CHANGES IN CANOPY COVER ALTER SURFACE AIR AND FOREST FLOOR TEMPERATURE IN A HIGH-ELEVATION RED SPRUCE (*PICEA RUBENS* SARG.) FOREST

Johnny L. Boggs and Steven G. McNulty[1]

Abstract.—The objective of this study is to describe winter and summer surface air and forest floor temperature patterns and diurnal fluctuations in high-elevation red spruce (*Picea rubens* Sarg.) forests with different levels of canopy cover. In 1988, a series of 10- x 10-meter plots (control, low nitrogen [N] addition, and high nitrogen addition) were established on Mount Ascutney, VT, to examine the influence of N fertilization on red spruce and balsam fir (*Abies balsamea* Mill.) forest N cycling, tree mortality, and forest growth. As a result of N addition to the plots, species mortality has occurred on the low N and high N plots with the control plots experiencing very little mortality. Consequently, the mortality experienced on the low N and high N plots reduced forest cover and created both patchy and open forest canopies. In 2002, we installed temperature probes on the existing high-elevation red spruce to begin describing surface air (2 cm above ground) and forest floor temperature (~ 2 cm below ground) patterns under different levels of canopy cover. In June 2006 we established four new 10- x 10-meter red spruce plots, girdling 50 percent of the trees in two plots and 100 percent in the other two plots to further test surface air and forest floor temperature ranges under an altered forest canopy. Summer diurnal fluctuations in surface air temperature were highest on the high N plots (9.5 °C to 12.8 °C) during all years except 2007, where the 100 percent girdled plots had the highest summer diurnal value, 19.7 °C. Winter diurnal fluctuations in surface air temperature were lowest on the high N plots for all years. Summer diurnal fluctuations in forest floor temperature were highest on the high N plots for all years, while the winter diurnal fluctuations in forest floor temperature showed little variability between plots. Summer mean maximum, mean minimum, and mean surface air and forest floor temperatures were higher on the high N and/or 100-percent girdled plots in any given year. Summer mean maximum air temperature was highly related to percent canopy cover (r^2 = 0.94, p=0.006). As a result of direct solar radiation and the hot air that reaches and heats the ground surface through gaps and open canopies, 1- or 2-year-old red spruce seedlings might be negatively affected.

INTRODUCTION

The degree to which seasonal surface air and forest floor temperature changes under different levels of canopy shading in red spruce (*Picea rubens* Sarg.) forests has not been described. In this study, the Mount Ascutney, VT, red spruce plots that were established in 1988 provide an opportunity to report seasonal surface air and forest floor temperature across plots with different levels of forest cover and forest floor characteristics (McNulty et al. 2005). Gap areas and forest canopy cover structure and composition influence how surface air and forest floor temperature means, maximums, minimums, and diurnal fluctuations are moderated (Balisky and Burton 1995). Duff thickness and soil moisture content have been shown to be secondary in controlling soil temperature. Percent canopy cover is the primary control on soil temperature in high-elevation Engelmann spruce (*Picea engelmannii Parry ex. Engelm.*)-subalpine fir forests (Balisky and Burton 1995). Forest canopy cover also controls forest floor litter accumulation and input that may in turn control red spruce regeneration

[1] Biological Scientist (JLB) and Research Ecologist (SGM), U.S. Forest Service, Southern Global Change Program, 920 Main Campus Drive Suite 300, Raleigh, NC 27606. JLB is corresponding author: to contact, call (919) 513-2973 or email at jboggs@ncsu.edu.

and establishment by limiting the contact between seedling roots and available soil nutrients (Klein et al. 1991). Spruce is an important tree species for the wood products industry, especially in the Northeast, as well as an important habitat and food source for birds, porcupines, and other area wildlife (Hart 1959, McIntosh and Hurley 1964).

During the 1980s, high rates of spruce decline and mortality were observed across New England and the southern Appalachians (Bruck 1984, Nicholas et al. 1992, Aber et al. 1998), and over the past 20 years many papers have shown a direct link between experimentally applied nitrogen (N) and N saturation, and forest decline and mortality (Schaberg et al. 2002, Magill et al. 2004, McNulty et al. 2005). These forests have also shown a lack of red spruce seedling establishment after a disturbance, but there is evidence of increases in birch (*Betula* spp.) regeneration and density in red spruce forests that have significant gaps or open canopies (Perkins et al. 1988, Klein et al.1991). Other changes that can occur during and after forest mortality or disturbances include increases in sunlight at the forest floor due to a loss of canopy cover (Perkins et al. 1988), increases in the forest floor thickness (Klein et al. 1991), increases in nutrient loss through leaching and displacement (McNulty et al. 2005), and increases in soil temperature and decreases in soil moisture content (Balisky and Burton 1995). Nutrients are available for plant uptake only when there is enough moisture in the soil to bring them into solution, thus soil moisture is critically important in tree species regeneration, establishment, and growth.

Cloud immersion has been linked to maximizing photosynthetic carbon gains in spruce-fir forests (Reinhardt and Smith 2008), suggesting that changes in cloudy conditions due to loss of canopy cover and changes in climate may affect species productivity and sustainability over the long term. Increases in regional mean annual air temperature can also affect area red spruce forests by altering their species composition via upslope migration of lower elevation deciduous forests into higher-elevation conifer forests (Beckage et al. 2008). These increases in mean annual air temperature, coupled with canopy cover alterations or loss in forest canopy shading, may exacerbate or speed up the influence of surface air and forest floor temperature on soil moisture content and the rate at which deciduous and conifer species regenerate and establish in these forests. Temperature data in high-elevation red spruce forests that have experienced accelerated rates of mortality and decreased canopy shading are limited. Thus, the objective of this study is to report and describe changes in seasonal and yearly mean surface air and forest floor temperature in red spruce forests with varying degrees of canopy cover.

MATERIALS AND METHODS

In 1988, we established a series of 10- x 10-meter paired plots (two controls, low N addition, and high N addition) on Mount Ascutney to examine the influence of N inputs on red spruce and balsam fir (*Abies balsamea* Mill.) forest N cycling, tree mortality, and forest growth. (See McNulty and Aber 1993 for detailed methodology and site description.) The low N and high N plots have experienced tree species mortality while very little mortality has occurred on the control plots. Mortality on the low N and high N plots reduced forest cover, creating both patchy (60-percent cover) and open forest canopies (45-percent cover). Because of the variability in canopy cover, these plots provide a gradient of surface air, forest floor temperature characteristics, and light inputs. In 2002, we installed four temperature probes in a fan pattern on the existing high-elevation red spruce to begin describing surface air (2 cm above ground) and forest floor temperature (~ 2 cm below ground) patterns under different levels of canopy cover. In June 2006 we established and installed temperature sensors on four new 10- x 10-meter red spruce plots, girdling 50 percent (referred to as “girdled50”) of the trees in two paired plots and 100 percent (referred to as “girdled100”) in the other two paired plots to further test surface air and forest floor temperature ranges under an altered forest canopy. Canopy cover was estimated for each plot based on visual observations. Duff layers were estimated during sensor installation.

We used Hobo H8 outdoor 4-channel external temperature loggers (Onset Corporation, Bourne, MA) to measure surface air and forest floor temperature across the 10- x 10-meter plots. Temperature measurements were recorded continuously at 1-hour intervals and summarized as summer (defined as June, July, August) and winter (defined as December of the previous year, and January, February, March of the following year) mean maximums, mean minimums, means, and diurnal fluctuations on each plot. If temperature data values were missing due to battery or logger failure, we estimated the missing temperature values using a linear model that was developed between paired plots as long as the r^2 was at least 0.90 and $p < 0.001$. A model outside of these criteria was not used to estimate temperature data.

RESULTS

Estimates of canopy cover using visual observations varied across plots, ranging from 30 percent to 90 percent (Table 1). Estimates of the duff layers are based on field observations and are shown in Table 1.

Diurnal Fluctuation

Summer diurnal fluctuations in surface air temperature were highest on the high N plots (9.5 °C to 12.8 °C) during all years except 2007, where the 100-percent girdled plots had the highest summer diurnal value, 19.7 °C (Table 2). Winter diurnal fluctuations in surface air temperature were lowest on the high N and girdled plots, the plots with the lowest percent canopy cover. Summer diurnal fluctuations in forest floor temperature were highest on the high N plots for all years. Winter diurnal fluctuations in forest floor temperature showed little variability between plots (Table 2).

Mean Maximum Temperature

The pattern of summer mean maximum surface air temperature was similar to that for diurnal fluctuations, where the highest values occurred on the high N plots during all years except 2007; the 100-percent girdled plots had the highest mean maximum surface air temperature value, 32 °C (Fig. 1a). Winter mean maximum surface air temperature was lower on the low N plots during all years except 2003/04 (i.e., December 2003/January, February, March 2004) when compared to the other plots (Fig. 1b). Summer mean maximum forest floor temperature was always higher on the high N plots for all years (Fig. 1c). Winter mean maximum forest floor temperature was lower on the control plots than on the other plots (Fig. 1d).

Mean Minimum Temperature

Plots with the lowest summer mean minimum surface air temperature varied across years (Fig. 2a). Winter mean minimum surface air temperature was lowest on the low N plots during all years except 2003/04 when compared to the other plots (Fig. 2b). Summer mean minimum forest floor temperature was always lowest on the control plots, averaging 0.9 °C lower than the low N plots and 1.2 °C lower than the high N plots (Fig. 2c). Winter mean minimum forest floor temperature was always lower on the control plots than on the other plots (Fig. 2d).

Mean Temperature

Summer mean surface air temperature was highest on the high N plots during all years except 2007, where the 100-percent girdled plots had the highest mean surface air temperature value, 17.8 °C (fig. 3a). Winter mean surface air temperature was lowest on the low N plots during all years except 2003/04 when compared to the other plots (Fig. 3b). Summer mean forest floor temperature was always higher on the high N plots than on the other plots (Fig. 3c). Winter mean forest floor temperature was lower on control plots when compared to the other plots (Fig. 3d).

Table 1.—Characterization of canopy cover. Cover values are based on visual observations in a high-elevation red spruce forest, Mount Ascutney, VT. The 2007 data are also shown for the girdled plots because the treatment (girdled in 2006) did not take effect until 2007. Estimates of the duff layers are also shown.

		Estimated canopy cover[a] (%)	
Plots	Duff layer[b] (cm)	2006	2007
Control	10	75	na
LowN	5	60	na
HighN	5	45	na
Girdled50	10	90	65
Girdled100	10	80	30

[a] Canopy cover was estimated for each plot based on visual observations. All the trees that were girdled did not die, thus, there is some canopy cover on the girdled100 plots.

[b] Approximately 50% of HighN plot surface has exposed organic soil, patchy duff layer.

Table 2.—Summer and winter mean diurnal fluctuations in original control and N addition plots and new girdled plots in a high-elevation red spruce forest, Mount Ascutney, VT. Summer defined as June, July, and August and winter defined as December of previous year and January, February, and March of following year. na = not available.

		Surface air temperature (°C)					Forest floor temperature (°C)				
Season	[a]Year	Control	LowN	HighN	Girdled 50	Girdled 100	Control	LowN	HighN	Girdled 50	Girdled 100
Summer	2002	7.9	9.5	12.3	na	na	105	1.2	1.6	na	na
Summer	2003	7.7	9.6	9.9	na	na	1.2	1.3	1.6	na	na
Summer	2004	7.3	9.4	9.5	na	na	1.3	1.4	1.6	na	na
Summer	2005	7.3	10.4	11.9	na	na	1.3	1.6	1.8	na	na
Summer	2006	6.8	11.7	10.7	6.0	6.3	3.4	4.1	4.8	2.4	2.1
Summer	2007	7.7	12.8	12.8	9.4	19.7	4.2	4.6	5.9	3.3	4.7
Winter	2003/04	2.5	2.8	0.8	na	na	0.3	0.2	0.1	na	na
Winter	2004/05	1.8	1.2	0.2	na	na	0.5	0.1	0.1	na	na
Winter	2005/06	4.2	4.2	3.0	na	na	0.5	0.1	0.2	na	na
Winter	2006/07	3.6	2.9	2.1	3.2	1.8	1.1	0.4	0.6	0.5	0.5

[a] Data for 2002 is for August only.

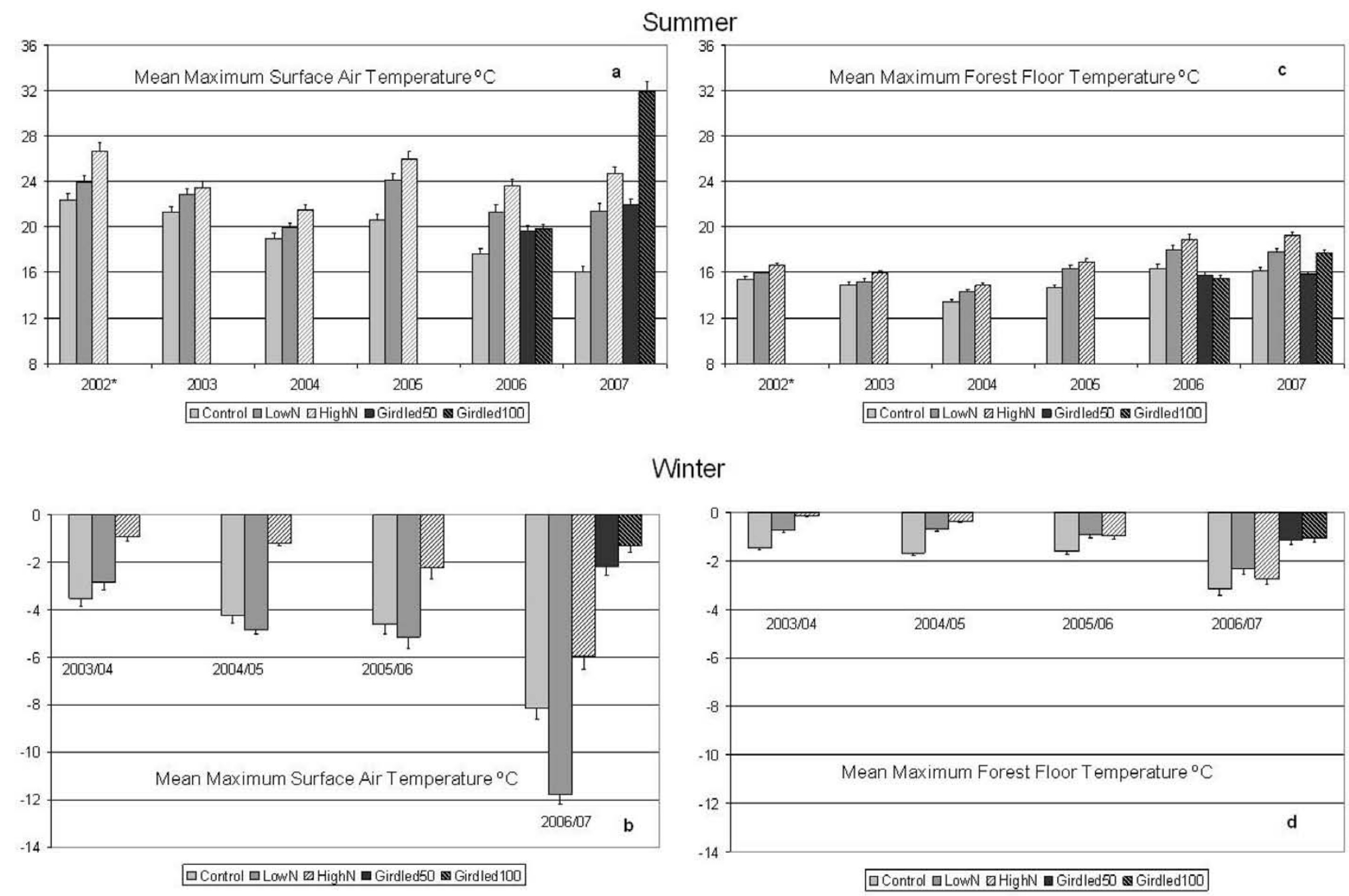

Figure 1.—Summer and winter mean **maximum** surface air and forest floor temperature in original control and N addition plots and new girdled plots in a high-elevation red spruce forest, Mount Ascutney, VT. Summer defined as June, July, and August and winter defined as December of previous year and January, February, and March of following year. *August 2002 only.

DISCUSSION

Summer and Winter Mean Maximum Temperature

We found the largest difference in summer mean maximum air temperature occurred in 2007 between the control and girdled100 plots, 15.8 °C. The largest difference in summer mean maximum forest floor temperature occurred in 2006 between the control and high N plots, 3 °C, suggesting that forest floor characteristics are moderating the effects of reduced canopy cover on summer mean maximum forest floor temperature by minimizing wide fluctuations. Research by Balisky and Burton (1995) found a 7- to 8- °C difference in daily mean maximum soil temperature when comparing the temperature in bare soil areas (no canopy cover) to areas covered with vegetation ranging from herbaceous to conifer trees 5 meters in height. Our summer mean maximum surface air and forest floor temperature patterns were fairly consistent across plots in that those with the lowest percent canopy cover (i.e., high N and girdled100) had the highest summer mean maximum surface air and forest floor temperatures during any year (Figs. 1a and 1c). The winter mean maximum surface air and forest floor temperatures were also consistent across plots, with the highest percent canopy cover generally having the lowest mean maximum surface air and forest floor temperatures in any given year (Figs. 1b and 1d).

Mean maximum temperatures are controlled by several factors including canopy cover, duff thickness, soil moisture, topographic shade, seasonal variations, air temperature, and other climatic and soil variables (Bonan 1991, Friedland et al. 2003, Rutherford et al. 2004). Solar radiation, air

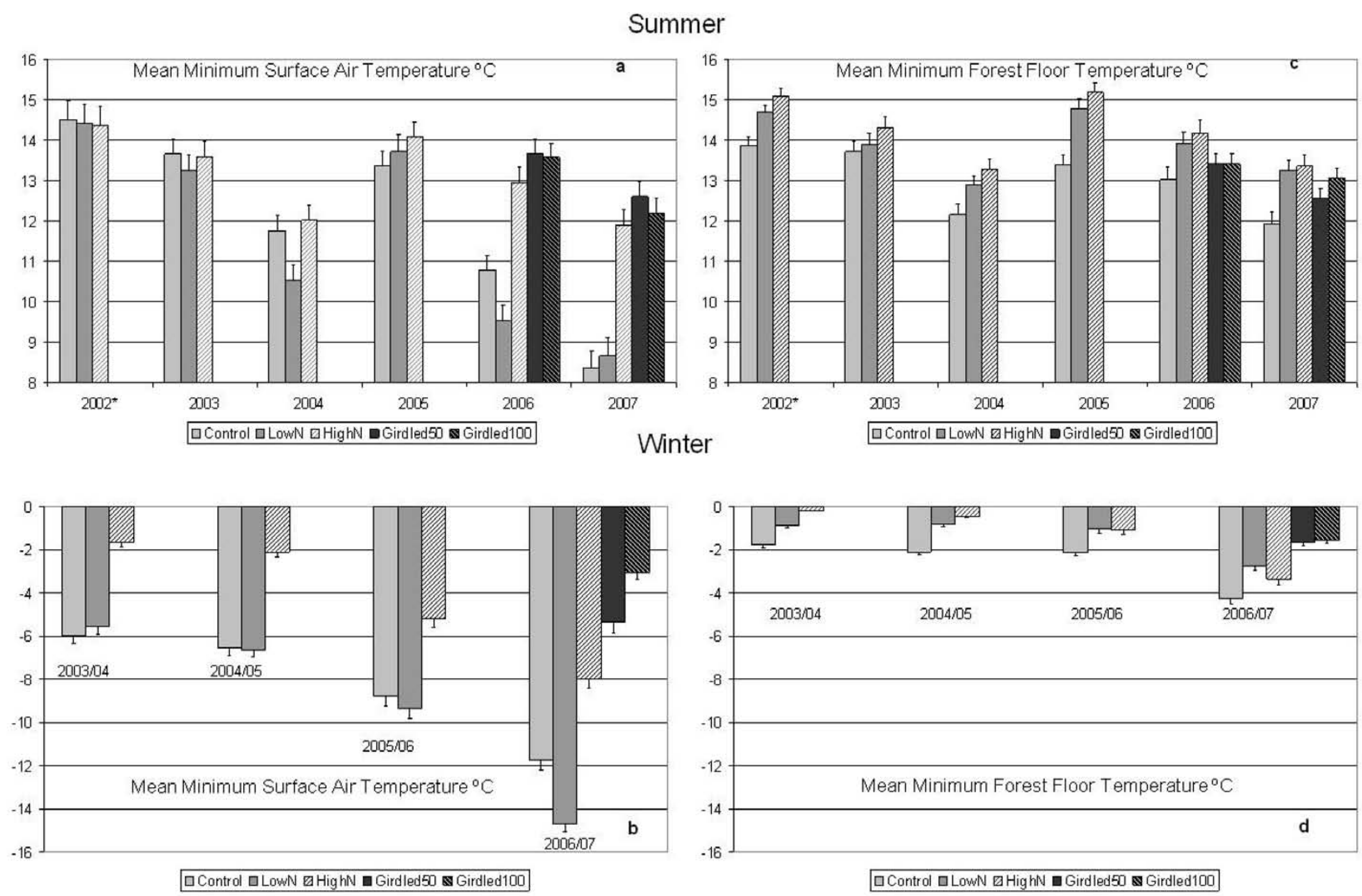

Figure 2.—Summer and winter mean **minimum** surface air and forest floor temperature in original control and N addition plots and new girdled plots in a high-elevation red spruce forest, Mount Ascutney, VT. Summer defined as June, July, and August and winter defined as December of previous year and January, February, and March of following year. *August 2002 only.

temperature, and topographic shape across the plots on Mount Ascutney were similar with some spatial microclimate and microsite differences (Geiger 1965). Our linear regression model suggests percent canopy cover is the principle control on summer mean maximum surface air temperature across all plots ($r^2 = 0.94$, $p = 0.006$); that is, components of the forest canopy structure are causing increases or decreases in summer mean maximum surface air temperature (Fig. 4a). In contrast, a mixture of canopy cover and non-canopy cover attributes (i.e., forest floor moisture and/or duff thickness) is probably controlling summer mean maximum forest floor temperature across plots as the relationship between percent canopy cover and summer mean maximum forest floor temperature ($r^2 = 0.33$, $p = 0.30$) is less connected than what was found between percent canopy cover and summer mean maximum surface air temperature (Figs. 4a and 4b).

Further evidence suggests that forest floor characteristics such as duff thickness and soil moisture are helping to moderate the effects of percent canopy cover on summer mean maximum forest floor temperature. For example, in 2007 the summer mean maximum surface air temperature was highest on the girdled100 plots, reaching 32 °C and accompanied by a summer mean maximum forest floor temperature of 18 °C (Figs. 1a and 1c). The high N plots had a summer mean maximum surface air temperature of only 25 °C and a summer mean maximum forest floor temperature of 19 °C (Figs. 1a and 1c). Although the girdled100 plots had a significantly higher summer mean maximum surface air temperature when compared to the high N plots, their summer mean maximum forest floor temperature was lower by 1 °C. The high N plots had a sparse intact duff layer and exposed organic soil, indicating the potential for high heat capacity and thermal conductivity.

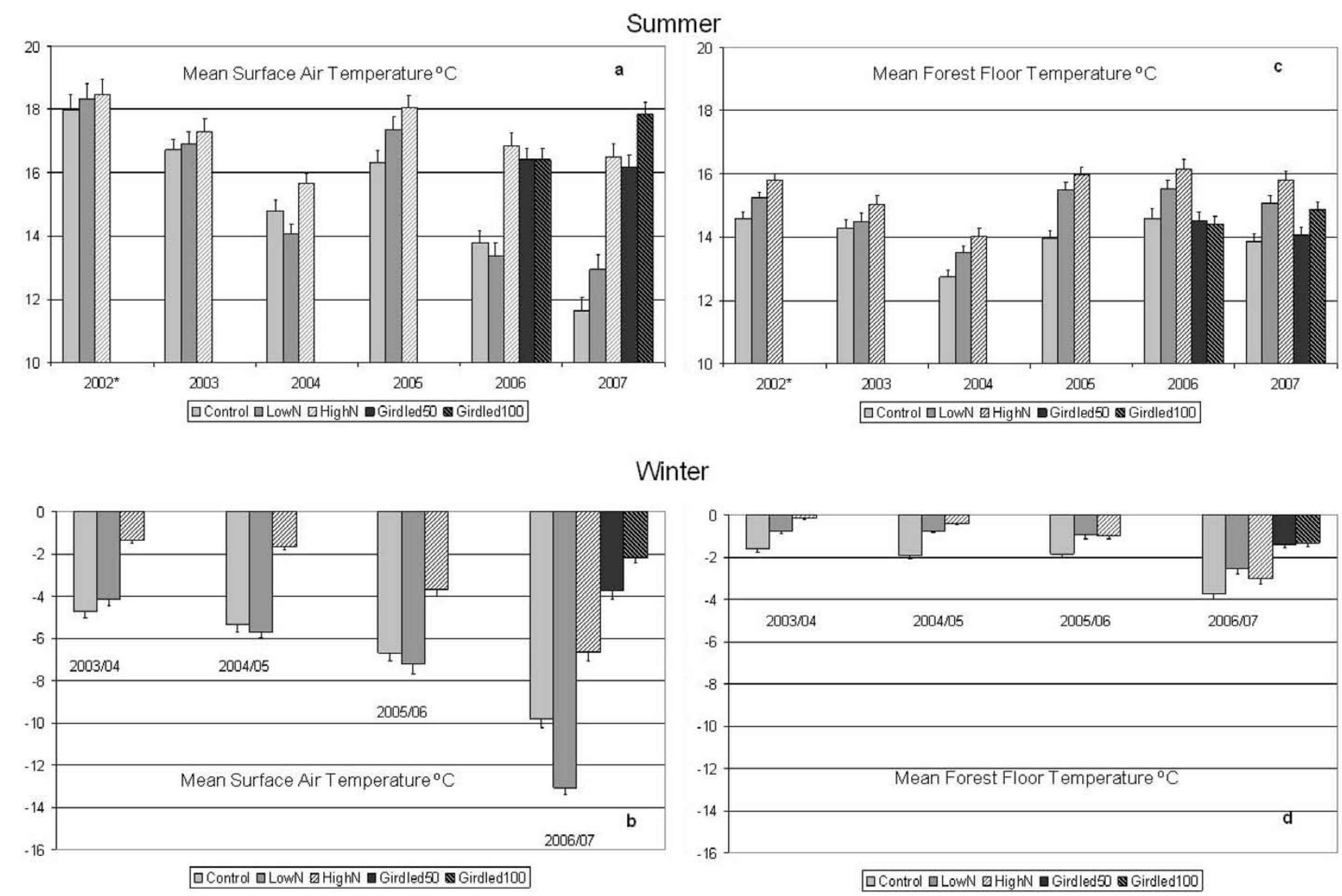

Figure 3.—Summer and winter mean surface air and forest floor temperature in original control and N addition plots and new girdled plots in a high-elevation red spruce forest, Mount Ascutney, VT. Summer defined as June, July, and August and winter defined as December of previous year and January, February, and March of following year. *August 2002 only.

Summer and Winter Mean Minimum Temperature

The summer mean minimum forest floor temperature in all years was higher than the summer mean minimum surface air temperature (Figs. 2a and 2c). This summer pattern in mean minimum temperatures was not surprising because the forest floor, having warmed up from the sun during the day, cools slower during the night than the surface air, resulting in slightly higher mean minimum temperatures.

Shading from the canopy cover had an effect on both winter surface air and forest floor temperature, with cooler temperatures occurring in the surface air (Fig. 2b) when compared to the forest floor (Fig. 2d). Forest floor temperature values were lower because components of the forest floor are buffering against the effects of extreme winter temperatures. Low soil temperature and winter temperature conditions have been studied to determine their relative role in species regeneration and establishment (Butt 1990, Friedland et al. 2003). Friedland and others (2003) and Vostral and others (2002) indicated that the lack of species establishment at higher elevations on Mount Ascutney is not due to winter temperature conditions but was maybe due to summer temperature controls. Summer soil temperatures ranging from 10 °C to 12 °C have been found to reduce conifer seedlings' growth potential (Vapaavuori et al. 1992). Our lowest summer mean minimum forest floor temperature occurred in 2007 on the control plots, 11.9 °C.

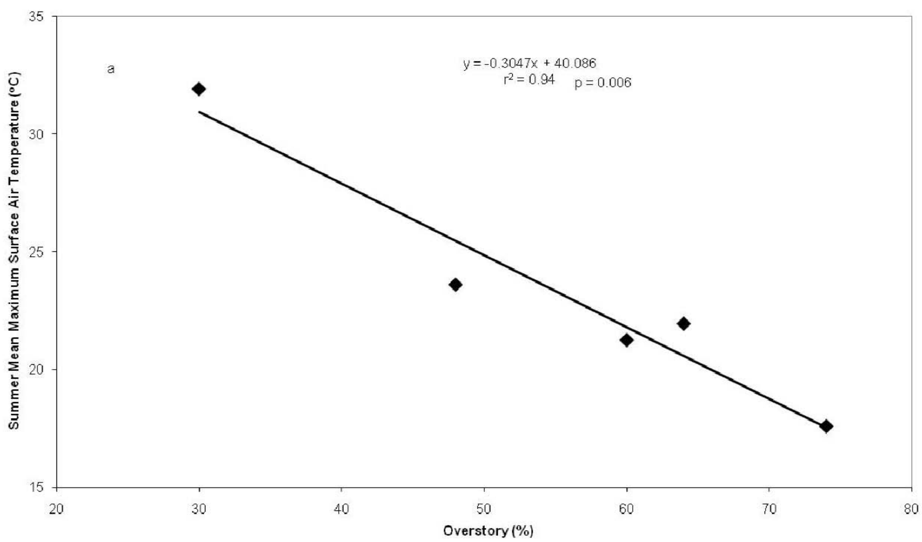

Figure 4a.—Regression analysis between estimated percent canopy cover and summer mean maximum surface air temperature across the original and girdled plots.

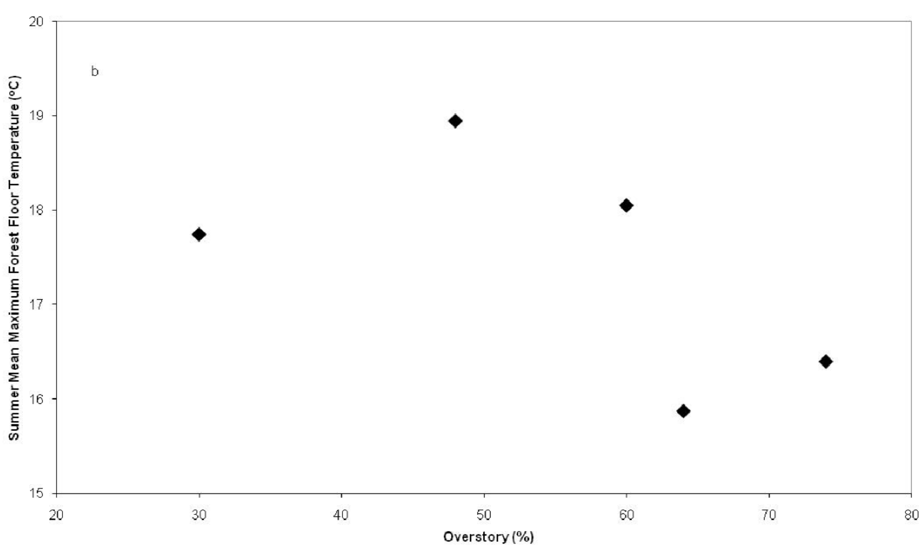

Figure 4b.—Relationship between estimated percent canopy cover and summer mean maximum forest floor temperature across the original and girdled plots.

Summer and Winter Mean Temperature

Our results showed that there were significant differences in summer mean surface air and forest floor temperature as a consequence of reduced levels of shade caused by species mortality on the original plots and tree canopy manipulation on the girdled plots (Figs. 3a and 3c). The most significant differences in the summer mean surface air temperature occurred between the control and girdled100 plots, with a difference of 5.5 °C in 2007. Summer mean forest floor temperature followed a similar pattern as the summer mean maximum forest floor temperature. The forest floor temperature on the high N plots was significantly higher than on the other plots. Plausible explanations for the summer mean air and forest floor temperature patterns are the same as outlined under the summer and winter mean maximum temperature section above.

CONCLUSIONS

Our results indicate that reductions in canopy cover in red spruce forests alter surface air and forest floor temperatures. However, surface air and forest floor temperatures respond differently to air temperature and radiation inputs. For example, our regression model showed that the relationship between percent canopy cover and summer mean maximum surface air temperature was more coupled than percent canopy cover and summer mean maximum forest floor temperature. This finding suggests that summer mean maximum forest floor temperatures were buffered by factors such as soil moisture content and duff thickness. In the long term, gaps in the forest canopy caused by species mortality may affect red spruce regeneration and establishment as seeds can be permanently damaged when exposed to temperatures higher than 33 °C (Hart 1965). A more detailed assessment of canopy cover using the fisheye method to estimate canopy openness may refine the relationship between canopy cover and temperature patterns. In addition, measurements of soil moisture regimes and microsite characteristics across our plots may help to explain how forest floor conditions are moderating canopy cover effects.

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