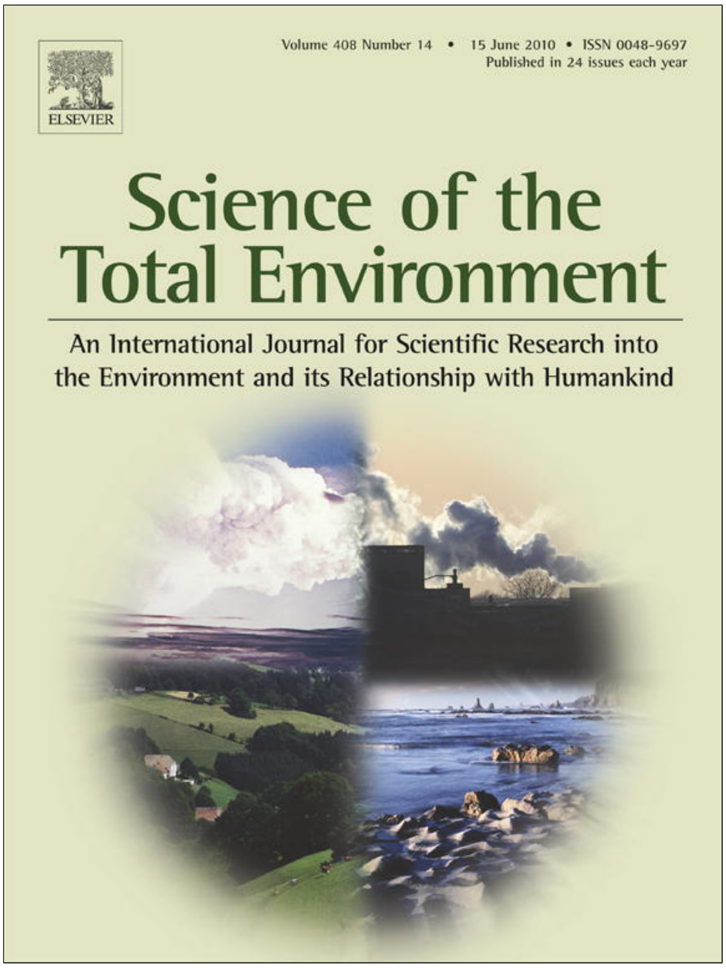
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Impacts of day versus night warming on soil microclimate: Results from a semiarid temperate steppe

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ABSTRACT

One feature of climate warming is that increases in daily minimum temperature are greater than those in daily maximum temperature. Changes in soil microclimate in response to the asymmetrically diurnal warming scenarios can help to explain responses of ecosystem processes. In the present study, we examined the impacts of day, night, and continuous warming on soil microclimate in a temperate steppe in northern China. Our results showed that day, night, and continuous warming (approximately 13 W m^{-2} with constant power mode) significantly increased daily mean soil temperature at 10 cm depth by 0.71, 0.78, and 1.71 °C, respectively. Night warming caused greater increases in nighttime mean and daily minimum soil temperatures (0.74 and 0.99 °C) than day warming did (0.60 and 0.66 °C). However, there were no differences in the increases in daytime mean and daily maximum soil temperature between day (0.81 and 1.13 °C) and night (0.81 and 1.10 °C) warming. The differential effects of day and night warming on soil temperature varied with environmental factors, including photosynthetic active radiation, vapor-pressure deficit, and wind speed. When compared with the effect of continuous warming on soil temperature, the summed effects of day and night warming were lower during daytime, but greater at night, thus leading to equality at daily scale. Mean volumetric soil moisture at the depth of 0–40 cm significantly decreased under continuous warming in both 2006 (1.44 V/V%) and 2007 (0.76 V/V%). Day warming significantly reduced volumetric soil moisture only in 2006, whereas night warming had no effect on volumetric soil moisture in both 2006 and 2007. Given the different diurnal warming patterns and variability of environmental factors among ecosystems, these results highlight the importance of incorporating the differential impacts of day and night warming on soil microclimate into the predictions of terrestrial ecosystem responses to climate warming.

1. Introduction

Soil microclimate, including soil temperature and moisture, is important in regulating the biological processes of terrestrial ecosystems (Field et al., 1992). For example, it can influence the quality and quantity of soil organic matter by affecting both plant production and decomposition processes (Chapin et al., 2002). Therefore, better understanding the impacts of climate change on soil microclimate is critical for predicting the physical and biological outcomes of ongoing global warming (Chen et al., 1999, 2008). Global mean temperature has increased by 0.76 °C since 1850 and is expected to rise 1.8–4.0 °C further by the end of this century (Solomon, 2007). Climate warming happens by enhancing downward infrared radiation which is dissipated through three energy pathways: sensible heat, latent heat, and soil heat fluxes (Chapin et al., 2002). The three energy pathways are responsible for increases in air temperature, ecosystem evapotranspiration that affects soil moisture, and soil temperature. In the past decades, manipulative warming experiments using infrared heaters have reported potential effects of climatic warming on soil microclimate. For example, Harte et al. (1995) reported that 15 W m^{-2} downward infrared flux increased summer soil temperature by up to 3 °C and reduced soil moisture by up to 25% in a montane meadow in Colorado, USA. Similarly, 78–191 W m^{-2} downward infrared flux in peatland mesocosms in northern Minnesota, USA elevated soil temperature at the 15-cm depth by 1.6–4.1 °C during the growing season (Bridgham et al., 1999). In a tallgrass prairie in Oklahoma, USA, infrared heaters with an output of 100 W m^{-2} caused 2.0–2.6 °C an increase in soil temperature, whereas the impacts on soil moisture varied with the clipping treatment (Wan et al., 2002). These studies, all with constant electrical output or continuous temperature increase, have improved our understanding of the impacts of climate warming on soil microclimate.

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Global records, however, have revealed a greater warming trend at night than during daytime (Karl et al., 1991; Easterling et al., 1997; McCarthy, 2001; Lobell and Ortiz-Monasterio, 2007). Although such an asymmetric diurnal warming is still under debate (Solomon, 2007), it has been widely observed over the land surface since 1950 (Easterling et al., 1997; Zhou et al., 2007). Due to diurnal variations in environmental factors, day and night warming may have differential impacts on daily soil temperature. Firstly, wind speed, which is negatively correlated with thermal radiation efficiency (Kimball, 2005; Kimball et al., 2008), is lower at night than during daytime because there is less kinetic energy being produced by heat at night (Shao et al., 2007). As a result, even with the same output of energy, infrared heaters will have greater thermal efficiency at night than during daytime (Wan et al., 2002). Secondly, the thermal transfer between air and soil during daytime and at night is in opposite directions (Shao et al., 2007). Because air temperature is lower and higher than soil temperature at night and during daytime, respectively, the transfer of thermal energy is from soil to air and air to soil at night and during daytime, respectively. Consequently, the energy input from the infrared heaters into the soil will be lost more quickly from soil to air, leading to a lower increase in soil temperature at night than during daytime. Finally, because the aerodynamic resistance is greater at night, less thermal radiation is required to raise canopy temperature (Kimball, 2005). If soil moisture is not limiting active transpiration from open stomata of plants, roughly twice as much thermal radiation is required to raise canopy temperature during daytime compared to night when stomata are closed. Thus, the effects of day and night warming on daily soil temperature will be largely dependent upon the concurrent physical processes occurring both during daytime and at night. Similarly, because ecosystem evapotranspiration mostly occurs during daytime, day and night warming are likely to differently affect soil moisture. Therefore, temporal (e.g., hourly, daily, and monthly) patterns of soil microclimate changes could be more important than the changes in the mean values (Chen et al., 2008).

Soil microclimate is not only directly affected by climate factors such as downward infrared radiation and wind speed, but it is also indirectly influenced by biotic factors such as plant productivity and vegetation cover (Dickinson, 1983; Harte et al., 1995). Moreover, given that temperature and water availability are the two critical factors in regulating plant growth, differential responses of soil microclimate to day and night warming may lead to subsequent changes in ecological processes in terrestrial biosphere, with consequent feedbacks to climate change. In fact, differential influences of day and night warming on ecological processes, including leaf- and ecosystem-level carbon (C) exchange (Turnbull et al., 2002, 2004; Wan et al., 2009; Xia et al., 2009a) and plant production (Rosenzweig and Tubiello, 1996; Alward et al., 1999; Volder et al., 2007) have well been documented. Therefore, knowledge of changes in soil microclimate (temperature and moisture) under day and night warming is critical for convincing projection of the responses and feedback of terrestrial biosphere to climate change.

As a part of a comprehensive research project (Wan et al., 2009; Xia et al., 2009a), we examined the differential effects of day and night warming on soil microclimate in a semiarid temperate steppe in northern China. Specific objectives of this study are to evaluate: (1) different effects of day and night warming on soil microclimate, (2) interactions of day and night warming in influencing soil microclimate, and (3) role of environmental factors in regulating the warming responses of soil microclimate.

2. Materials and methods

2.1. Experimental site, design and warming facility

The experimental site is located at a semiarid temperate steppe (42°02′ N, 116°17′ E, 1324 m a.s.l) in Inner Mongolia, China. Long-term (1953–2007) mean annual precipitation is approximately 383 mm with 90% distributed in the growing season (from May to October). Mean annual temperature is 2.1 °C with monthly mean temperature ranging from 18.9 °C in July to −17.5 °C in January. According to the Chinese or FAO classification, the sandy soil at the study site is chestnut, with mean bulk density of 1.31 g cm^{-3} and pH of 7.7. More detailed site description is presented in Wan et al. (2009).

The experiment used a random block design with 6 treatments, including control (C), day (6:00 am–6:00 pm, local time; D) warming, night (6:00 pm–6:00 am; N) warming, continuous (24 h; W) warming, nitrogen addition, and continuous warming plus nitrogen addition, and replicated 6 times. Thirty-six 3 × 4 m plots were arranged in 6 × 6 matrix, with a 3-m distance between any two adjacent plots. The effects of nitrogen addition and continuous warming plus nitrogen addition were not included in this study.

All the warmed plots were heated by MSR-2420 infrared radiators (Kalglo Electronics Inc, Bethlehem, PA, USA) suspended 2.25 m above the ground. In order to simulate the shading effects, we also put a "dummy" heater with the same shape and size as the infrared heater in the control plot. All the heaters under the warming treatments were set at an electrical power input of approximately 1600 W. For wind speed of about 4 m s^{-1} across the year, the efficiency for this type of infrared heater is about 10% (Kimball, 2005), so the thermal radiation impinging on the plots was on the order of 13.3 W m^{-2}. The warming treatment started from 23 April 2006.

2.2. Measurements of soil temperature, moisture, and controlling factors

Soil temperatures at the depth of 10 cm were recorded automatically with a Datalogger (STM-01 Soil Temperature Measurement System, Henan Electronic Institute, Zhengzhou, China) with one temperature sensor at the center in each plot. Six measurements were taken with 10-min intervals, and averages of the six measurements were stored as the hourly averages. Soil moisture at four depths (0–10, 10–20, 20–30, and 30–40 cm) was measured weekly using Diviner-2000 Portable Soil Moisture Probe (Sentek Pty Ltd., Balmain, Australia). Photosynthetic active radiation (PAR), vapor-pressure deficit (VPD), and wind speed were measured from an eddy covariance tower adjacent (approx. 200 m) to the experimental plots.

Ecosystem water exchange was measured with a transparent chamber (0.5 × 0.5 × 0.5 m), which allows >90% of photosynthetic active radiation pass through, attached to an infrared gas analyzer (IRGA; LI-6400, Li-Cor, Lincoln, NE, USA). At two opposite corners of each plot, the chamber was placed and sealed on an aluminum frame which was inserted into the soil to a 2–3 cm depth. Two small fans continuously mixed the air inside the chamber during measurements. After 20 s of steady-state, nine consecutive recordings of water vapor concentration were taken during a 90-s period at 10-s intervals. During the measuring time period, increases in air temperatures within the chamber were less than 0.2 °C. H_2O flux rate was determined from the time-courses of the concentrations to calculate evapotranspiration (ET). We measured ET at 3-h intervals (06:00, 09:00, 12:00, 15:00, 18:00, 21:00, 0:00, and 03:00 local time) every two weeks during the growing season.

Vegetation cover was recorded at the end of August in both 2006 and 2007 from two permanent 1 × 1 m quadrats in each experimental plot. During the measurements, a 1 × 1 m frame with 100 equally distributed grids (10 × 10 cm) was put above the canopy in each quadrat. We recorded the cover of each species in all grids and summed them as the species cover in each quadrat. The vegetation cover in each plot was the sum of cover of all species.

2.3. Data analysis

Because the datalogger of soil temperature was setup in late July, 2006, only data since August, 2006 could be included into the analysis. We first used two-way analysis of variance (ANOVA) with day (D) and night (N) warming as the two factors to examine their effects on daytime, nighttime, and daily mean soil temperature, daily maximum and minimum soil temperature, and soil moisture. However, no interaction (all $P>0.05$) between day and night warming was found. Thus, Duncan multiple range test as a mean separation test was used to examine the differences between the control and warming treatments in this study. We plotted the summed effects of day and night warming against the effects of continuous warming, and the difference in its slope of linear regression from the 1:1 line was examined by t-test. The continuous-warming effects were not equal to the summed effects of day and night warming if the regression slope did not overlap with the 1:1 line (Zavaleta et al., 2003; Xia et al., 2009a). Repeated-measures ANOVAs were used to examine the effects of warming and depth on soil moisture. Between-subject effects were evaluated as warming treatments and depths, and within-subject effects were time-of-season. Simple and multiple linear regression analyses were used to determine relationships between the warming effects on soil microclimate and the controlling factors. Soil temperature was not included in the regression analysis because we aim to test the roles of other environmental factors, except for temperature itself, in controlling warming effects on soil temperature. Soil moisture was also not included in the multi-regression analysis because the continuous data during the experimental period were not available. All statistical analyses were conducted with SAS software (SAS Institute Inc., Cary, NC, USA).

3. Results

3.1. Soil temperature

The annual (from August 2006 to July 2007) average of daily mean soil temperature at the 10-cm depth in the control plots was 6.90 °C, with 16.88 °C in the growing season (May–October) and −3.13 °C in the non-growing season (November–April; Fig. 1a). Day, night, and continuous warming significantly increased daily mean soil temperature by 0.71, 0.78, and 1.71 °C, respectively (all $P<0.05$; Table 1; Fig. 1b). Daytime (6:00 am–6:00 pm) mean soil temperature was significantly increased by 2.06 °C ($P<0.05$) under continuous warming, but not significantly enhanced under both day and night warming (both $P>0.05$; Table 1; Fig. 2b). Nighttime mean soil temperature (Fig. 2c) was significantly elevated by 0.60, 0.74, and 1.35 °C (all $P<0.05$) under day, night, and continuous warming, respectively. Infrared heaters also differently affected daily minimum and maximum soil temperature. The magnitudes of the increases in daily maximum soil temperature were 2.81 °C ($P<0.05$), 1.13 °C ($P<0.05$) and 1.10 °C ($P<0.05$) in the continuous, day, and night-warming plots, respectively. Day, night, and continuous warming elevated daily minimum soil temperature by 0.66, 0.99, and 1.38 °C (all $P<0.05$; Table 1), respectively.

Table 1
Annual averages (mean ± 1SE) of soil temperature. C, control; D, day warming; N, night warming; W, continuous warming. *Different lowercase letters* are statistically different at $P<0.05$.

	Daily	Daytime	Nighttime	Maximum	Minimum
C	6.90 (0.16)^{c}	8.40 (0.26)^{b}	5.40 (0.09)^{c}	9.55 (0.34)^{b}	2.62 (0.09)^{c}
D	7.61 (0.12)^{b}	9.21 (0.20)^{b}	6.00 (0.09)^{b}	10.68 (0.31)^{b}	3.28 (0.13)^{b}
N	7.68 (0.29)^{b}	9.21 (0.39)^{b}	6.14 (0.19)^{b}	10.65 (0.48)^{b}	3.61 (0.14)^{b}
W	8.61 (0.13)^{a}	10.46 (0.24)^{a}	6.75 (0.09)^{a}	12.36 (0.36)^{a}	4.00 (0.09)^{a}

Across the experimental period, the hourly patterns of changes in temperature under continuous warming showed a one-peak curve with the greatest increase at 12:00 (Fig. 2a). In addition, the increments in soil temperature induced by continuous warming were statistically significant in all the 24 h (Table S1). Both day and night warming significantly elevated soil temperature during the time period from 17:00 to 8:00, whereas no changes in soil temperature were detected from 10:00 to 17:00. From 8:00 to 10:00, night, but not day, warming significantly impacted soil temperature (Table S1; Fig. 2a).

Across the growing season (May–October), daily mean soil temperature was significantly elevated by 0.86, 1.01, and 2.10 °C (all $P<0.05$) under day, night, and continuous warming, respectively. However, over the non-growing season, only continuous warming significantly increased daily mean soil temperature (1.31 °C; $P<0.05$). When analyzed by month, the increments in soil temperature induced by continuous warming were statistically significant in all the months (Table S2). Significant increases in soil temperature ($P<0.05$) were found in February–April and August–November under day warming and in most months except for January, June, and December under night warming (Table S2).

By pooling the data from all observational days, we plotted the summed effects of day and night warming against the effects of

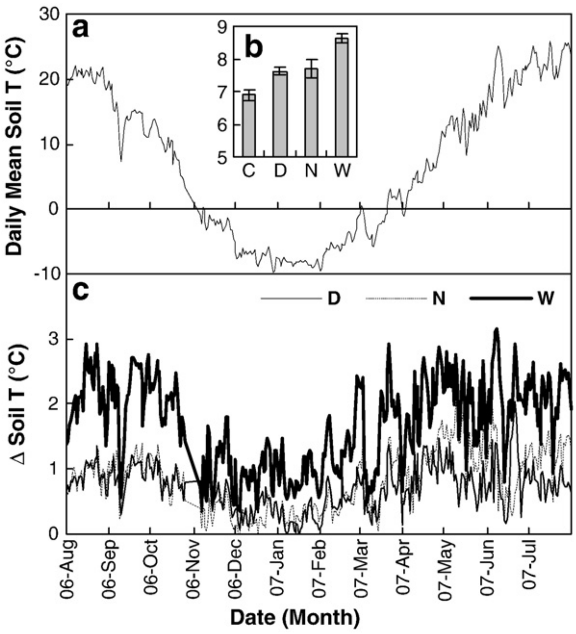

Fig. 1. Daily mean soil temperature in the control plots (a) with annual means (insets mean ± 1SE; b) under different treatments and warming-induced changes in soil temperature (c) from 1 August 2006 to 31 July 2007 at the depth of 10 cm. C, control; D, day warming; N, night warming; W, continuous warming.

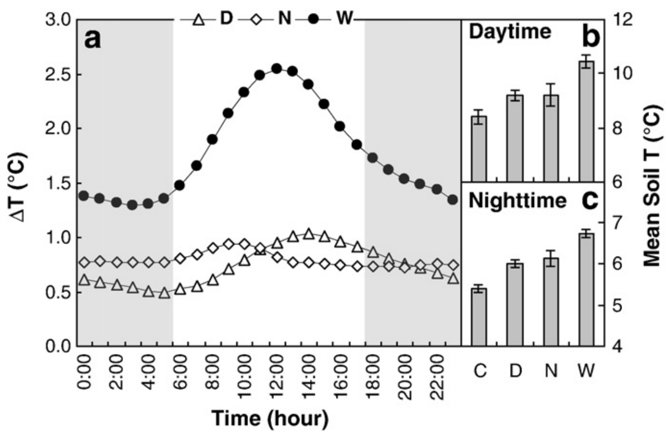

Fig. 2. Diurnal patterns of the effects of day, night, and continuous warming on soil temperature (a) and means soil temperature (means ± 1SE) during day- (b) and nighttime (c) at the depth of 10 cm from August, 2006 to July, 2007. The shaded area denotes the nighttime, and time here is solar time. D, day warming; N, night warming; W, continuous warming.

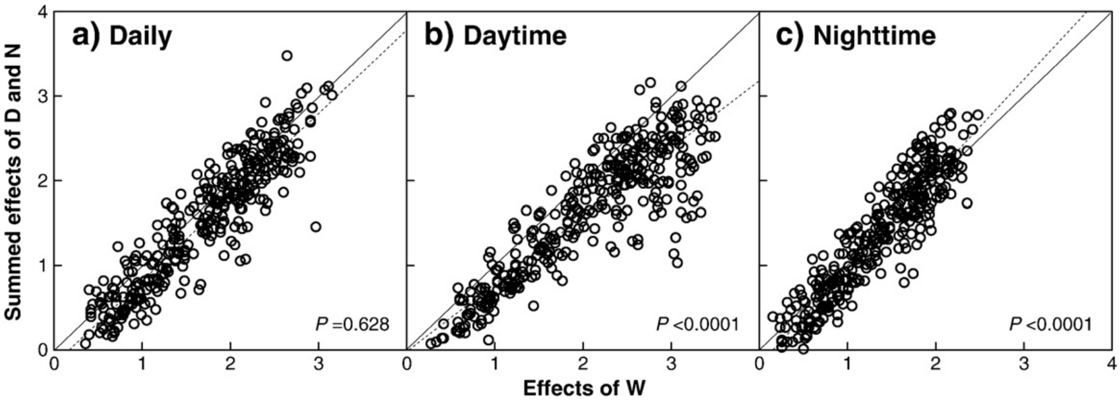

Fig. 3. Summed effects of day (D) and night (N) warming and effects of continuous warming (W) on (a) daily, (b) daytime, and (c) nighttime mean soil temperature. If $P>0.05$, the slopes for the line function (dashed lines) overlap the 1:1 line (solid lines), suggesting that the effects of continuous warming are equal to the summed effects of day and night warming. The individual regression in the three panels are all statistically significant (a, $r^2=0.85$, $P<0.001$; b, $r^2=0.78$, $P<0.001$; c, $r^2=0.86$, $P<0.001$).

continuous warming. Although the intercept of the linear regression was significantly lower than zero, the slope of daily mean soil temperature (0.9898) was not different from the 1:1 line (*t*-test; $P=0.628$; Fig. 3a). When divided the data into day- and nighttime, the slope was lower than one during daytime (0.8021, $P<0.0001$; Fig. 3b) but greater than one at night (1.1205, $P<0.0001$; Fig. 3c).

3.2. Soil moisture

The mean volumetric soil moisture at the 0–40 cm depth in the control plots was 8.81% across the two growing seasons of 2006 and 2007. Repeated-measures ANOVA showed that warming and depth significantly affected soil moisture in both 2006 and 2007 (both $P<0.001$; Table 2; Fig. 4). No interactive effect of warming and depth was found on volumetric soil moisture in either 2006 or 2007 (both $P>0.05$, Table 2). Volumetric soil moisture was reduced by 0.88 V/V% (absolute difference, $P=0.029$) in 2006, but was not changed in 2007 ($P>0.10$) under day warming. No effect of night warming on volumetric soil moisture was detected in either year (both $P>0.10$). Significant decreases in volumetric soil moisture were found in both 2006 (1.44 V/V%; $P<0.001$) and 2007 (0.76 V/V%; $P=0.040$) under continuous warming (Fig. 4).

3.3. Controlling factors and their impacts on the warming-induced changes in soil temperature

Wind speed in this system exhibited a diurnal variation, being greatest in the afternoon (15:00; 5.64 m s^{-1}) and lowest before sunrise (5:00; 2.88 m s^{-1}; Fig. S1a). In addition, wind speed in this area was significantly greater (*t*-test, $P<0.001$) during daytime (4.65 m s^{-1}) than at night (3.18 m s^{-1}; Fig. S1b). This pattern was not changed during the experimental period from August 2006 to July 2007 (Fig. 5a). Furthermore, the mean wind speed for daily, daytime and nighttime was all greater (all $P<0.05$) in the non-growing season (4.61, 5.50, and 3.72 m s^{-1}, respectively) than in the growing season

Table 2
Results (*P*-values) of repeated-measures ANOVAs on the effects of warming, depth and their interactions with time (*T*) on volumetric soil moisture in 2006 and 2007.

	2006	2007
Warming	<0.0001	0.002
Depth	<0.0001	0.002
T	<0.0001	0.026
Warming × Depth	0.137	0.999
T × Warming	0.168	0.077
T × Depth	<0.0001	<0.0001
T × Warming × Depth	0.710	0.230

(3.50, 4.14, and 2.86 m s^{-1}, respectively). Similar seasonal patterns of daytime PAR and VPD were observed in this ecosystem. The greatest of daytime PAR and VPD occurred in May (946.51 μmol m^{-2} s^{-1}) and June (1.73 kPa), respectively, while the lowest values were both found in January (348.86 μmol m^{-2} s^{-1} and 0.10 kPa) (Fig. 5b).

Linear regression analyses indicated that the changes in soil temperature under the continuous ($r^2=0.16$, $P<0.001$), day ($r^2=0.02$, $P<0.0001$), and night ($r^2=0.10$, $P<0.001$) warming treatments were all negatively correlated with wind speed (Fig. 6a, d). The slope under day warming was marginally greater ($P=0.089$) than that under night warming (Fig. 6d). From August 2006 to July 2007, changes in soil temperature under continuous warming were linearly increased with daytime PAR ($r^2=0.43$, $P<0.001$; Fig. 6b) and VPD ($r^2=0.55$, $P<0.001$; Fig. 6c). Similarly, the temperature increases under both day and night warming showed positive linear dependence upon daytime PAR ($r^2=0.28$, $P<0.001$; $r^2=0.47$, $P<0.001$; Fig. 6e) and VPD ($r^2=0.32$, $P<0.001$; $r^2=0.50$, $P<0.001$; Fig. 6f). In addition, the slopes against both PAR and VPD were greater ($P<0.0001$) under night than day warming. Results of stepwise regression analyses showed that 63.1% of the variance in continuous-warming effects on daily soil temperature could be explained by daytime VPD (partial $r^2=0.53$, $P<0.001$), nighttime wind speed (partial $r^2=0.08$; $P<0.001$), and daytime PAR (partial $r^2=0.02$, $P<0.001$). PAR alone accounted for 95.4% ($P<0.001$) and 81.4% ($P<0.001$) of the changes in hourly and monthly average soil temperature under continuous warming, respectively (Table 3).

When divided into day- (6:00–18:00) and nighttime (18:00–6:00), linear regression analysis revealed that soil temperature changes under day warming had a negative relationship ($r^2=0.09$, $P<0.001$) with daytime wind speed (Fig. 7a), whereas no correlation ($P>0.10$) was detected between temperature changes under night warming and daytime wind speed (Fig. 7c). However, nighttime mean wind speed negatively affected both day ($r^2=0.11$, $P<0.001$; Fig. 7b) and night ($r^2=0.05$, $P<0.001$; Fig. 7d) warming effects on soil temperature.

Stepwise multiple regression analyses demonstrated that, at the hourly scale, VPD alone explained 97.5% ($P<0.001$) of the variances in soil temperature changes under day warming, whereas 70.4% of the soil temperature changes under night warming could be accounted for by the combination of wind speed (partial $r^2=0.26$, $P=0.011$), PAR (partial $r^2=0.17$, $P=0.023$), and VPD (partial $r^2=0.28$, $P=0.003$). At the daily scale, daytime VPD (partial $r^2=0.29$, $P<0.001$; partial $r^2=0.46$, $P<0.001$), nighttime wind speed (partial $r^2=0.06$, $P<0.001$; partial $r^2=0.006$, $P=0.045$), and daytime PAR (partial $r^2=0.02$, $P<0.001$; partial $r^2=0.05$, $P<0.001$) together explained 37.3 and 51.4% of the soil temperature changes under day and night warming, respectively. At the monthly scale, daytime PAR

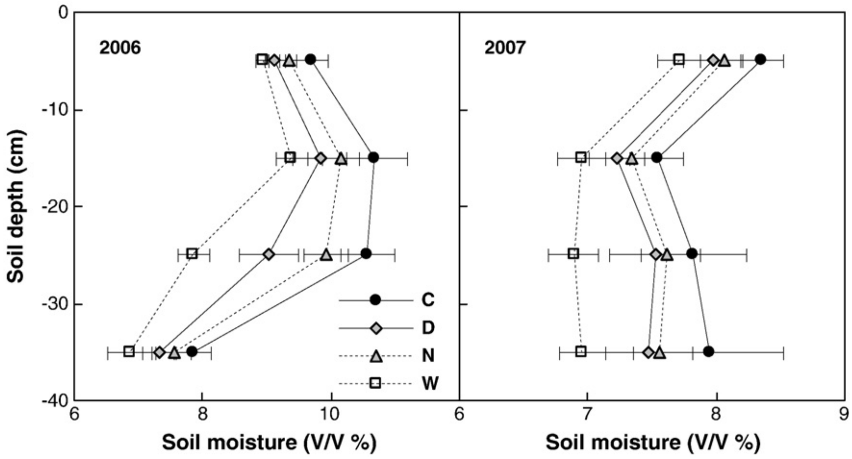

Fig. 4. Volumetric soil moisture (means ± 1SE) at the four soil depths along the soil profile in the two growing seasons of 2006 and 2007. C, control; D, day warming; N, night warming; W, continuous warming.

alone contributed 70.5 and 89.8% to the variances in the soil temperature changes under day and night warming, respectively (Table 3).

Across the 24 plots, averaged daily soil temperature over the experimental period showed a negative linear correlation with mean volumetric soil moisture ($r^2 = 0.25$, $P = 0.014$; Fig. 8a) and vegetation cover ($r^2 = 0.23$, $P = 0.018$; Fig. 8b). In addition, the warming-induced changes in daily soil temperature also negatively depended upon the warming-induced changes in volumetric soil moisture ($r^2 = 0.24$, $P = 0.042$; Fig. 8c) and vegetation cover ($r^2 = 0.12$, $P = 0.155$; Fig. 8d).

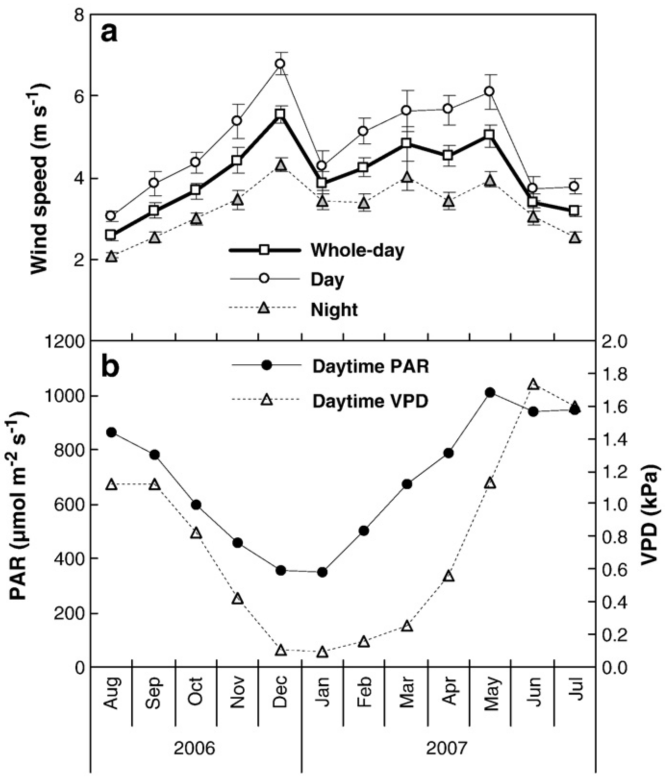

Fig. 5. Dynamics of (a) daytime, nighttime, and daily mean wind speed and (b) daytime photosynthetic active radiation (Daytime PAR) and daytime vapor-pressure deficit (Daytime VPD) from 1 August 2006 to 31 July 2007.

4. Discussion

4.1. Soil temperature

Changes in soil temperature induced by infrared heaters in other ecosystem types (all with an electrical input of 1500 W), such as subalpine meadow (up to 3 °C; Harte et al., 1995), peatlands (1.6–4.1 °C; Bridgham et al., 1999), and tallgrass prairie (2.0–2.6 °C; Wan et al., 2002), were greater than those reported in the present study under the continuous-warming treatment (1.71 °C). The continuous warming in this study increased daily maximum more than minimum soil temperature, leading to amplification of the diurnal soil temperature range in this ecosystem. The increases in diurnal soil temperature range (1.43 °C) induced by the continuous warming in this ecosystem were greater than that in a previous study (0.7 °C; Wan et al., 2002) which used similar approaches to quantify the warming effects in a tallgrass prairie in USA. These results support the prediction that the warming effects on soil temperature are greatly dependent on ecosystem type (Chen et al., 2008).

This study, to our knowledge, is the first field experiment to examine the differential impacts of day and night warming on soil temperature. The greater effect of night than day warming on nighttime soil temperature is reasonable because only the night-warming plots, but not the day-warming plots, were heated over night. At the hourly scale, night warming increased soil temperature more than day warming did nearly through the entire nighttime period (20:00–6:00; Table S1; Fig. 2a). During daytime, it was unexpected that the impact of night warming on daytime mean soil temperature was equal to that of day warming. The hourly dynamic of warming effects showed that night warming elevated soil temperature more than day warming did in the morning (before 11:00), whereas day warming caused greater increases in soil temperature than night warming between 11:00 and 18:00 (Fig. 2a). The greater positive effects of night warming on soil temperature in the morning (6:00–11:00) after the infrared heaters were turned off than at night (18:00–5:00) suggest strong lagged effects of night warming on soil temperature. Our observations in this study are inconsistent with the results reported in Mols, Denmark (see Fig. 5D in Beier et al., 2004) where infrared reflectors were used to heat canopy and soil at night and the magnitudes of soil temperature increases declined after the infrared reflectors were removed.

In the theoretical calculations done by Kimball (2005), when the wind speed is above about 0.5 m s^{-1}, the heating requirement for a standard alfalfa canopy during daytime is roughly double that at night

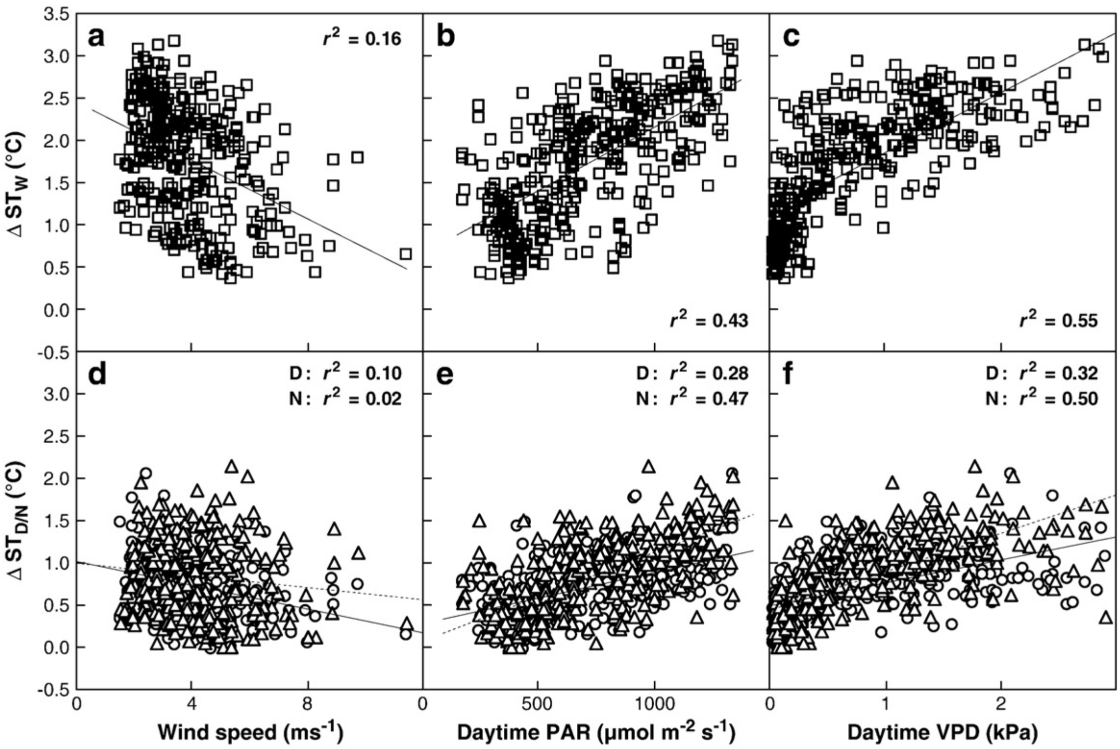

Fig. 6. Temporal dependence of soil temperature increases under continuous (a, b, and c), day, and night (d, e, and f) warming upon wind speed, daytime photosynthetic active radiation (Daytime PAR), and daytime vapor-pressure deficit (Daytime VPD) from 1 August 2006 to 31 July 2007. D, day warming; N, night warming; W, continuous warming. Day warming: cycles and solid lines; Night warming: triangles and dotted lines.

because of the closing stomata. However, in this study, the increase in daily mean soil temperature under night warming (0.78 °C) was only slightly greater than that under day warming (0.71 °C). Two possible reasons could explain the small difference between day and night warming on daily mean soil temperature. Firstly, given the relatively low soil moisture (Fig. 4) and canopy cover (31.8%–51.0%; Fig. 8b) at this site, half or more of the thermal radiation was absorbed directly by the soil surface, therefore temperature changes would not be affected much by stomatal opening and closing. Secondly, on the one hand, greater daytime wind speed could have caused greater energy loss in the day-warming plots than the night-warming plots. On the other hand, the thermal transfer from the soil to the air at night could have caused greater energy loss in the night-warming than day-warming plots. As a consequence, the net energy loss over the 24-h diurnal cycle might have been approximately equal between the day-warming and night-warming plots, leading to similar temperature increases under these two warming regimes.

Table 3
Results of stepwise regression analyses between the hourly, daily, and monthly increases in soil temperature at the depth of 10 cm and vapor-pressure deficit (VPD), photosynthetic active radiation (PAR) and wind speed. Wind speed was divided into day- and nighttime averages and daytime VPD and PAR were used for analysis of daily data. D − C = Day warming minus control, N − C = Night warming minus control, W − C = Continuous warming minus control.

	Variable entered	Coefficient	Partial r^2	Probability
Hourly				
D − C	VPD	0.4633	0.9752	<0.0001
N − C	Wind speed	−0.0144	0.2578	0.0113
	PAR	−0.2832	0.1658	0.0228
	VPD	0.0002	0.2806	0.0003
W − C	PAR	0.0009	0.9538	<0.0001
Daily				
D − C	Daytime VPD	0.1549	0.2864	<0.0001
	Nighttime wind speed	−0.0726	0.0631	<0.0001
	Daytime PAR	0.0003	0.0235	0.0006
N − C	Daytime VPD	0.2654	0.4611	<0.0001
	Daytime PAR	0.0005	0.0468	<0.0001
	Nighttime wind speed	−0.0282	0.0061	0.0454
W − C	Daytime VPD	0.4814	0.5259	<0.0001
	Nighttime wind speed	−0.1622	0.0844	<0.0001
	Daytime PAR	0.0005	0.0209	<0.0001
Monthly				
D − C	Daytime PAR	0.0009	0.7050	0.0006
N − C	Daytime PAR	0.0015	0.8979	<0.0001
W − C	Daytime PAR	0.0020	0.8137	<0.0001

At the daily scale, the regression analysis showed no difference between the effects of continuous warming and the summed effects of day and night warming on soil temperature (Fig. 3a). However, the summed changes in temperature under day and night warming were lower during daytime but greater at night than those under continuous warming (Fig. 3b, c). In terrestrial ecosystems, different biological processes occur at night and during daytime, and even the same process changes greatly between day- and nighttime. For example, photosynthesis occurs during daytime, while there is only respiration at night. Therefore, day and night warming are likely to differently affect terrestrial processes and the summed effects of day and night warming could not be predicted by those of continuous warming. For example, in the same ecosystem, it has been found that the changes in both soil respiration and gross ecosystem productivity under continuous warming are not equal to the summed changes under day and night warming (Xia et al., 2009a). However, most manipulative experimental studies (Rustad et al., 2001) have been conducted with continuous warming, and some large-scale climate–carbon models (Cao et al., 2004; Sitch et al., 2005; King et al., 2006) usually use daily, monthly, and annual mean temperatures as climate driver in predicting the terrestrial C cycling under global warming. Our observations in this study and two previous studies (Wan et al., 2009; Xia et al., 2009a) in the same manipulative experiment are critical for improving model simulation and projection of terrestrial feedbacks to climate warming.

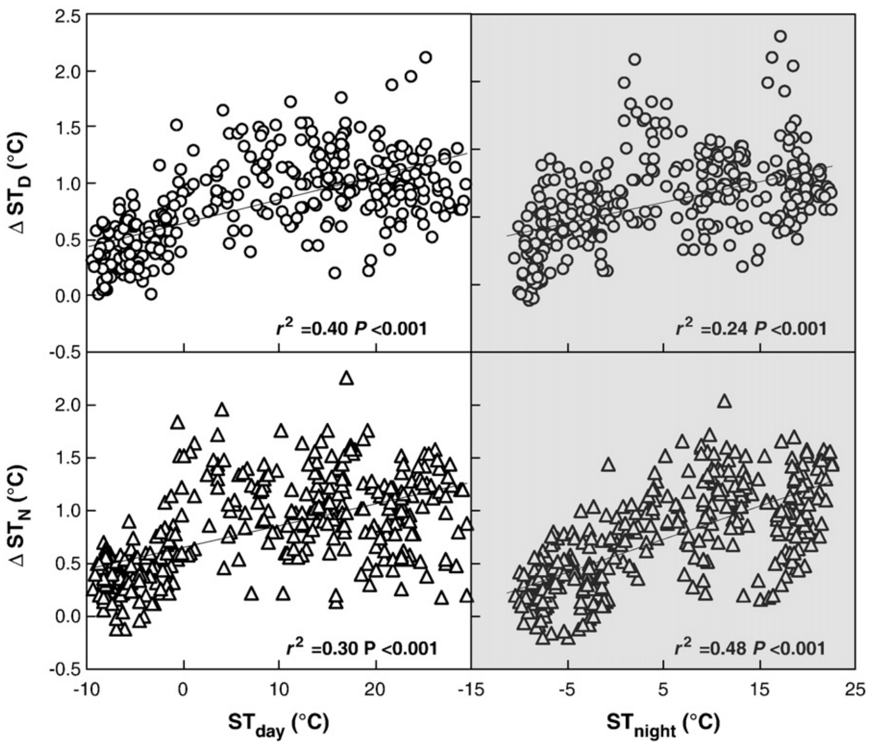

Fig. 7. Temporal dependence of soil temperature increases at the depth of 10 cm to day (cycles) and night (triangles) warming on day- (a, c) and nighttime (b, d) mean wind speed. The shaded area denotes the nighttime.

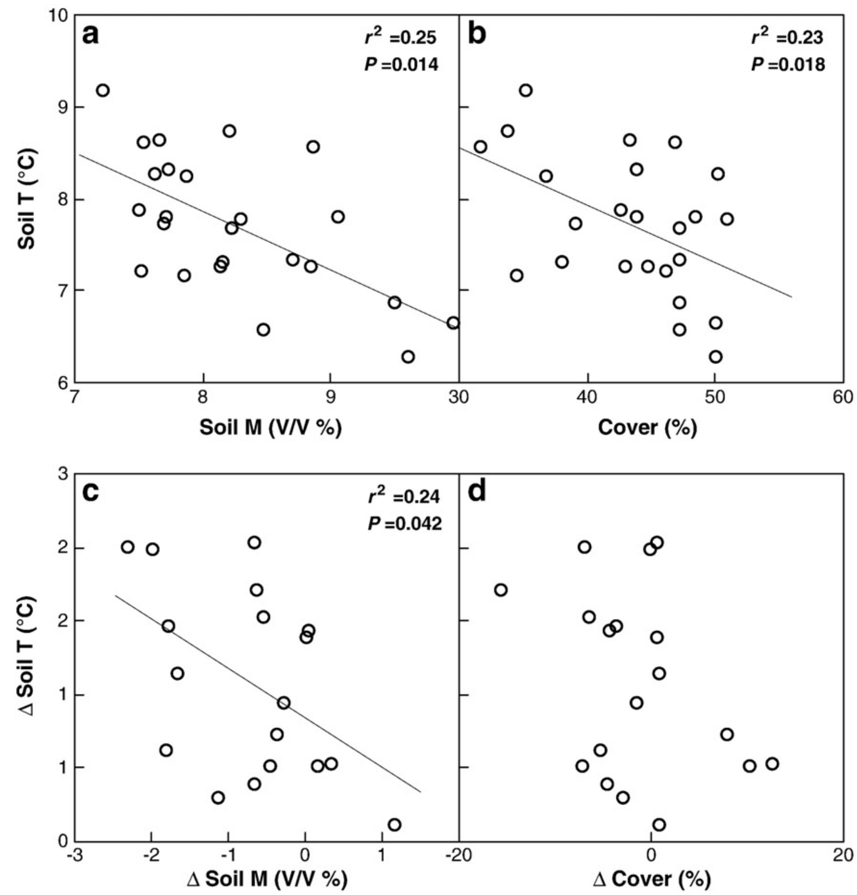

Fig. 8. Spatial dependence of mean soil temperature at the depth of 10 cm on (a) mean volumetric soil moisture at the depth of 0–40 cm and (b) vegetation cover and the warming-induced changes in soil temperature at the depth of 10 cm upon warming-induced changes in (c) volumetric soil moisture at the depth of 0–40 cm and (d) vegetation cover.

4.2. Soil moisture

In the present study, we found that soil moisture was differently affected by day, night, and continuous warming. The reduction in soil moisture under continuous warming was consistent with other warming studies using infrared heaters (Harte et al., 1995, 1996; Niu et al., 2008). The insignificant reduction of soil moisture under night warming in both 2006 and 2007 was consistent with a recent warming study (+1.2 °C during daytime and +1.7 °C at night; Luo et al., 2009) in the Tibetan plateau where no change in soil moisture was detected under greater night warming. Loss of soil water would reduce latent heat flux and enhance warming effects on soil temperature because more energy by infrared heaters dissipates as soil heat flux (Chapin et al., 2002). This speculation is supported by our data that not only daily mean soil temperature was negatively correlated with soil moisture (Fig. 8a), but also warming-induced increases in soil temperature decreased with warming-induced changes in soil moisture (Fig. 8c). In addition, our results are consistent with findings of a previous study in which warming-induced increases in soil temperature were negatively correlated with soil moisture (Wan et al., 2002).

In this study, no interactive effects between warming and depth was found on soil moisture, suggesting that the negative effects of warming on soil moisture occur at all depths from 0 to 40 cm (Fig. 4). However, we found greater negative impacts of warming on soil moisture in 2006 than 2007. This could be attributed to the greater effects of warming treatments on evapotranspiration in 2006 than 2007 (Fig. 9). In the steppe ecosystem, transpiration accounts for the majority of water loss from soil to the atmosphere (Wan, unpublished data). Greater precipitation, soil water availability and canopy cover in 2006 than in 2007 (Xia et al., 2009b) imply greater plant biomass growth and transpiration in 2006, thus enhancing warming responses of evapotranspiration and soil water availability.

4.3. Biotic and abiotic factors that influence warming effects on soil temperature

Environmental factors, such as wind speed, solar radiation, and vapor-pressure deficit, have been used in many biophysical models (e.g., Penman–Monteith equation; Monteith, 1965) to predict the energy balance between land surface and the atmosphere. Linear regression analyses in this study demonstrated that warming effects on daily mean soil temperature were greatly influenced by environmental conditions, including wind speed, daytime PAR, and daytime VPD (Fig. 6). Multiple regression analysis showed that continuous-warming effects on daily mean soil temperature were mainly related

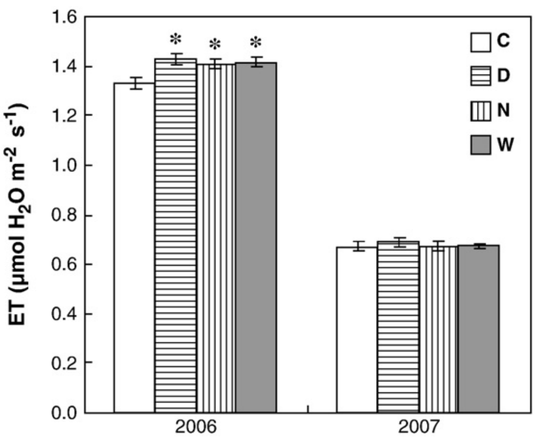

Fig. 9. Seasonal mean evapotranspiration (ET) determined in the static chambers across 2006 and 2007. C, control; D, day warming; N, night warming; W, continuous warming. Significance between treatments and control are indicated by an asterisk (*) ($P<0.05$).

to daytime VPD, while solar radiation was the dominant factor affecting the warming-induced increases in hourly and monthly soil temperature (Table 3). In addition, solar radiation and VPD were the dominant factors in controlling changes in monthly and daily soil temperature, respectively. At the hourly scale, the effect of day warming on soil temperature was determined by VPD, while night-warming effect was mainly controlled by wind speed. Our observations indicate that the variations in abiotic factors, including VPD, PAR, and wind speed, are important in regulating the effects of warming on soil temperature at different temporal scales.

Changes in VPD are determined by the interactions between latent and sensible heat fluxes from ecosystems. Sensible heat flux can warm air and increase the quantity of water vapor that air can hold. On the other hand, evaporation of water would cool down the soil surface and reduce the temperature difference between the soil and the air, resulting in lower sensible heat flux and thus greater latent heat flux (Chapin et al., 2002). Therefore, higher VPD causes greater evaporation and soil water consumption, leading to a greater increase in daily mean soil temperature under the warming treatment (Fig. 6c, f). The dependence of continuous-warming effects upon VPD in this study is similar to that in a tallgrass prairie reported in a previous study which found VPD is the primary factor influencing daily and monthly increase in average soil temperature (Wan et al., 2002). Solar radiation can strongly impact diurnal patterns of warming effects on soil temperature, especially in the sites where the soil was dried by the heaters (Harte et al., 1995). Warming-induced reduction in soil moisture not only increases the partition of infrared radiation to soil heat flux that raises soil temperature, but also causes more solar radiation to be partitioned to soil heat flux instead of latent heat. As a result, the increases in soil temperature showed a positive dependence upon daytime PAR (Table 3; Fig. 6b, e) and a midday peak under the continuous warming (Fig. 2a) in this study. By generating surface turbulence (Chapin et al., 2002), wind blows the energy from infrared heaters away and weakens the warming effects on soil temperature (Table 3; Fig. 6a, d). In previous studies (Wan et al., 2002; Kimball, 2005; Kimball et al., 2008), wind speed has also been shown to negatively impact thermal radiation efficiency of the infrared heaters. Kimball (2005) provided a theoretical equation that predicts the decrease of efficiency as a function of heater physical properties and increase in wind speed.

In this study, the greater reduction in soil moisture under day than night warming indicates more solar radiation (mainly in daytime) partitioned to soil heat flux that increases daytime mean soil temperature in the plots of day than night warming, implying that day warming elevates daytime mean soil temperature more than night warming. However, the stronger wind during daytime than at night could have counteracted the positive impacts of day warming on daytime mean soil temperature. Over the diurnal cycle, the elevation of soil temperature under day warming increased slowly from 6:00 and the peak value occurred at about 14:00. Effect of night warming, however, lasted until 10:00 and exceeded by day warming at about 11:00. Negative dependence of the changes in daytime soil temperature upon daytime wind speed under day warming only indicates that wind has a greater negative impact on the effects of day warming than night warming during daytime. Therefore, the increases in daytime mean and daily maximum soil temperature under night warming were similar to those under day warming in this study. At night, wind speed is lower than that during daytime, causing greater thermal radiation efficiency of night warming than day warming. However, increases in soil temperature induced by night warming did not diminish during daytime, whereas increases in soil temperature under day warming declined rapidly at night (Fig. 2a). The latter could have been attributable to the rapid decrease in air temperature after sunset and the thermal transfers from soil to the air (Shao et al., 2007). Thus, nighttime mean and daily minimum soil temperature was increased more by night than day warming in this study. At the daily scale, the negative impact of wind speed (Fig. 6d; $P<0.001$) on the increases in soil temperature was greater under day than night warming, whereas the positive influences of daytime PAR (Fig. 6e; $P<0.001$) and VPD (Fig. 6f; $P<0.001$) on the increases in soil temperature were greater under night than day warming. As a result, daily mean soil temperature could be increased more by night than day warming in this ecosystem.

Biotic factors such as vegetation cover can also influence warming effects on soil temperature because vegetation can intercept the radiation from infrared heaters and reduce the energy input into the soil (Harte et al., 1995). In this study, aboveground net primary productivity was not affected by day or night warming in the first 3 growing seasons (Wan et al., 2009), suggesting that the short-term responses of soil temperature to warming treatments in this ecosystem is mainly controlled by abiotic factors. In the long term, the environmental factors have been suggested to change under the ongoing global change. For example, a general decrease in solar radiation at Earth's surface has been reported in the past years (Gilgen et al., 1998; Liepert, 2002). The reduction in solar radiation is likely to negatively impact the warming effects on soil temperature, especially during daytime. Recently, a decreasing trend of wind speed has been reported over the continental US (Pryor et al., 2009). In our system, wind speed also showed a declining trend during the past 50 years (Fig. S2), enhancing the efficiency of infrared radiations on soil temperature in the future. Thus, the simultaneously changes in the environmental factors can substantially influence the soil temperature in response to climate warming. In addition, warming-induced changes in vegetation cover may also be important in controlling the warming effects on soil temperature in the long term because a decreasing and an increasing trend of ANPP changes under day and night warming, respectively, have been observed previously in this ecosystem (Wan et al., 2009). In fact, mean soil temperature was lower in the plot with denser vegetation (Fig. 8b) and a negative dependence ($P=0.155$) of the warming-induced changes in soil temperature on the warming-induced changes in vegetation cover was found in this study (Fig. 8d). Our observations indicate that the concomitant changes in biotic and abiotic factors will have profound influences on soil temperature in a warmer world in the future.

4.4. Implications for impacts of climate change on C processes in temperate steppe

Irrespective of the no difference in the increases of daily and daytime soil temperature under day and night-warming treatments, the greater effects of night warming on nighttime mean soil temperature than day warming suggest that day and night warming may differentially affect soil biological processes. In fact, we have found that night warming stimulated soil respiration, whereas day warming had no effect in this system (Xia et al., 2009a). The positive effects of night warming on soil respiration was ascribed to not only its impacts on soil microclimate, but also the enhancement of ecosystem C assimilation by night warming (Xia et al., 2009a). The positive impact of night warming on ecosystem C assimilation has been ascribed to the photosynthetic overcompensation which was driven by the increased nighttime respiration and carbohydrate consumption in the leaves under night warming (Wan et al., 2009). Therefore, warming-induced changes in air temperature, which influences aboveground C processes, are also important in regulating ecosystem C responses to day and night warming. Because wind speed is greater during daytime and lower at night, infrared heaters increased air temperature at night, but it had no effect during daytime (Zhang et al., unpublished data). In our study, day warming did not change day- or nighttime mean leaf temperature, while night warming increased nighttime mean leaf temperature only (Wan et al., 2009). Thus, the impacts of climate change on ecosystem C exchange are determined by the responses of both above- and belowground C processes and their interactions to elevated temperature.

5. Conclusions

This study has revealed the equal effects on soil temperature between day and night warming during daytime, while the greater impacts of night than day warming at night. In addition, the effects of continuous warming were not equal to the summed effects of day and night warming on soil temperature either during daytime or at night. Because warming is often applied as a constant output of infrared radiation in field experiments and a constant elevation of daily mean temperature in modeling studies (Karl et al., 1991; McCarthy, 2001; Zhou et al., 2007), our observations indicate that influences of climate warming on ecosystem processes should consider not only the continuous-warming effects but also the differential impacts of day and night warming (Xia et al., 2009a). Given that the diurnal asymmetrical pattern of climatic warming varies greatly among regions (Solomon, 2007) and that the effects of day and night warming are strongly dependent on biotic and abiotic factors, our findings highlight the need for future research to incorporate regional environmental variables and the differential impacts of day and night warming on ecosystem processes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.scitotenv.2010.03.016.

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