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# Changes in microclimate induced by experimental warming and clipping in tallgrass prairie

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## Abstract

**In order to facilitate interpretation and comparison of warming effects on ecosystems across various habitats, it is imperative to quantify changes in microclimate induced by warming facilities. This paper reports observed changes in air temperature, soil temperature and soil-moisture content under experimental warming and clipping in a tallgrass prairie in the Great Plains, USA. We used a factorial design with warming as the primary factor nested with clipping as the secondary factor. Infrared heater was used in order to simulate climatic warming and clipping to mimic mowing for hay or grazing. The warming treatment significantly increased daily mean and minimum air temperatures by 1.1 and 2.3 °C, respectively, but had no effect on daily maximum air temperature, resulting in reduced diurnal air-temperature range. Infrared heaters substantially increased daily maximum (2.5 and 3.5 °C), mean (2.0 and 2.6 °C) and minimum (1.8 and 2.1 °C) soil temperatures in both the unclipped and clipped subplots. Clipping also significantly increased daily maximum (3.4 and 4.3 °C) and mean (0.6 and 1.2 °C) soil temperatures, but decreased daily minimum soil temperature (1.0 and 0.6 °C in the control and warmed plots, respectively). Daily maximum, mean and minimum soil temperatures in the clipped, warmed subplots were 6.8, 3.2 and 1.1 °C higher than those in the unclipped, control subplots. Infrared heaters caused a reduction of 11.0% in soil moisture in the clipped subplots, but not in the unclipped subplots. Clipping reduced soil-moisture content by 17.7 and 22.7% in the control and warmed plots, respectively. Experimental warming and clipping interacted to exacerbate soil-moisture loss (26.7%). Overall, infrared heaters simulated climate warming well by enhancing downward infrared radiation and by reducing the diurnal air-temperature range.**

*Keywords:* climate warming, clipping, infrared heater, soil moisture, solar radiation, tallgrass prairie, temperature, vapour-pressure deficit, wind speed

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## Introduction

Climate warming has increased global mean temperature by about 0.6 °C over the past century and will continue to increase it by 1.4–5.8 °C in the 21st century (Houghton *et al.*, 1995, 1996; IPCC, 2001). Substantial efforts have been made in order to study the potential impacts of climate warming on terrestrial ecosystems by manipulating temperature in the field with a variety of warming facilities. Those facilities include: (1) greenhouses (GHs) and open-top chambers (OTCs) (Chapin & Shaver 1985; Havström *et al.*, 1993; Oechel *et al.*, 1998; Richardson *et al.*, 2000), (2) soil-heating pipes/wires–such as buried fluid pipes (Rykbost *et al.*, 1975a, b; Chapin & Bloom, 1976), buried electric-resistance wires (Van Cleve *et al.*, 1990; Peterjohn *et al.*, 1993; Bergh & Linder, 1999) and above-ground electric-resistance wires (Hillier *et al.*, 1994), (3) infrared reflectors (Zeiher *et al.*, 1994; Luxmoore *et al.*, 1998) and (4) infrared heaters (Harte *et al.*, 1995; Nijs *et al.*, 1996; Bridgham *et al.*, 1999). It has not been carefully examined, however, how effectively these facilities simulate patterns of climate warming that are occurring in the real world. The patterns revealed by historical records and predicted by General Circulation Models (GCMs) include: (1) greater warming in winter than in summer, (2) a greater increase in daily minimum than maximum air temperature, leading to a reduction in the diurnal

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temperature range and (3) decreased soil moisture in summer in midlatitude regions (Mitchell *et al.*, 1990; Maxwell, 1992; King, 1994; Smith *et al.*, 1996; Houghton, 1997; IPCC, 2001).

In order to evaluate the effectiveness of warming facilities, we need to compare microclimatic parameters (e.g. air temperature, soil temperature and soil moisture) in experimental plots with those predicted for climate warming. Climate warming happens by enhancing downward infrared radiation, which is dissipated through one or a combination of three major energy pathways: sensible heat, latent heat and soil heat fluxes. The three energy pathways are responsible for warming of the air, increases in evapotranspiration and heating of the soil (Shaver *et al.*, 2000). Depending on their heating mechanisms, various warming facilities may have different effects on the three microclimatic parameters. Quantification of microclimate changes will not only help compare various warming facilities but also facilitate interpretation and comparison of warming effects on ecosystems across various habitats (Shaver *et al.*, 2000; Rustad *et al.*, 2001).

Among the above warming facilities, infrared heaters most closely simulate processes of climate warming by enhancing downward infrared radiation (Harte & Shaw, 1995). Changes in soil temperature and soil moisture under infrared heaters have been reported in a Rocky Mountain subalpine meadow in Colorado (Harte *et al.*, 1995) and in Minnesota wetlands, USA (Bridgham *et al.*, 1999). However, air temperatures have not been described for these sites, leaving a possibility for speculation that infrared heaters may warm the surface of plants and soils, but not the surrounding air (Schulze *et al.*, 1999; Shen & Harte, 2000). Actually, air temperature manipulated with infrared heaters was once reported to increase in Eschikon, Switzerland (Nijs *et al.*, 1996). Unfortunately, this experiment only lasted for 3 weeks and was largely neglected. In addition, it has not been reported in the literature how the heaters or other facilities affect daily maximum and minimum air/soil temperatures. Daily maximum and minimum temperatures are important parameters for evaluation of warming facilities relative to the patterns of climate warming.

As a concurrent phenomenon of climate warming, human-caused land-use/cover change can alter regional and global budgets of energy and water fluxes through changes in vegetation coverage and albedo of the earth's surface (Walker *et al.*, 1999). Reduced vegetation coverage through mowing or grazing may change the boundary layer near the soil surface, increase energy absorbed and emitted by the soil and amplify the diurnal soil-temperature range. Plant removal can have opposite effects on evaporation (positive) and transpiration (negative), resulting in an unpredictable net effect on soil moisture (Dahlgren & Driscoll, 1994). Climate warming and land-use/cover change may play an interactive role in affecting microclimate (Vitousek, 1992; Shaver *et al.*, 2000).

This study was designed in order to characterize changes in microclimate under experimental warming and clipping. It is a part of a comprehensive warming experiment in a tallgrass prairie in the Great Plains, USA, where we used infrared heaters in order to mimic climate warming and clipping for simulating mowing for hay, which is a wide land-use practice in tallgrass prairie in the Great Plains, USA (Luo *et al.*, 2001). Specific objectives are to evaluate: (1) effectiveness of infrared heaters in altering air and soil temperatures and soil moisture, (2) differences between observed microclimate changes achieved with infrared heaters and climatic warming patterns predicted by GCMs, (3) interactions of experimental warming with clipping in terms of microclimate changes in tallgrass prairie and (4) roles of environmental factors in affecting the responses of air and soil temperatures.

## Materials and methods

### *Experimental site, design and warming facility*

The experimental site is located at the Great Plain Apiaries (34°58′54″N, 97°31′14″W), 25 miles from the Norman campus of the University of Oklahoma. This site has not been grazed for the past 20 years. The grassland is dominated by C4 grasses – *Schizachyrium scoparium*, *Sorghastrum nutans* and *Eragrostis* spp. – and C3 forbs – *Ambrosia psilostachyia* and *Xanthocephalum texanum*. Mean annual temperature is 16.0 °C with monthly mean temperature of 3.1 °C in January and 28.0 °C in July. The annual precipitation is 967.2 mm (average values from 1948 to 1999, data from Oklahoma Climatological Survey).

The experiment uses a paired factorial design with warming as the main factor nested with clipping. There are five pairs of 2 × 2 m plots. In each pair, one plot has been warmed continuously using infrared heaters since 21 November 1999 and the other is the control. One 165 × 15 cm infrared heater (Kalglo Electronics Inc, Bethlehem, Pennsylvania, USA) has a radiation output of about 100 watts $m^{-2}$ and is suspended 1.5 m above the ground in each warmed plot. In the control plot, one 'dummy' heater with the same shape and size as the infrared heater is suspended 1.5 m high in order to simulate the shading effects of the heater. For each paired plot, the distance between the control and the warmed plot is approximately 5 m in order to avoid heating the control plot by infrared heater. The distances between the individual sets of paired plots vary from 20 to 60 m.

Each 2 × 2 m plot is divided into four 1 × 1 m subplots. Two diagonal subplots in each plot were clipped 10 cm above the ground on 15 November 1999 and 28 July 2000; the other two are the unclipped controls. Clipping removed about 85% of the above-ground biomass (unpublished data). After clipping, plants were allowed to grow until next clipping. The four treatments in the experiment are unclipped control (UC), unclipped warmed (UW), clipped control (CC) and clipped warmed (CW).

### *Air- and soil-temperature measurements*

At the centre of each plot, a T-type thermocouple was used in order to monitor air temperature at the height of 25 cm above the ground, thus only the effect of warming on air temperature was considered. Thermocouples were sheltered using perforated polyvinyl chloride (PVC) tubes with open ends (15 cm in length, 5 cm in diameter). The PVC tubes were horizontally fastened on wood stacks. Thermocouples were put into the PVC tubes through a small hole at the middle part and positioned, so they would not touch the wall of the PVC tubes. This design avoids the direct heating effect of upward and downward radiation on the sensor and keeps the air immediately surrounding the sensor at the same temperature level with the canopy air inside the plots.

At the centers of each clipped subplot and each unclipped subplot, thermocouples were used in order to measure soil temperature at the depth of 2.5 cm. All the thermocouples were connected to a CR10 datalogger (Campbell Scientific Inc., Utah, USA). Air and soil temperatures were measured every 10 minutes, and then averages within 1 h were stored in an SM196 Storage Module. Daily maximum and minimum values for air and soil temperatures and the times at which they occurred were also recorded.

On 29 December 1999, soil temperatures at three depths (0, 5 and 10 cm) were measured using a 51 K/J thermometer (Fluke Co., Everett, Washington, USA) in all subplots of paired plots 2 and 3. On 4 January 2000, the spatial pattern of surface-soil temperature was measured on a 30-cm grid in paired plots 2, 3 and 4 using a Dew Point Microvoltmeter (Wescor Inc., Utah, USA).

### *Soil-moisture measurement*

Soil-moisture content was measured gravimetrically twice a month. Soil samples at the top 5 cm were taken from one clipped and one unclipped subplots in each plot and oven-dried at 105 °C for 24 h and weighed. Soil moisture was expressed as a percent of dry soil on a mass basis.

### *Statistical analysis*

All the temperature and soil moisture data in this paper were collected from the experimental plots within the first year (1 December 1999–30 November 2000) of the warming study. Solar radiation, wind speed and vapour-pressure deficit (VPD) data were derived from a MESONET station 500 m north of our experimental site (Oklahoma Climatological Survey). Statistical significance of warming and clipping treatments was evaluated by analysis of variance (ANOVA). In order to test the spatial evenness of soil-surface temperature, we applied a two-way ANOVA using $x$ and $y$ coordinates as main effects. Multiple regression analysis was used in order to analyse the relationships of changes in air and soil temperature as well as their diurnal ranges with solar radiation, wind speed, VPD and soil moisture. All significant factors were selected into models using a stepwise method. Path coefficients were calculated in order to compare the relative importance of various factors in affecting the response of air and soil temperatures. All the statistical analyses were performed using SAS (SAS Institute Inc. 1989–96, North Carolina, USA).

## Results and discussions

### *Air temperature*

Warming effects of infrared heaters on air temperature were greater at night than during the daytime. Hourly air temperature increased by nearly 2 °C at midnight in the warmed plots, but there was essentially no increase as a result of warming at noon (Fig. 1). Experimental warming enhanced daily mean air temperature more in summer than in winter (Figs 2a, b). Measured daily mean air temperature in the warmed plots was, over the experimental period of 1 year, 1.1 °C higher than that in the control plots (Table 1).

Daily minimum air temperature in the warmed plots significantly increased by 2.3 °C compared to that in the control plots (Fig. 2b, Table 1). Experimental warming had no significant effect on daily maximum air temperature in the warmed plots in comparison with that in the control plots. The differential responses of daily maximum and minimum air temperatures to the infrared heaters resulted in a reduction in the diurnal air-temperature range (the difference between daily maximum and minimum temperatures). The diurnal air-temperature range in the warmed plots decreased by 2.2 °C ($P < 0.001$) compared to that in the control plots (Fig. 2d).

The effects of environmental factors – solar radiation, VPD and wind speed – on the responses of air temperature to experimental warming varied with various temporal scales. Multiple regression analysis showed that wind speed (WS, $\mathrm{m\,s^{-1}}$), solar radiation (SR, $\mathrm{J\,m^{-2}\,s^{-1}}$) and VPD (kPa) had significant effects on the hourly values of heater-induced increments in air temperature ($\Delta T_{\text{hourly} \quad \text{air}} = 2.5883 - 2.2405\,\mathrm{WS} - 0.00227\,\mathrm{SR} + 1.0219$ VPD, $r^2 = 0.957$, $p < 0.0001$) with path coefficients of

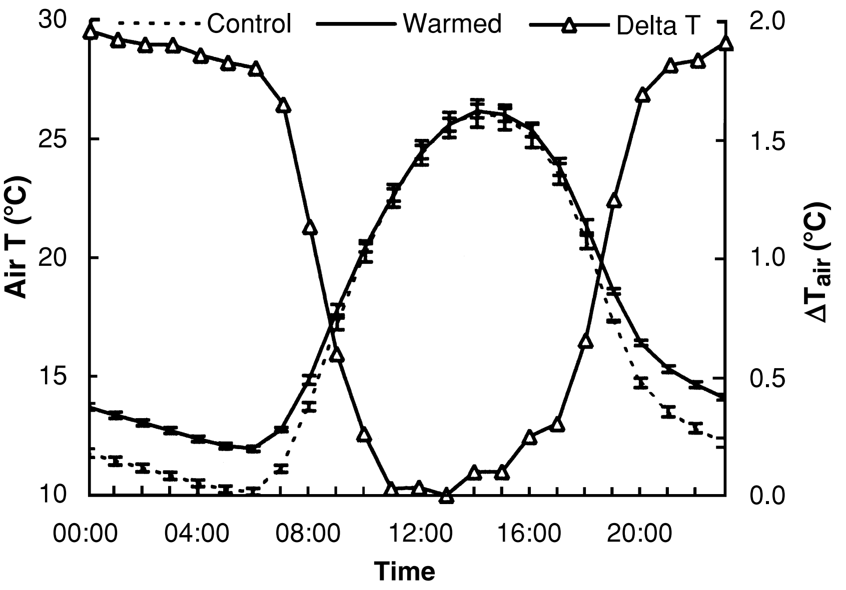

**Fig. 1** Hourly values of air temperature (mean ± 1SE) in and the difference between the control and warmed plots. Each value is the annual average from 1 December 1999 to 30 November 2000.

**Table 1** Annual averages of air and soil temperatures and their increases (°C)

| | Maximum | Mean | Minimum |
|---|---|---|---|
| **Air temperature** | | | |
| Control | 28.2(1.48) | 16.8(0.27) | 7.7(0.40) |
| Warming | 28.3(0.75) | 17.9(0.24) | 10.0(0.28) |
| Difference | 0.1[0.0978] | 1.1[0.0002] | 2.3[0.0004] |
| **Soil temperature** | | | |
| Unclipped control | 20.8(1.33) | 17.3(0.29) | 14.7(0.35) |
| Unclipped warming | 23.3(1.97) | 19.3(0.55) | 16.5(0.37) |
| Clipped control | 24.2(1.14) | 17.9(0.33) | 13.8(0.23) |
| Clipped warming | 27.6(1.25) | 20.5(0.28) | 15.9(0.21) |
| UW − UC | 2.5[0.0804] | 2.0[0.0009] | 1.8[0.0028] |
| CW − CC | 3.5[0.0027] | 2.6[0.0002] | 2.1[0.0000] |
| CC − UC | 3.4[0.0240] | 0.6[0.0353] | −1.0[0.0181] |
| CW − UW | 4.3[0.0049] | 1.2[0.0166] | −0.6[0.0082] |
| CW − UC | 6.8[0.0033] | 3.2[0.0002] | 1.1[0.0026] |

Notes: UW − UC = Unclipped warmed minus unclipped control, CW − CC = Clipped warmed minus clipped control, CC − UC = Clipped control minus unclipped control, CW − UW = Clipped Clipped minus unclipped warmed, CW − UC = Clipped warmed minus unclipped control. Values in parentheses are standard deviations, $n = 5$; values in brackets are significance levels of ANOVA.

−0.7508, −0.7048 and 0.6906, respectively. Increases in daily mean air temperature were primarily affected by wind speed with a path coefficient equaling −0.6406 (Figs 3a, b), then by daily mean VPD (path coefficient = 0.3004), and daily total solar radiation (path coefficient = 0.1346), yielding $\Delta T_{\text{daily air}} = 1.7008 - 1.1720\,\text{WS} - 0.2627\,\text{VPD} + 0.0000399\,\text{SR}$, $r^2 = 0.646$, $p < 0.0001$. Increases in monthly mean air temperature were under the influence of wind speed (path coefficient = −0.5914) and VPD (path coefficient = 0.4387), but not solar radiation ($\Delta T_{\text{monthly air}} = 2.4980 - 1.9124\,\text{WS} + 0.2998\,\text{VPD}$, $r^2 = 0.8690$, $p < 0.0001$) (Fig. 3c).

The reduced diurnal air-temperature ranges caused by infrared heaters are consistent with the effects of climate warming predicted by GCMs. A likely explanation for the reduced diurnal temperature range under climate warming is increases in cloud cover, which tend to obstruct daytime sunshine and to reduce the escape of terrestrial radiation at night (Houghton, 1997; IPCC, 2001). At the plot scale in our experimental site, the reduction in the diurnal temperature range is probably related to wind speed, VPD and the relative contributions of infrared radiation from heaters to the total energy flux. Wind blows the energy from infrared heaters away from the warmed plots, resulting in a less increase in air temperature. When VPD is higher, more energy from the heaters is converted to sensible heat, resulting in a greater air-temperature increase. During the daytime, the added energy from infrared heaters is small relative to the total energy fluxes, causing little increases in daily maximum air temperature. At night, the additional energy from the heater accounts for a large fraction of the total energy flux, leading to a large increase in daily minimum air temperature.

Infrared heaters in our experimental plots amplified the seasonal variation in daily means air temperature, whereas GCMs predict the opposite (Walker *et al.*, 1999). In Oklahoma, wind speed is greater in winter than in summer, resulting in a reduced effect on air temperature

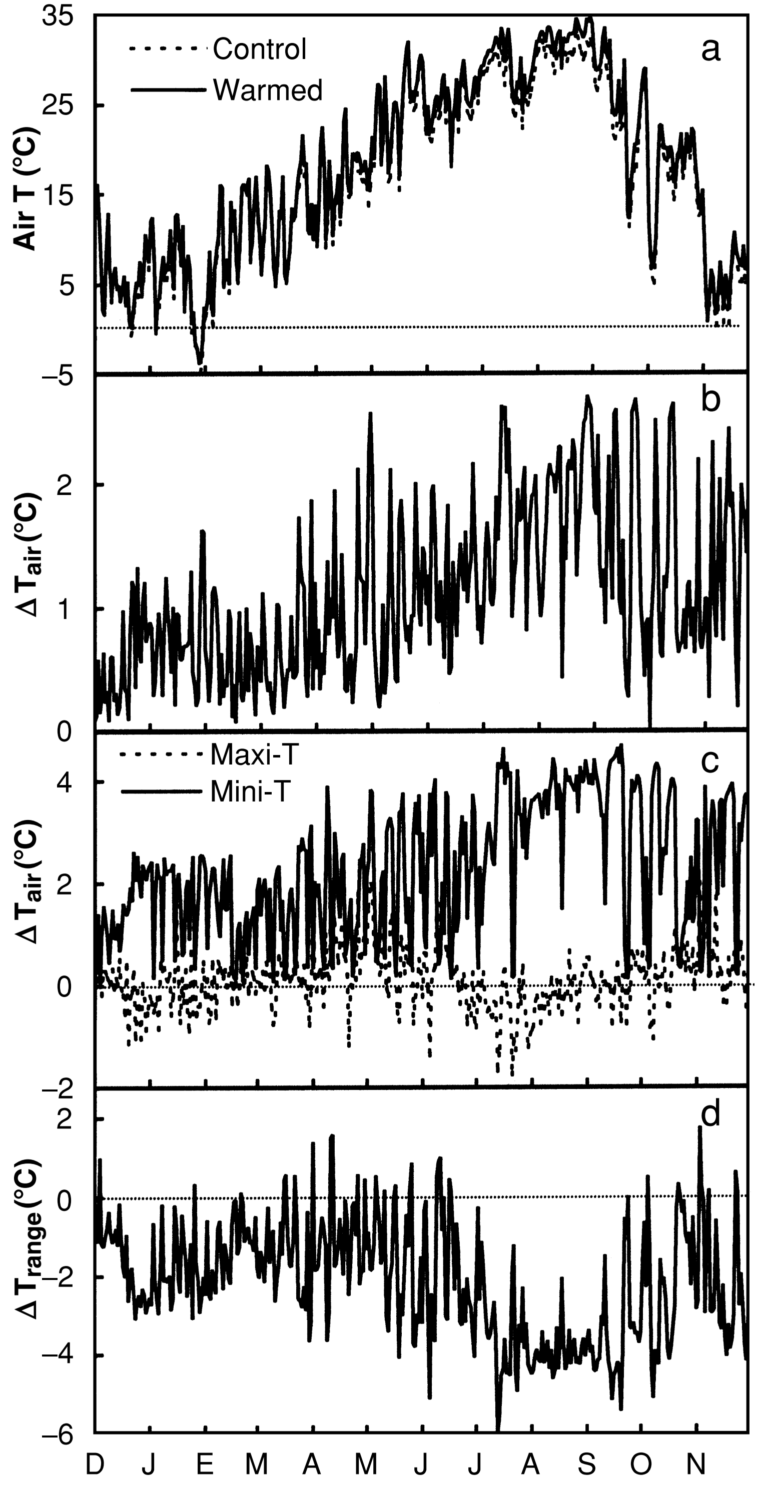

**Fig. 2** Daily mean air temperatures in the control and warmed plots (a), heater-induced increases in daily mean air temperature (b), daily maximum and minimum air temperatures (c) and the diurnal air temperature range (d).

in winter owing to the negative correlation as shown in Fig. 3. In addition, because of severe drought and a large VPD in the summer of 2000, a large portion of added energy from the heaters is dissipated as sensible heat, leading to larger increases in air temperature in summer than in winter.

### *Soil temperature*

Infrared heaters caused relatively constant increases in hourly values of soil temperature in the warmed plots in comparison with that in the control plots without clipping. With clipping, heater-induced increases in soil

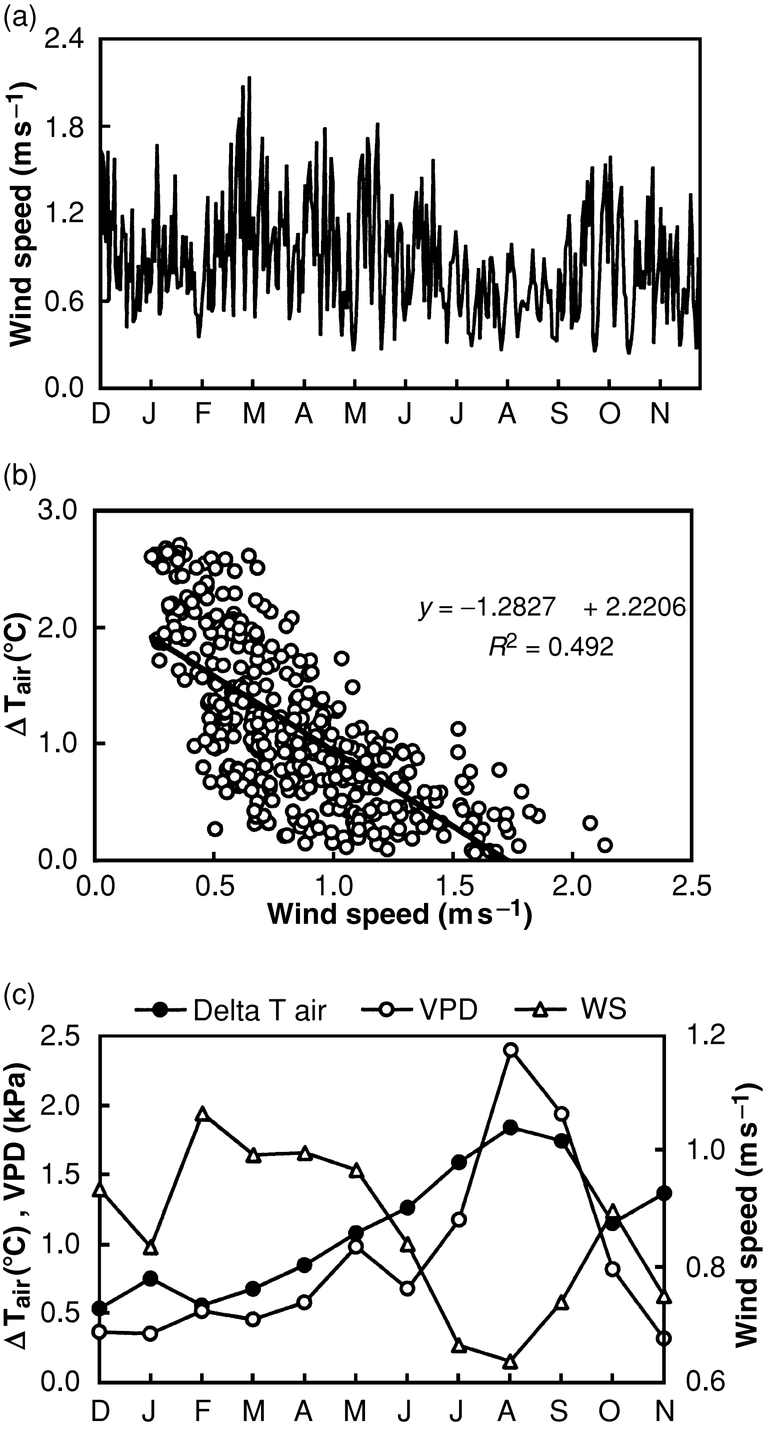

**Fig. 3** (a) Seasonal variations in daily mean wind speed, (b) Linear relationship between heater-induced increases in daily mean air temperature and daily mean wind speed, (c) Monthly mean values of VPD, wind speed, and heater-induced increases in air temperature.

temperature were greater during the daytime than at night with a peak at noon (Fig. 4). Clipping increased soil temperature during the daytime, but decreased soil temperature at night in both the control and warmed plots. Soil temperature increased by nearly 6.5 °C in midday and 1.3 °C in predawn in the warmed, clipped subplots as compared to values in the unclipped, control subplots.

Infrared heaters increased the yearly averages of soil temperature by 2.0 and 2.6 °C in the unclipped and clipped subplots, respectively (Table 1). Clipping elevated the annual averages of soil temperature by 0.6

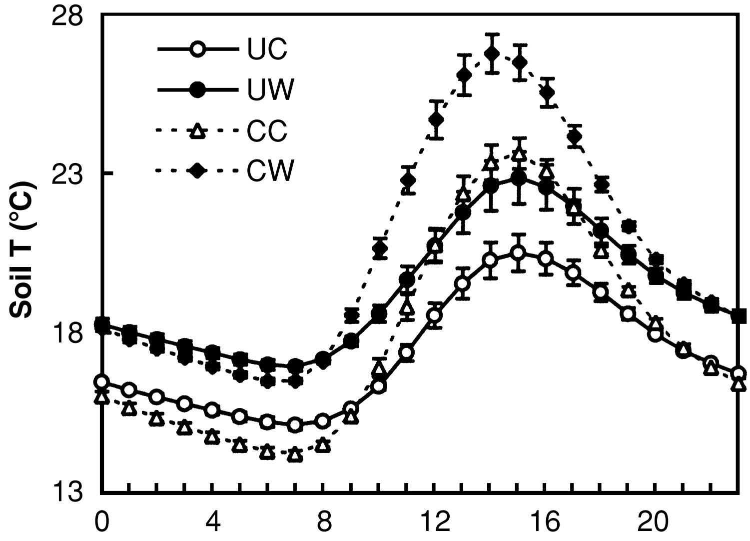

**Fig. 4** Hourly soil temperatures (mean ± 1 SE) in unclipped control (UC), unclipped warmed (UW), clipped control (CC) and clipped warmed (CW) subplots. Each value is the annual average from 1 December 1999 to 30 November 2000.

and 1.2 °C in the control and warmed plots, respectively. Annual averages of soil temperature increased by 3.2 °C in the clipped, warmed subplots as compared to the unclipped, control subplots. Increases in soil temperature varied with seasons with peaks in summer during a severe drought (Fig. 5).

Infrared heaters differentially affected daily maximum vs. minimum soil temperatures. Daily maximum soil temperature in the warmed plots increased by 2.5 without clipping and by 3.5 °C with clipping relative to controls (Table 1). Infrared heaters enhanced daily minimum soil temperature by 1.8 without clipping and 2.1 °C with clipping. Clipping increased daily maximum soil temperature by 3.4 and 4.3 °C, but decreased daily minimum soil temperature by 1.0 and 0.6 °C in the control and warmed plots, respectively. Daily maximum and minimum soil temperatures in the clipped, warmed subplots increased by 6.8 and 1.1 °C, respectively, compared to the unclipped, control subplots.

The differential responses of daily maximum and minimum soil temperatures to warming and clipping resulted in amplifications of the diurnal soil-temperature range (Fig. 6). Warming increased the diurnal soil-temperature range by 0.7 without clipping and by 1.4 °C with clipping (Fig. 6a). Clipping elevated the diurnal soil-temperature range by 4.3 and 5.0 °C in the control and warmed plots, respectively (Fig. 6b). The diurnal soil-temperature range in the clipped warmed subplots increased by 5.7 °C in comparison with that in the unclipped control subplots (Fig. 6c).

Soil-moisture content affected the responses of daily mean soil temperature. Increases in daily mean soil temperature as a result of warming are negatively correlated with soil-moisture content ($r^2_{\mathrm{UW-UC}} = 0.263$, $r^2_{\mathrm{CW-CC}} = 0.259$, $p < 0.05$, Fig. 7a). Similarly, changes in daily mean soil temperatures induced by both clipping ($r^2_{\mathrm{CC-UC}} = 0.519$, $r^2_{\mathrm{CW-UW}} = 0.431$, $p < 0.001$, Fig. 7b) and the interaction of warming and clipping ($r^2 = 0.1380$, $p > 0.05$, Fig. 7c) also showed negative correlations with soil-moisture content. Our results are consistent with those in a subalpine meadow in Colorado, USA with the same type of warming facility (Harte *et al.*, 1995). In that study, increases in soil temperature were greater in the study area with lower soil-moisture content (0.93 °C in 1991 and 0.87 °C in 1992) than those in the study area with higher soil-moisture content (0.00 °C in 1991 and 0.17 °C in 1992). Higher soil-moisture content might cause more infrared radiation from heaters dissipated as latent heat and less as soil heat flux, resulting in smaller increases in daily mean soil temperature.

Multiple regression analysis indicated that solar radiation was the dominant factor affecting increases in hourly values of soil temperature, whereas VPD was the primary factor influencing daily and monthly increases in average soil temperatures (Table 2). These factors may alter energy exchange between the warmed plots and the ambient environment, alter heat fluxes among the three energy pathways, change the proportion of enhanced infrared radiation to the total energy budget and affect soil-moisture content.

Increases in soil temperature caused by infrared heaters in our study are higher than those for a subalpine ecosystem in Rocky Mountains (Harte *et al.*, 1995) and similar to those in Minnesota wetlands (Bridgham *et al.*, 1999) using the same type of heating facility. The results from this study suggest that seasonal changes in plant canopy coverage may not affect responses of soil temperature to infrared heaters.

Infrared heaters had relatively even effects on soil temperature along the soil profile from 0 to 10 cm. Soil

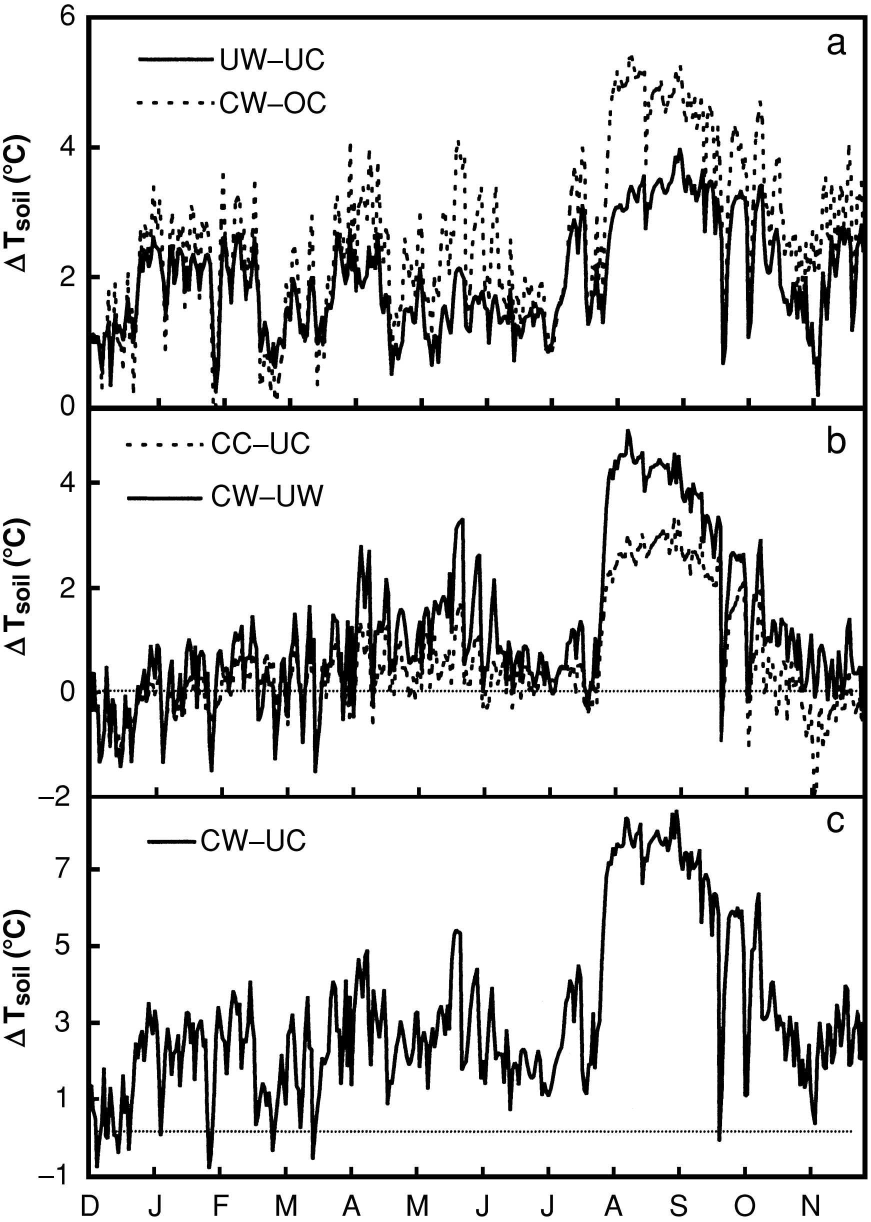

**Fig. 5** Increases in daily mean soil temperature because of (a) warming, (b) clipping and (c) interaction of warming and clipping. UW – UC = Unclipped warmed minus unclipped control, CW – CC = Clipped warmed minus clipped control, CC – UC = Clipped control minus unclipped control, CW – UW = Clipped warmed minus unclipped warmed, CW – UC = Clipped warmed minus unclipped control.

temperatures in the warmed plots were significantly higher than those in the control plots at all three depths either without (Fig. 8a) or with clipping (Fig. 8b).

We also measured spatial distributions of temperature at the soil surface. Results of two-way ANOVA showed no significant difference of soil-surface temperature between any two rows or columns in the warmed plots (Fig. 9). The even distribution of heating effects over the plot surface resulted from parabolic reflectors above the heating rod that uniformly deliver infrared radiation over the plot (Loik & Harte, 1997).

### *Differential responses of air and soil temperatures*

Our results indicate that air temperature responded less to experimental warming than did soil temperature, probably because of fast lateral exchange of energy between the warmed plots and ambient atmosphere.

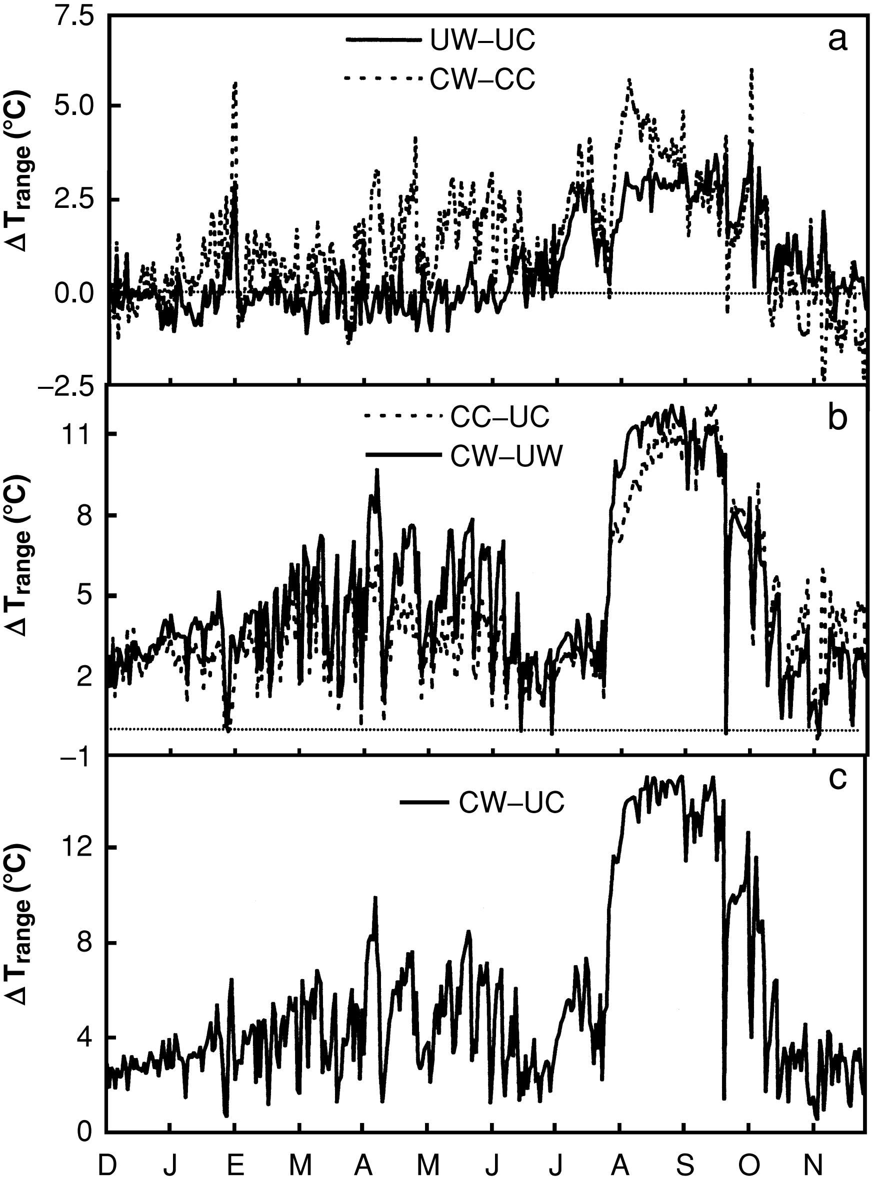

**Fig. 6** Changes in the diurnal soil temperature range associated with (a) warming, (b) clipping and (c) interaction of warming and clipping. See Fig. 5 for abbreviations.

However, infrared heaters reduce the diurnal range of air temperature, but amplify the diurnal range of soil temperature. Under climate warming, the difference between increases in air and soil temperatures may be less than that in our experimental plots (Kane *et al*., 1992). Because air and soil temperatures affect various ecosystem processes, the differential increases in air and soil temperatures caused by infrared heaters may result in various experimental outcomes (Shaver *et al*., 2000). For example, changes in air temperature mainly affect ecophysiological processes in the above-ground plant tissues – such as plant photosynthesis and respiration. Changes in soil temperature influence processes occurring in the soil – such as plant-root respiration and microbial activities. The large increase in soil temperature may stimulate more carbon (C) release, whereas small increases in air temperature will have little effect on photosynthesis. Thus, the net effects of the differential increases in air and soil temperature may result in decreases in net ecosystem productivity.

### *Soil moisture*

Soil-moisture content in the warmed plots relative to that in control plots was not significantly altered by infrared heaters without clipping ($P > 0.10$), but

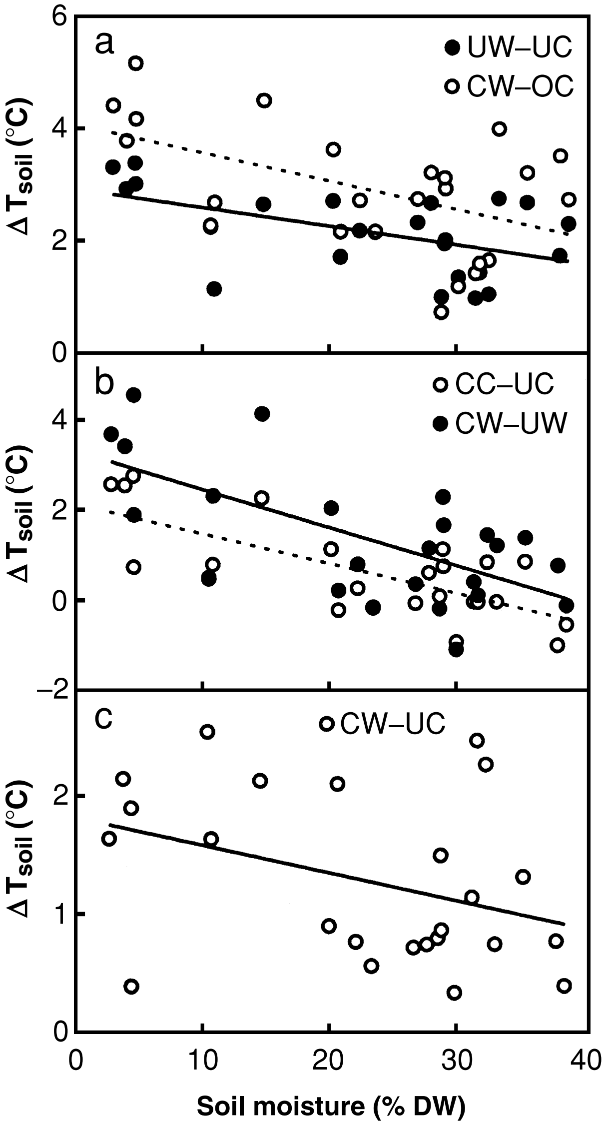

**Fig. 7** Effect of soil moisture on the response of soil temperature to (a) warming, (b) clipping and (c) their interactions. See Fig. 5 for abbreviations.

**Table 2** Path coefficients* and $r^2$ of stepwise multiple regression analyses between the hourly, daily, and monthly increases in soil temperature with vapour-pressure deficit (VPD), solar radiation and wind speed

| | VPD | Solar radiation | Wind speed | $r^2$ |
|---|---|---|---|---|
| Hourly $\Delta T_{soil}$ | | | | |
| UW – UC | −0.3871 | +0.8320 | +0.4398 | 0.9429 |
| CW – CC | +0.5620 | +1.0973 | −0.6962 | 0.9692 |
| CC – UC | | +0.9347 | +0.5478 | 0.9096 |
| CW – UW | | +1.0108 | +0.3327 | 0.9590 |
| CW – UC | | +1.0178 | +0.3154 | 0.9699 |
| Daily $\Delta T_{soil}$ | | | | |
| UW – UC | +0.7408 | −0.2043 | −0.3647 | 0.5879 |
| CW – CC | +0.6915 | | −0.3339 | 0.6524 |
| CC – UC | +0.7925 | +0.0835 | | 0.7170 |
| CW – UW | +0.7452 | +0.1395 | −0.0624 | 0.7226 |
| CW – UC | +0.7854 | | −0. 1885 | 0.6927 |
| Monthly $\Delta T_{soil}$ | | | | |
| UW – UC | +1.3430 | −0.6563 | | 0.8903 |
| CW – CC | +0.8726 | | | 0.7615 |
| CC – UC | +1.1264 | | +0.2618 | 0.9659 |
| CW – UW | +0.9478 | | | 0.8983 |
| CW – UC | +0.9468 | | | 0.8965 |

*The absolute values of path coefficients represent the relative importance of various factors in affecting the responses of air and soil temperature. The signs (+ and –) stand for positive or negative roles of these factors in influencing the responses of air and soil temperature.

significantly decreased by 11.0% ($P < 0.05$) with clipping. Clipping significantly decreased soil moisture by 17.7 ($P < 0.001$) and 22.7% ($P < 0.001$) in the control and warmed plots, respectively. Soil-moisture content in the clipped, warmed subplots was reduced by 26.7% ($P < 0.001$, Fig. 10) compared to the unclipped, control subplots.

In a Rocky Mountain subalpine meadow ecosystem, summer soil-water content was significantly decreased by 25% with the same type of heating facility (Harte *et al.*, 1995; Loik & Harte, 1997). Extra energy provided by infrared heaters in the warmed plots was partially dissipated as latent heat, resulting in more evapotranspiration and decreased soil-moisture content. Although it may reduce plant transpiration by removing above-ground biomass, clipping may increase evaporation from the soil surface owing to less plant coverage and boundary layer resistance and increases in soil temperature. Loss of soil moisture would decrease latent heat flux, leading to more energy dissipated as sensible heat (air warming) and soil heat flux (soil warming). Our data support this mechanism in which soil-temperature increase is negatively correlated with soil-moisture content. For plants exposed to soils with low water content under experimental warming, plant-water potential may decrease, leading to reductions in stomatal conductance and photosynthetic $CO_2$ fixation (Loik & Harte, 1997; Loik *et al.*, 2000).

### *Comparison with other warming facilities*

Infrared heaters used in our experimental site increased daily mean and minimum air temperatures, did not affect daily maximum air temperature and decreased the diurnal air-temperature range. Infrared heaters also increased

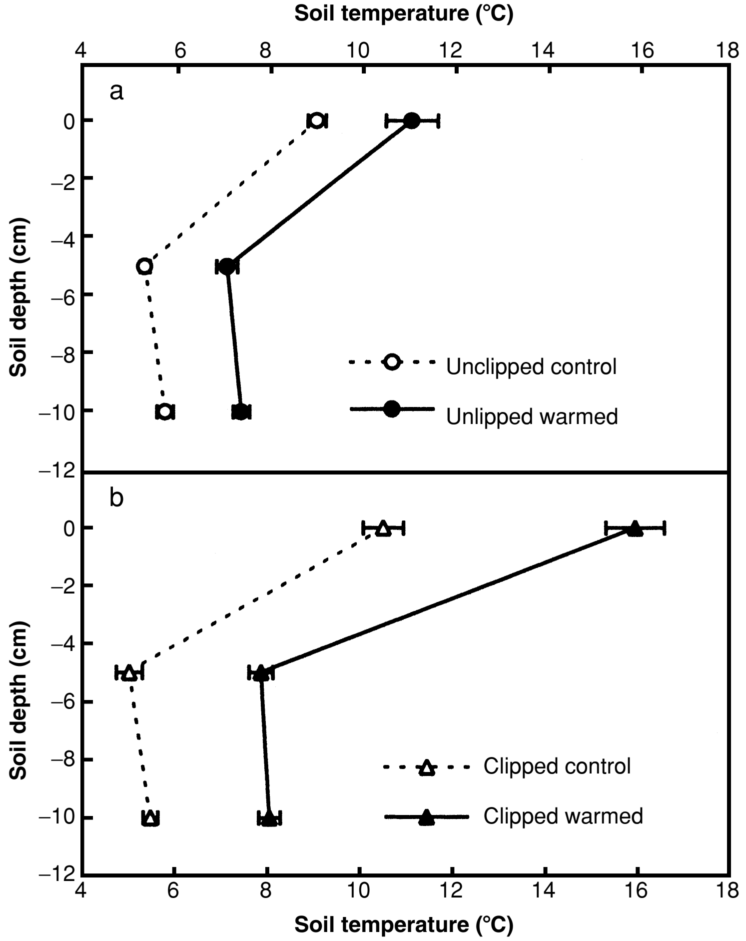

**Fig. 8** Soil temperatures (mean ± 1SE) at three soil depths in the (a) unclipped and (b) clipped subplots showed constant increases along the soil profiles. Measurements were taken on 29 December 1999.

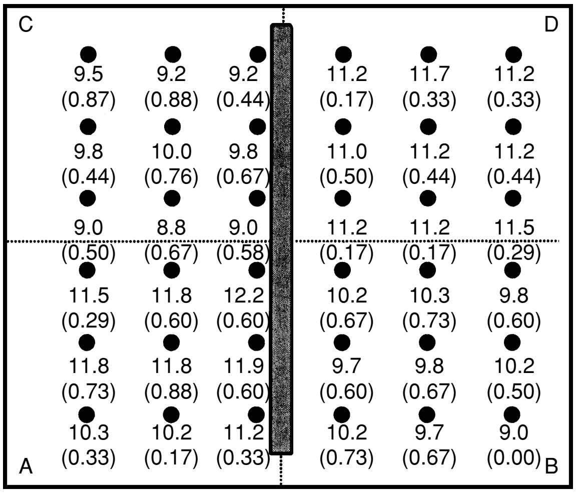

**Fig. 9** Spatial pattern of soil surface temperature (mean ± 1SE) in the warmed plots measured on 4 January 2000. Subplots *A* and *D* are the clipped subplots, *B* and *C* are the unclipped subplots. The dark rectangle in the center part is the footprint of the infrared heater.

daily maximum, mean and minimum soil temperatures and the diurnal soil-temperature range. However, air and soil temperatures showed differential responses to enhanced infrared radiation, with air temperature responding less than soil temperature. The effect of infrared heaters on soil moisture depended on land use patterns as mimicked by clipping. Environmental factors – such as solar radiation, wind speed, VPD and soil moisture – affected the responses of air and soil temperatures to infrared heaters in our study.

Greenhouses and OTCs are widely used at various habitats across the world in order to manipulate temperature in field (Chapin & Shaver, 1985; Havström *et al.*, 1993; Marion *et al.*, 1997; Richardson *et al.*, 2000). Within a day, GHs/OTCs increase air temperature in the daytime when there is incoming solar radiation and decrease air temperature at night (Wookey *et al.*, 1993; Kennedy, 1995a, b; Marion *et al.*, 1997; Suzuki & Kudo, 1997; Werkman *et al.*, 1999), leading to an amplification of the diurnal air- temperature range (Debevec & MacLean, 1993; Havström *et al.*, 1993; Hollister & Webber, 2000). Over the

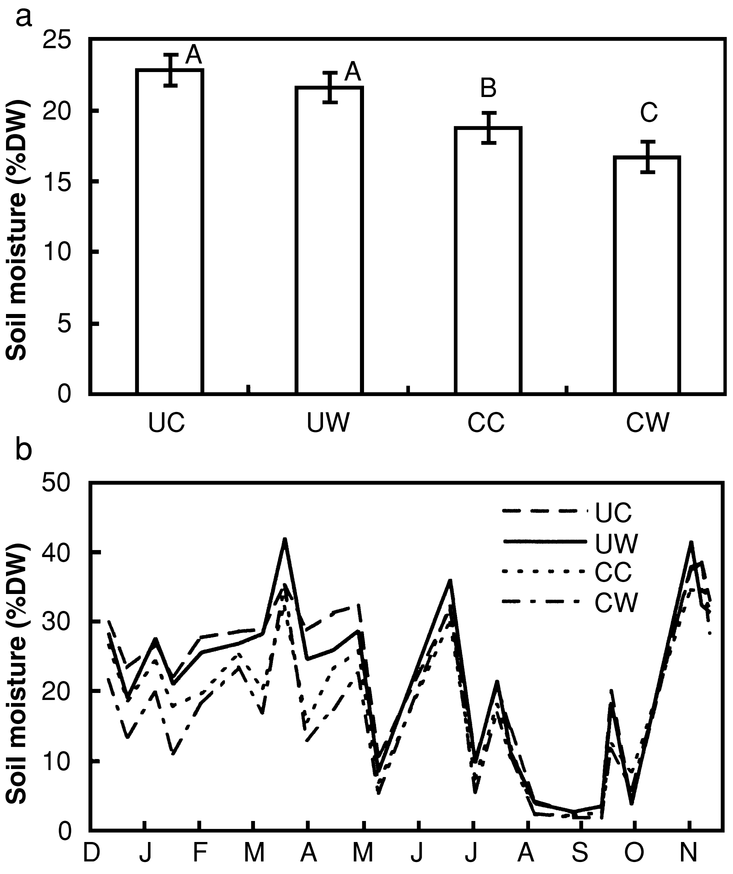

**Fig. 10** (a) Annual averages (Mean ± 1SE), (b) Seasonal variations of soil-moisture contents. See Fig. 4 for abbreviations.

seasons, GHs/OTCs elevate daily mean air temperature more in the summer than in the winter (Kennedy, 1995b; Marion *et al*., 1997; Stenström *et al*., 1997). In addition, GHs/OTCs – especially those in the Arctic, sub-Arctic, Antarctic and alpine regions – are often used in summer and are not operational in winter owing to severe weather (Kennedy, 1995a). Summer studies may be adequate for understanding plant responses, but miss an important period of predicted large increases in temperature, which is critical for quantifying annual budgets of C and other biogeochemical compounds. Reported changes in soil temperatures in GHs/OTCs are inconsistent, being unchanged (Havström *et al*., 1993; Suzuki & Kudo, 1997; Hobbie *et al*., 1999) or experiencing increased daily mean and maximum soil temperatures and decreased daily minimum soil temperature (Wookey *et al*., 1993; Michelson *et al*., 1996; Oechel *et al*., 1998; Robinson *et al*., 1998; Shaver *et al*., 1998; Day *et al*., 1999). In general, GHs/OTCs cause much greater increases in air temperature than in soil temperature (Havström *et al*., 1993; Robinson *et al*., 1995; Suzuki & Kudo, 1997; Jones *et al*., 1998; Day *et al*., 1999; Welker *et al*., 2000) and have no effects on soil moisture in some studies (Chapin & Shaver, 1985; Shaver *et al*., 1986; Havström *et al*., 1993; Robinson *et al*., 1998). Although GHs/OTCs do not generate microclimates similar to predicted climate warming, they require no electricity supply and are convenient for use in remote regions (Karl *et al*., 1991; Kennedy, 1995a).

Soil-heating pipes/wires can keep constant increases in soil temperature (2.5–10 °C) in the heated plots compared to the control plots (Rykbost *et al*., 1975a,b; Van Cleve *et al*., 1990; Hillier *et al*., 1994; McHale *et al*., 1998; Hartley *et al*., 1999). These facilities generate soil-temperature gradients away from pipes and/or wires (Verberg *et al*., 1999) and hardly affect air temperature unless they are combined with other facilities; that is, GHs or OTCs (Hartley *et al*., 1999). Without changes in air temperature, plants experience change only in their root systems and will, therefore, react differently to what is expected under climate warming. Soil-moisture content has been reported to decrease by soil-heating pipes/wires (Peterjohn *et al*., 1994; Hantschel *et al*., 1995; Rustad & Fernandez, 1998). Overall, soil-heating pipes/wires create a novel thermal environment in the rhizosphere for roots and microbes, whereas the aerial environment for the above-ground part of plant remains unchanged.

Infrared reflectors only act at night and raise the nighttime and minimum air temperatures. They usually have no effect on daytime air temperature. Consequently, infrared reflectors may cause an increase in plant respiration and no change in plant photosynthesis. Indeed, it has been reported that plant growth and primary productivity are reduced in the plots under infrared reflectors in comparison with those under control (Zeiher *et al*., 1994; Luxmoore *et al*., 1998). Infrared reflectors are supposed to affect both air and soil temperatures although no report has been published on the changes in soil temperature so far (Zeiher *et al*., 1994; Luxmoore *et al*., 1998).

## Conclusions

Infrared heaters add a constant amount of downward infrared radiation that is dissipated through the three pathways of energy dissipation; that is, sensible heat to warm the air, latent heat to increase evapotranspiration and soil conductive heat flux to warm the soil (Shaver *et al*., 2000). Contrary to the speculation that infrared heaters do not warm the air (Schulze *et al*., 1999; Shen & Harte, 2000), our experimental results have shown that infrared heaters significantly increase daily mean and minimum air temperatures and adequately simulate the diurnal pattern of air temperature under climate warming. Infrared heaters can manipulate both air and soil temperatures without the need to combine with other warming facilities. However, infrared heaters have only been used in a few ecosystems with low-stature plants so far. With the advantages of nonperturbation to gas composition, precipitation, light, wind speed, and pollination and no physical disturbance to soil, infrared heaters may have a broad application across various habitats where electricity supply is available.

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