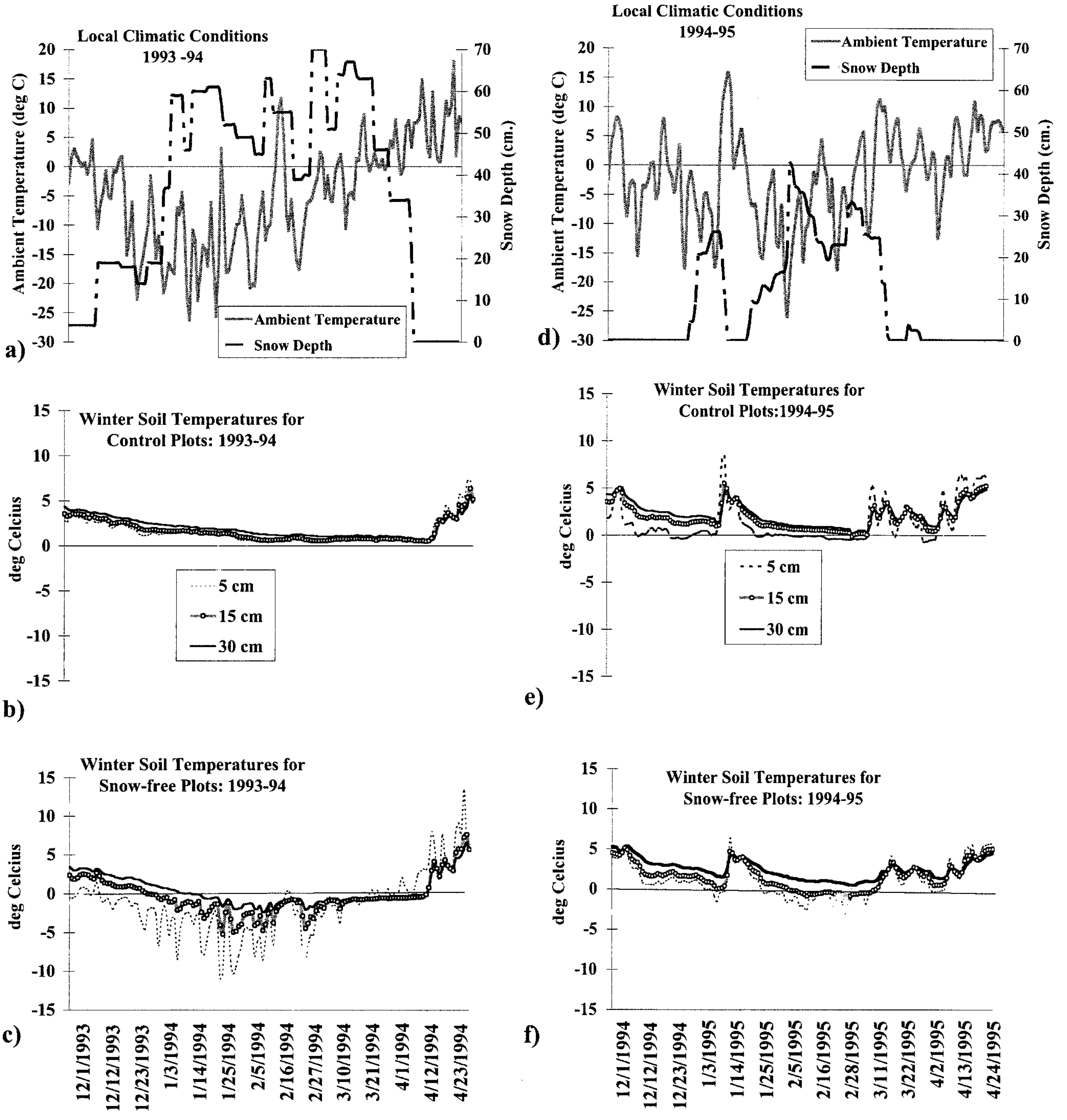

Fig. 5. Average daily values of local conditions and soil temperatures at three depths for a cold, snowy winter (a-c; 1993-1994) and a warm winter (d-f; 1994-1995) in a Vermont mixed-hardwood forest. Winters are defined as 1 December through 30 April.

fragipan layer inhibits root growth much beyond this zone (Allen 1973). In these top layers, much of the N transfers between soil, decomposing leaf litter, and soil organisms (such as fungi) occur (e.g., Frey et al., 2000).

The effect of air temperature on soil temperature declined rapidly with soil depth, but this depended strongly on the extent of snow cover. Within this forest, our results indicate that soil is as effective an insulator as snow against cold at the 30-cm soil depth unless the winter snow cover is both persistent and deep. In effect, soil at 30 cm is not additionally insulated by shallow or temporally patchy snow cover. Bertrand et al. (1994) found that a snow pack of 30 cm provided sufficient insulation to prevent root freezing and subsequent die-back in mature sugar maples. In contrast, shallower soil was strongly influenced by changes in air temperature, but this effect was clearly moderated by the presence of snow on the ground. These results are similar to others who found that persistent snow cover was an effective soil insulator in a Minnesota Bluegrass agro-

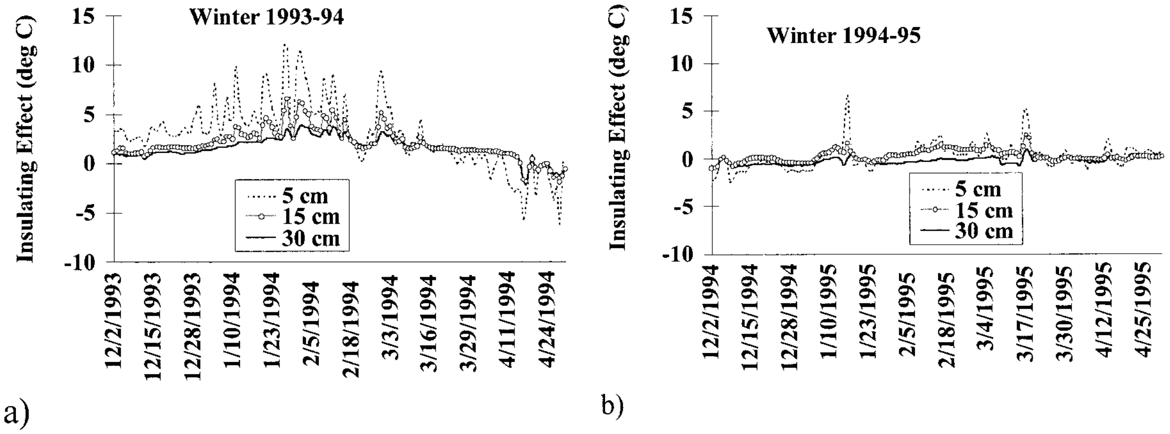

Fig. 6. Average daily difference in soil temperatures between control and snow-free plots at three soil depths for (a) a cold, snowy winter (1993-1994) and (b) a warm winter (1994-1995) in a Vermont mixed-hardwood forest. Shown is the insulation effect (= control soil temperature minus snow-free soil temperature). Winters are defined as 1 December through 30 April.

ecosystem (Baker, 1971), a montaine meadow (Brooks et al., 1998), and a northeastern hardwood forest (Hardy et al., 2001).

The greatest effect of snow removal occurred during the cold, snowy winter of 1993 to 1994. In the snow-free plot, average monthly soil temperatures were below 0°C to a depth of 30 cm for much of the season. In contrast, average monthly soil temperatures in the control plot were consistently above 0°C. The snow-free plot also experienced greater day-to-day variation in temperature and more daily freezes and thaws throughout the winter and than the control plot soils.

Whereas the thermal dynamics of the soil in the 1993 to 1994 snow-free plot are useful to understanding the effect of a reduction of snow without a corresponding increase in ambient temperature, the 1994 to 1995 results show the effect of a warm winter with and without snow removal. Winter of 1994 to 1995 is unique among the four years that we studied because snow cover on the ground was sporadic and shallow. Monthly soil temperatures were similar for the control and snow-free plots in 1994 to 1995 except in February, when there was the longest continuous incidence of snow. The other months had little snow cover, yet the average soil temperatures were as warm as the 1993 to 1994 controls. Although similar to the 1993 to 1994 controls on average, the day-to-day variation in soil temperature during 1994 to 1995 was approximately three to four times as high, despite a lower variability in daily ambient temperature. For these reasons, in 1994 to 1995, these soils were not well insulated against changes in ambient temperature. In contrast to 1993 to 1994, during this warmer winter control soils were more prone to freeze–thaw events throughout winter than snow-free soils.

Soil freezes can cause the break down of soil aggregates, root desiccation, and rapid release of nutrients from organic matter and subsequent leaching from the soil. For example, in a field experiment in a northeastern mixed-deciduous forest, Groffman et al. (2001b) found that a simulated early winter snow drought caused mild soil freezing throughout winter that resulted in increases in soil nitrate over controlled soils in sugar maple stands. Additionally, early season snow drought has been shown to increase mortality of fine roots in northern hardwood forests (Groffman et al., 1999; Tierney et al., 2001). Ron Vaz et al. (1994) found that soil freezing and freeze–thaw events increased P release in an organic-rich soil. Nutrient release before the end of winter dormancy of trees and soil microbes can result in leaching of nutrients and loss to the ecosystem through stream water. Additionally, if there is excessive fine-root damage because of soil freezing there will be a reduced ability of trees to take up nutrients during early spring, also resulting in nutrient loss to the forest. Fitzhugh et al. (2001) found an increase in both soil solution and subsequent export of C, N, and inorganic P in New Hampshire forest soils when early winter snow was removed. Brooks et al. (1998) found that nitrate export during snowmelt in a montaine meadow was significantly greater from soil under inconsistent snow cover (that caused winter soil freezing) than from under soil with persistent snow cover that prevented soil freezing.

Because deciduous hardwoods are dominant in our study site and become dormant in winter, an increase in the number of soil freezes and freeze–thaw events may cause rapid nutrient releases from organic matter at a time when overall forest demand is relatively low. This may further reduce the amount of nutrients available in spring for new growth. Therefore, a winter with many freezes and freeze–thaw cycles potentially causes nutrient losses from the ecosystem, a breakdown of soil aggregates, and a spring nutrient limitation (Lehrsch et al., 1991). Root desiccation, caused by an increase in soil freeze–thaw events, has also been linked to the incidence of sugar maple dieback through the triggered release of abscissic acid (Auclair et al., 1996).

CONCLUSIONS

If the current IPCC climate change predictions of an increase of average annual temperature preferentially in northern hemisphere winter months are accurate, the

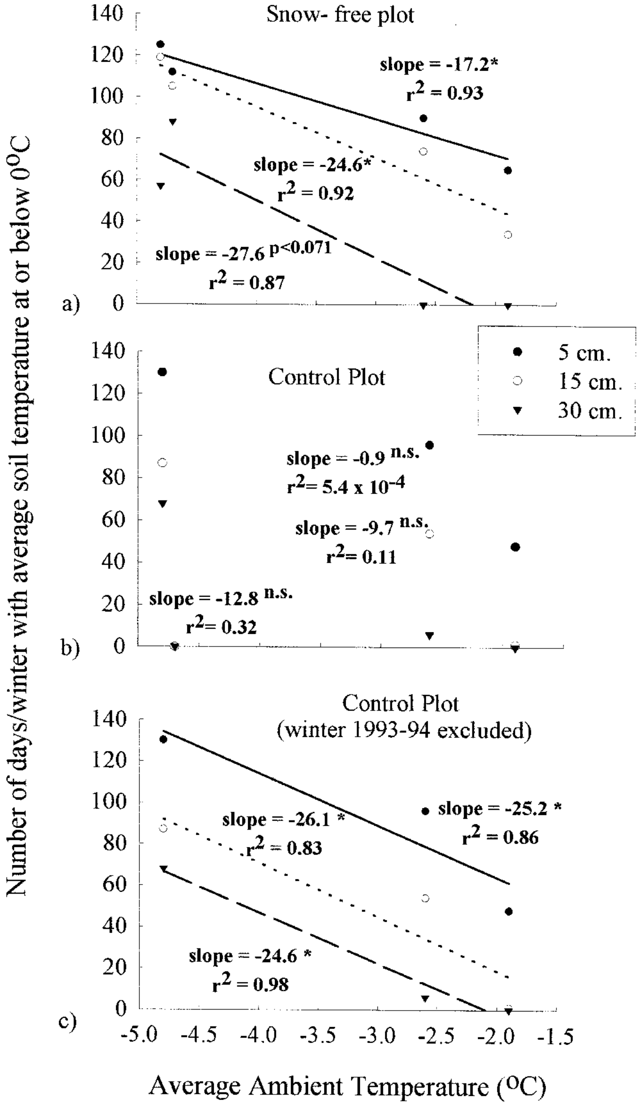

Fig. 7. Relationship between ambient air temperature and number of days/winter when the soil temperature is ≤0°C in a Vermont mixed-hardwood forest. Shown are regression lines for soil at three depths. Line slopes that are significant at $p < 0.05$ are indicated with a star (*), and those that are non-significant are indicated with a 'n.s'. Winters are defined as 1 December through 30 April.

incidence of cold, snowy winters like that of 1993 to 1994 will be increasingly rare, and warmer winters like that of 1994 to 1995 will become more common (Houghton et al., 2001; IPCC, 2001). This has a potential to temporally change the biogeochemistry in northeastern forests as a result of a change in the variability of soil temperature that occurs preferentially in the top 15 cm. With an increased potential for nutrient loss over winter (the period of plant dormancy) coupled with the breakdown of soil aggregates and an increase in root mortality, there may be an increase in nutrient losses via leaching in northern hardwood forest ecosystems. This may result in a nutrient limitation during the period of spring growth. Such a change could result in a decline in productivity of tree species with high nutrient demands in the spring and an increase in the mortality of the dominant (and economically important) sugar maple.

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