Article

Chinese Science Bulletin

Ecology

March 2013 Vol.58 No.8: 907–912
doi: 10.1007/s11434-012-5596-y

Effects of vegetation height and density on soil temperature variations

SONG YanTao[1], ZHOU DaoWei[2*], ZHANG HongXiang[2], LI GuangDi[3], JIN YingHua[1] & LI Qiang[2]

[1] *Institute of Grassland Science, Northeast Normal University; Key Laboratory of Vegetation Ecology, Ministry of Education, Changchun 130024, China;*

[2] *Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130102, China;*

[3] *Graham Centre for Agricultural Innovation (alliance between Industry & Investment NSW and Charles Sturt University), Wagga Wagga Agricultural Institute, PMB, Wagga Wagga, NSW 2650, Australia*

Received April 30, 2012; accepted September 24, 2012; published online January 9, 2013

Reduction in vegetation cover caused by human activities has a great impact on soil temperature. It is important to assess how soil temperature responds to reduction of vegetation height and density. In this paper we first report the trends of mean annual soil surface and air temperatures recorded at the meteorological stations near the Ecological Research Station for Grassland Farming (ERSGF) from 1961 to 2007, then we setup an experiment using reed (*Phragmites australis*) stalks with different heights and densities to simulate effects of different vegetation height and density on soil and air temperatures. The warming rates of the mean annual soil and air temperatures were 0.043 and 0.041°C a^{-1}, respectively. Changes of soil temperature were characterized by both increased mean annual maximum and minimum soil temperatures. At the experimental site, mean daily temperature, mean daily maximum soil and air temperatures increased significantly. In contrast, mean daily minimum soil temperature increased significantly while mean daily minimum air temperature decreased significantly as the height and density of reed stalks reduced during the experimental period. Mean diurnal soil temperature ranges were smaller than mean diurnal air temperature ranges. These results highlight that the importance of vegetation cover on soil and air temperatures.

vegetation cover reduction, human activities, global warming, temperature difference, soil temperature

Citation: Song Y T, Zhou D W, Zhang H X, et al. Effects of vegetation height and density on soil temperature variations. Chin Sci Bull, 2013, 58: 907–912, doi: 10.1007/s11434-012-5596-y

There is general consensus that the global climate has changed rapidly, and the global mean surface temperature has increased by 0.74°C between 1906 and 2005 [1]. The warming pattern shows that mean annual minimum temperature has increased almost two orders of magnitude of maximum temperature, i.e. an asymmetric diurnal temperature increase [2,3]. Apart from studies on atmospheric temperature continuously published, more focus on variation of soil temperature and its factors has emerged recently [4–9].

Soil temperature is a crucial factor involved in determining/affecting the rates of biochemical reactions and has a strong influence on plant and root growth [2,6]. Diurnal soil temperature range is particularly important in plant growth, such as seed germination and early season growth which are highly correlated with daily maximum temperature of the soil rather than with air temperature [7]. Similar to increased air temperature, soil temperature also increases based on the long-term trend. Hu and Feng [8] reported that soil temperature at 10 cm depth increased 0.031°C a^{-1} from 1967 to 2002 in the contiguous United States. A study recorded 27-year soil temperature at 5 depths showed a significant increase at a grassland in the Netherlands, and the warming rate of soil temperature was higher than air tem-

*Corresponding author (email: zhoudaowei@neigae.ac.cn)

perature [9]. However, there is little information about the variation of soil temperature. The variation pattern of soil temperature may differ from atmospheric temperature. Furthermore, the factors that cause soil temperature increase are not clear.

Soil temperature is determined by the soil surface heat energy balance [9,10], and ground cover. For example, changes in vegetation types or reduction of plant litter by human activities could change soil temperature through affecting the energy flux [2,10]. Scull [11] showed that vegetation cover was negatively correlated with soil temperature in Central New York State, USA. Plant litter removal also increased the soil temperature in grassland by 5–8°C at the beginning of the growing season [6].

Vegetation cover of the earth's surface has been transforming by land-use practices [12]. As a result, natural vegetation coverage including height and density decreased gradually [13,14]. Grazing is a natural process, but overgrazing usually results in shorter sward and reduced community density [14]. In extreme cases, overgrazing leads to high proportions of bare ground such as in many part of the Songnen Plain in Northeast China [15]. Other activities such as the burning or harvesting of forests have similar effects [12,16]. In general, reduction of vegetation height and density is becoming increasingly common in natural landscape in China. However, the consequence of this reduction in vegetation height and density on global warming has received little attention.

Because of the presence of intensive heat flux exchange among atmosphere-vegetation-soil [6,10,11], exploring the interactions among air, soil temperatures and vegetation features is helpful for deeply understanding the variation tendency of global climate warming. In this study, firstly, we analyzed the long-term trends of mean, maximum, minimum and amplitude of annual soil surface and air temperatures during 1961–2007 in the south of the Songnen Plain, and then, a field experiment was conducted in native grassland to compare the soil temperature changes with different heights and densities of reed stalks (*Phragmites australis*). The objectives of this study were: (1) to illustrate changes patterns of soil warming based on a long-term record; and (2) to examine the effect of vegetation height and density on soil temperature.

1 Materials and methods

1.1 Meteorological data collection

Monthly data sets of air temperature and soil surface temperature from 1961 to 2007 were collected from 5 meteorological stations at Baicheng, Qianguo, Tongyu, Da'an and Changling in Songnen Plain. Soil surface temperatures at Tongyu were only available from 1963 to 2006. All meteorological data were recorded on bare soil surface without vegetation cover.

1.2 Experimental site

The experiment was conducted at the Ecological Research Station for Grassland Farming (ERSGF) in Songnen Plain, Northeast China (44°33′N, 123°31′E, and elevation 145 m, Figure 1). The research station is in semi-arid, continental climate with an annual frost-free period between 140 and 160 d. Mean annual temperature and mean annual precipitation are 5.2°C and 453 mm from 1953 to 2007, respectively. Most precipitation is distributed between June and September. The annual potential evapotranspiration is approximately 3.5 times of the mean annual precipitation [17]. The main soil type is meadow chernozem with pH value ranging from 7.5 to 9.0. The natural grassland was dominated by *Leymus chinensis* [18].

1.3 Experimental design

The manipulative experiment was carried out on a native grassland from April to September in 2008. The existing vegetation was mowed before the experiment started. The dried stalks of reed were inserted into ground with three heights (30, 50 and 70 cm) and three densities (3, 5 and 10 cm distance between stalks) to simulate different vegetation height and density. There were 4 treatment combinations, i.e. 30×10 (height×density), 30×5, 50×5, 70×3. Plots without reed stalk were used as control (CK). There were three replicates for each treatment. The stalks were connected through fine strings to fix them to soil surface. The plot size was 2×2 m^2, with a 1-m buffer between two plots. The diameter and weight of each stalk were approximately 2.9 mm and 0.2 g/10 cm, respectively.

A NYZ-III Multipoint Automatic Temperature Recorder (Changchun Meteorological Instrument Research Institute, Changchun, China) was used to measure air (10 cm above soil surface) and soil temperatures (5 and 20 cm below soil surface). The sensors of the recorder were fixed at the center of each plot and temperature was recorded every 1 h during the experimental period.

1.4 Statistical analyses

Annual mean, maximum, minimum, amplitude of air temperature ($T_{\text{a-ave}}$, $T_{\text{a-max}}$, $T_{\text{a-min}}$ and $T_{\text{a-diff}}$), and annual mean, maximum, minimum, amplitude of soil temperature ($T_{\text{s-ave}}$, $T_{\text{s-max}}$, $T_{\text{s-min}}$ and $T_{\text{s-diff}}$) were calculated from the original data sets from the five meteorological stations. The tendency of temperature increasing or decreasing was derived from the slope of the linear regression using the least squares method [9].

The temperature data collected from the field experiment were analyzed using a one-way analysis of variance (ANOVA) for daily mean (Mean), maximum (Max), minimum (Min) and amplitude (Max-Min) of air and soil temperatures. A *post hoc* least significant difference test (LSD) was used to compare the multiple treatment mean values. Shallow soil

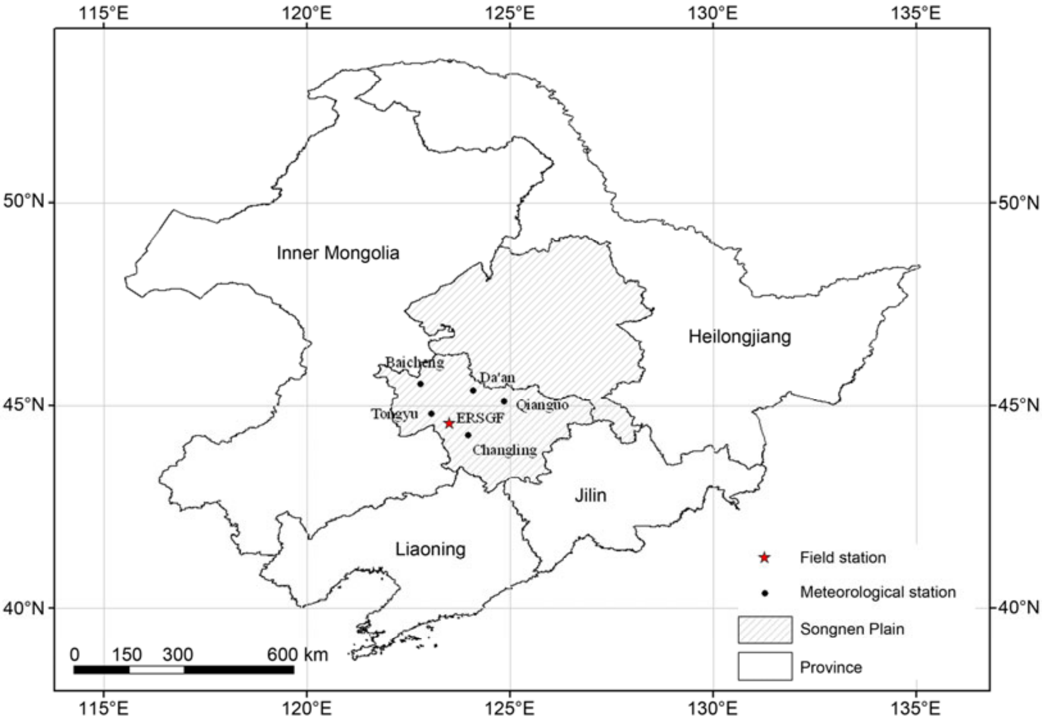

Figure 1 Distribution of the five meteorological stations and the field station in this study.

temperature defined by averaging the 5 and 20 cm deep soil temperatures in this study. All statistical analyses were carried out using SPSS (Version 13.0, SPSS Inc., Chicago, USA).

2 Results

2.1 Long-term trends of air and soil surface temperatures

From 1961 to 2007, $T_{a\text{-ave}}$, $T_{a\text{-max}}$, $T_{a\text{-min}}$, and $T_{a\text{-diff}}$ increased significantly by the rate of 0.041 (R^2=0.44, P<0.01), 0.025 (R^2= 0.17, P<0.01), 0.056 (R^2=0.61, P<0.001) and −0.031°C a^{-1} (R^2=0.45, P<0.001), respectively (Figure 2(a)). During the same period, $T_{s\text{-ave}}$, $T_{s\text{-max}}$, $T_{s\text{-min}}$, and $T_{s\text{-diff}}$ also increased, by the rate of 0.043 (R^2=0.44, P<0.001), 0.043°C a^{-1} for $T_{a\text{-max}}$ (R^2=0.198, P=0.002), 0.053 (R^2=0.54, P<0.001) and −0.010°C a^{-1} (R^2=0.02, P<0.05), respectively (Figure 2(b)). The annual mean and maximum of soil temperatures increased at a higher rate than those of air temperatures (Figure 2).

2.2 Air and soil temperatures at manipulative experiment

Mean daily air temperature showed a similar but more fluctuating pattern with time than soil temperature, and soil temperature at 20 cm depth was least variable (Figure 3). At 5 and 20 cm depth, the treatments with shorter and lower density reed had greater increase in temperature. However, the differences of air temperature between treatments were small (Figure 3(a)).

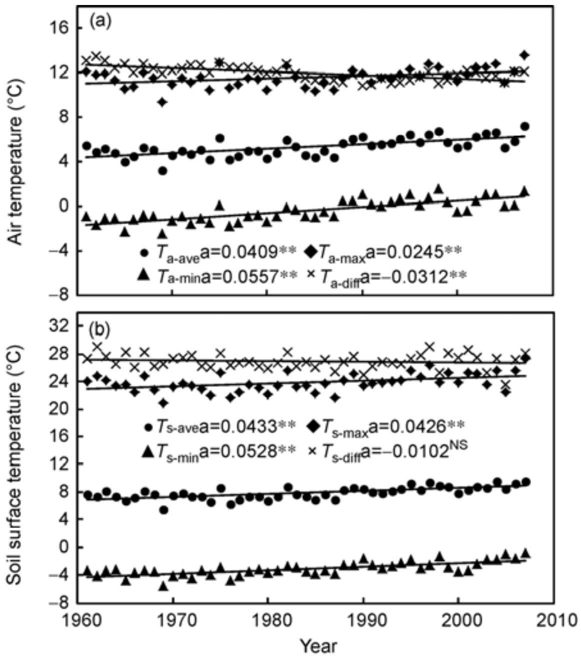

Figure 2 Linear trends of annual (a) air and (b) soil surface temperatures from 1961 to 2007 for five meteorological stations near the study site. The solid line represents the linear fitting, where a (°C a^{-1}) is the regression slope. **, P<0.01; NS represents not significant.

2.3 Mean, maximum, minimum and amplitude of air and soil temperatures at manipulative experiment

Mean daily air temperature increased significantly as height and density of reed stalks decreased, with a 2°C difference

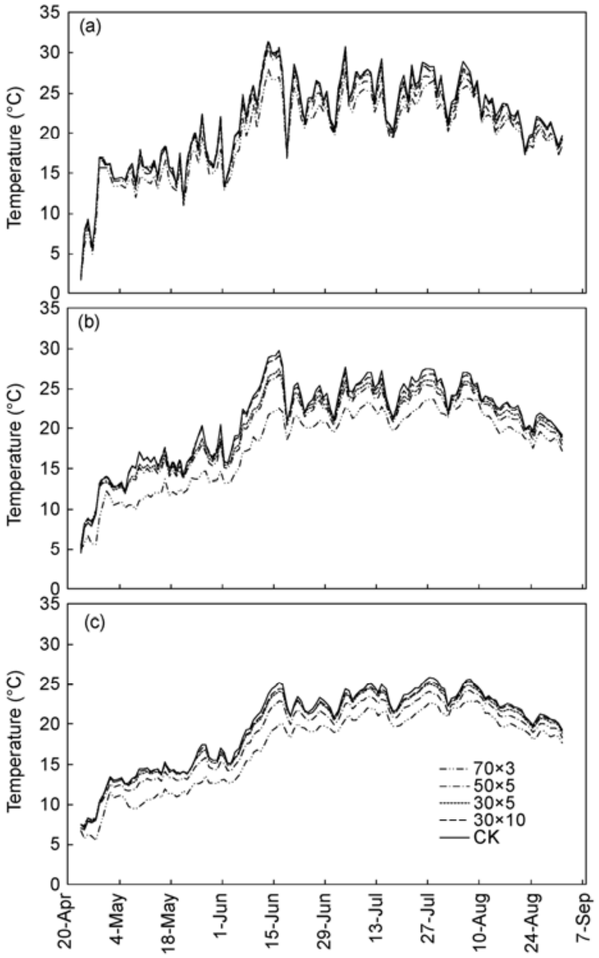

Figure 3 Changes in mean daily air and soil temperatures (°C) from 23 April to 1 September 2008. (a) Air temperature at 10 cm above soil surface, (b) soil temperature at 5 cm below soil surface, and (c) soil temperature 20 cm below soil surface.

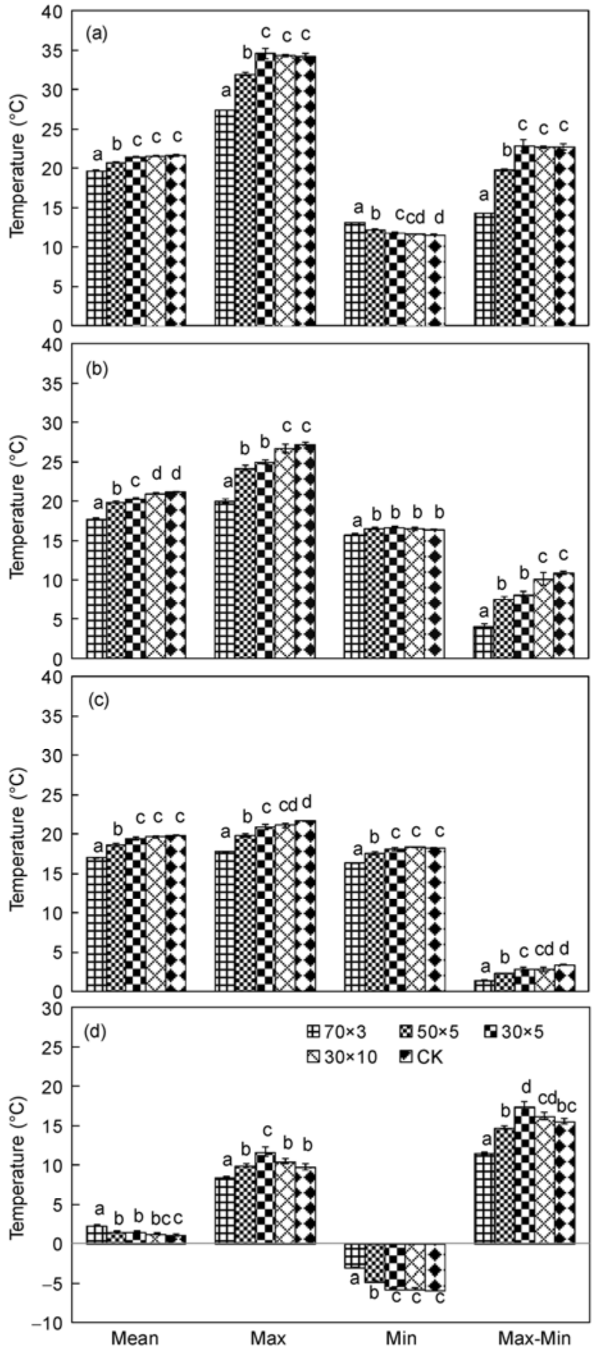

Figure 4 Mean, Max, Min and Max-Min temperatures from 23 April to 1 September 2008 in different treatments at (a) 10 cm above soil surface, (b) 5 cm below soil surface, (c) 20 cm below soil surface, and (d) temperature difference between air and soil shallow temperature. Bars (mean ± SE) with different letters are significantly different ($P < 0.05$).

between the control and the 70×3 treatment (P<0.05). The mean air temperatures of 30×5, 30×10 and the control treatments were significantly higher than those of the 70×3 and 50×5 treatments (Figure 4(a)). Mean maximum and amplitude of air temperatures had similar results to the mean daily temperature (Figure 4(a)). However, the mean daily minimum air temperature had the opposite pattern, in which temperature decreased significantly as height and density of reed stalks decreased.

For soil temperatures at the 5 and 20 cm below soil surface, the Mean, Max, Min and Max-Min temperatures all increased significantly as the height and density of reed stalks decreased (Figure 4(b) and (c)). Mean soil temperature at 20 cm depth was lower than that at 5 cm depth (Figure 4(b) and (c)).

2.4 Temperature difference between air and shallow soil temperatures at manipulative experiment

Mean daily air temperatures at 10 cm above the soil surface were higher than shallow soil temperatures except mean daily minimum temperatures (Figure 4(d)). Temperature difference between mean daily air and shallow soil temperatures of the 70×3 treatment was significantly higher than other treatments (Figure 4(d)), and the control had the lowest value. Temperature difference of mean daily maximum and mean amplitude showed a similar pattern (Figure 4(d)).

3 Discussion

Few studies have compared patterns of soil warming and air warming in long-term record, and no report has considered the effect of vegetation coverage on soil temperatures. Our results from long-term records demonstrated that the warming rate of soil surface temperature was higher than that of air temperature during the years 1961–2007. Soil temperature was characterized by both increased mean annual maximum and minimum soil temperatures, whereas the increase in air temperature was primarily due to increased mean annual minimum air temperature. Mean, maximum, and minimum air and soil temperatures changed significantly as height and density of reed stalks changed. We also analyzed the temperature difference between air and soil temperatures which is often been overlooked in the field experiments about global warming research.

Land cover change influences both air and soil temperatures [7]. Our field experiment showed that the air and soil temperatures increased as the height and density of reed stalks decreased (Figure 3). It is probably due to the fact that the solar radiation was intercepted or reflected by the reed stalks instead which reduced the radiation absorption of soil and therefore resulted in lower soil and air temperatures nearby [6,11]. Smaller diurnal temperature range was detected in the plots covered with higher and denser reed stalks (Figure 4). Many studies have suggested that seed germination and early season growth were more correlated with maximum daily soil temperature (so long as the minima are not lethal) than with air temperature [7]. Our results showed that reed stalks significantly decreased both air and soil maximum temperatures (Figure 4). Interestingly, the differences between air and soil temperatures were significant different among the treatments (Figure 4(d)). In other words, the reduced height and density of vegetation decreased the difference between air and soil temperatures in the growing season. This is caused by the reduction of vegetation height and density which can increase the heat flux between soil and atmosphere. The variation of the difference between air and soil temperatures may alter the microenvironment and affect the structure and dynamics of plant communities. For example, the aboveground and underground growth rate of plants would respond to the variation of temperature [7], which in turn would influence the interactions and feedbacks between plant and soil. Zheng [19] found that decreasing temperature difference between soil and air temperatures significantly affected seeding height and mass, root length, fine root number of *Convolvulus arvensis*, as well as its distribution.

The Songnen grassland (Figure 1) became seriously degraded because of heavy grazing, excessive cutting, as well as the out-of-control exploitation for fuels and medical plants [14,20]. Degradation is represented by apparent reduction of height and density of plants as well as the reduction of vegetation cover [20]. The mean height of *L. chinensis* grassland in Songnen Plain reduced from 80 cm in the early 1950s to 60 cm in 1960’s and 40 cm in 1990’s, while the vegetation cover in summer was 85%, 70%–80% and 60%–70% during those periods [20]. Furthermore, in 1990’s, the mean height was only 10–15 cm with vegetation cover as 10%−20% in the severely degraded grassland [20]. In the degraded grassland, ground is still covered by herbaceous vegetation, however, the community height and plant density reduced. Vegetation cover reduction of grassland reduces the shading of the ground beneath it and increases soil temperature. Results from long-term trend analysis showed that soil temperatures of five meteorological stations from May to September increased by 0.045 (R^2=0.452, P<0.001) and 0.059°C a^{-1} (R^2=0.624, P<0.001) at 5 and 20 cm depth, respectively (unpublished data). The field experiment also showed that reduction of plant height and density resulted in increasing soil temperatures (Figures 3 and 4), which might contribute to warming of the soil over the long term.

The increasing soil temperature caused by cover reduction of grassland vegetation would increase soil evaporation, affecting plant on water use, and restricting the recovery of degraded grassland [4,9,18]. In a *L. chinensis* steppe of the Inner Mongolia, vegetation height and density reduction by grazing increased soil temperature, decreased soil moisture and therefore decreased grassland productivity [21]. Soil temperature warming also may increase the soil respiration, consume more soil organic matter, alter the carbon cycles, and accelerate the harm of grassland desertification and sandstorms [12,18]. Furthermore, the interactions between the underlying surface and the atmosphere can impact on the weather and climate change at various scales [22]. Studies of soil temperature warming contribute to our knowledge on understanding surface energy processes and regional environmental and climatic conditions [8], i.e. soil temperature warming heats up the lower atmospheric circulation as well as modifies local atmospheric circulations, and therefore can affect regional weather and climate.

The increase of global mean atmospheric temperature is now regarded as being more rapid for the mean annual minimum temperature than that of the maximum temperature, leading to asymmetric warming of atmosphere [1,3,23]. The tendency of air temperature from the meteorological stations in this study also showed an asymmetric warming pattern. In addition, the diurnal air temperature range decreased significantly (Figure 2(a)). However, little is known about the soil temperature warming pattern [9]. We found that the warming rates of mean, maximum and annual minimum soil surface temperatures were increased significantly from 1961 to 2007 (Figure 2(b)). Interestingly, the mean annual soil surface temperature did not show such an asymmetric warming compared to that of the air temperature. Instead, the warming rate of minimum soil surface temperature is similar to that of maximum soil surface temperature. The warming pattern of soil temperature affected soil organism communities [24] and belowground biological processes, including the dynamics of soil organisms, plant root growth, seed germination, nutrient uptake and decomposition [9].

Under the background of global climate change, the warming rate of soil temperature was found to be faster than that of the air temperature (Figure 2). The manipulative experiment also showed that the temperature difference between air and soil temperatures decreased with the reduction of reed height and density (Figure 4(d)), which indicated faster increasing of soil temperature than air temperature if the vegetation cover is reduced (Figure 4(a)–(c)). The different variation of air and soil temperature may have complex potential effects on the grassland ecosystem. For example, the asymmetric warming pattern of air and soil temperature may change the adaptive strategies of plant as the aboveground and underground growing in two different interfaces.

4 Conclusions

The warming rate of soil temperature is higher than that of air temperature. The maximum and minimum soil temperatures have the similar warming trends which lead to insignificant change of the diurnal soil temperature range. Reduction of plant height and density is likely to be an important factor that increases soil temperature and results in the asymmetric warming pattern between air and soil temperatures. Our observations indicate that influences of climate change on ecosystem processes should consider not only the air or soil temperature warming but also the asymmetric warming pattern between air and soil temperatures.

Turkington Roy, Xinxin Xue, and Wang Ping provided helpful comments on the manuscript. We are especially grateful for Cai Hongyan who helped produce Figure 1. We thank the editor and reviewers for helpful revisions. This work was supported by the National Basic Research Program of China (2011CB403200, 2011CB403203).

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