

RESEARCH ARTICLE

Impact of diurnal unsymmetrical warming on soil respiration in an agroecological system of the Lhasa region

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Abstract

Purpose

The impact of diurnal unsymmetrical rise in temperature on soil respiration (R_s) is not fully understood; thus, we explored such a warming influence on R_s in an agroecological system of the Lhasa.

Materials and methods

A field warming experiment (C: control; DW: daytime warming; NW: nighttime warming; DW+NW: daytime plus nighttime warming) was carried out in a naked barley ecological system.

Results and discussion

The DW, NW and DW+NW treatments dramatically increased soil temperature and decreased soil moisture but did not markedly modify R_s . The effects of DW and NW on soil respiration sensitivity (Q_{10}) during the daytime and nighttime were different; they had no effects on daytime Q_{10} of R_s , but a significant inhibitory effect on nighttime Q_{10} of R_s .

Conclusions

A diurnal unsymmetrical rise in temperature brought about different results for the Q_{10} of R_s but did not cause changes in R_s under different experimental treatments in agroecological systems of the Lhasa.

Introduction

Global surface temperature shows a slower increase during the day than at night[1]; due to the complexity of geographic elements and the interaction of climatic factors, there is still a significant asymmetry in global warming[2]. The magnitude of nighttime temperature increase is

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significantly higher than daytime[3], and both temperatures' impacts on terrestrial ecological systems are most likely different from each other[4, 5]. For instance, a daytime rise in temperature has a stronger effect on net nitrogen mineralization than a nighttime rise does at the global scale [6]. The Qinghai-Xizang Plateau is experiencing noticeable diurnal unsymmetrical rise in temperature [7]. Although increasing numbers of warming studies have discovered the influence of rise in temperature on cold and high-altitude ecological systems on the Qinghai-Xizang Plateau[8–10], only a few have explored the influence of diurnal unsymmetrical rise in temperature on cold and high-altitude meadows[11, 12]. However, besides these meadows, there are several other cold and high-altitude ecological systems (e.g., agroecological system)[13–20] which have not been researched. Agroecological systems, mainly distributed in semiarid valley districts, are experiencing noteworthy rises in temperature[21–23] and are extremely fragile because of high elevation (generally 3000–4500 m), low air temperature and arid/semiarid climatic circumstances in the Qinghai-Xizang Plateau[24–26]. Therefore, it is necessary to explore how diurnal unsymmetrical warming can affect the agroecological system.

Soil respiration is closely related to the global carbon cycle[27]. This nonuniformity of day-night temperature increase profoundly affects the response and feedback of terrestrial ecosystems' carbon cycles to global climate change. R_s is estimated to be more susceptible to rise in temperature in agroecological systems than other ecological systems (e.g., grassland ecological systems) considering that rural soils have better soil moisture (SM) and ventilation [28]. Several studies have explored the impact of experimental warming on R_s in a variety of agroecological systems [29, 30]; but there are inconsistent results, reporting both positive[11] and negligible[31, 32] effects, on the impact of warming on R_s in the Qinghai-Xizang Plateau. Although increasing numbers of studies concentrate on the impact of experimental warming on R_s in forest and grassland ecological systems[8, 32], only two studies have explored the influence of rise in temperature on R_s in agroecological systems of the Qinghai-Xizang Plateau [29, 30]. These two studies only explored the influence of rise in temperature on R_s during a single growing season, whereas the impact of rise in temperature on R_s may change within the year in cold and high-altitude districts [33]. Furthermore, [30] reports the impact of DW+NW treatment on R_s only during the daytime (8:00–20:00), while [29] shows the impact of DW+NW treatment on R_s during only the daytime (8:00–20:00) and only nighttime (20:00–8:00). Therefore, how diurnal unsymmetrical warming can modify R_s in agroecological systems of the Qinghai-Xizang Plateau remains unclear.

To the best of our knowledge, studies of the effect of diurnal unsymmetrical warming on R_s in the Qinghai-Tibet Plateau have only been carried out in alpine meadows[11]. However, the response of R_s to asymmetric warming in agroecological systems has not been studied. Since the naked barley ecological system is one of the dominant agroecological systems in the Lhasa [34], a diurnal unsymmetrical warming experiment (C: control; DW: 8:00–20:00; NW: 20:00–8:00; DW+NW: 8:00–8:00) was carried out during two growing seasons in 2015–2016 to compare the impacts of the DW, NW and DW+NW treatments on R_s and Q_{10} of R_s in such an ecological system of the Lhasa region.

Materials and methods

Research area and experimental design

The study area is located at the Lhasa Agroecosystem Research Station, Tibet Autonomous Region in China(91°21'E, 29°41'N, 3688 m). The annual average temperature is 7.9°C, and the average annual precipitation is 425 mm. Since the 1970s, the soil in this area has been used for cultivating crops. A number of studies described the research area conditions (e.g., climate traits) [29, 30]. Infrared heaters (Kalglo Electronics Inc., Bethlehem, PA, USA) were positioned

on the ground approximately 1.7 m in the center of each 2 m×2 m plot and used to enhance soil temperature (T_s) during the two growing seasons of a naked barley ecological system (April 23–August 24 in 2015; April 15–August 16 in 2016). The dimensions and installation heights of infrared heaters, sowing rates and rows of naked barley, and sizes of and distances between sample plots matched those given in a previous study [29]. The field experiment was completely randomized design, with four treatments (C, DW, NW and DW+NW) and four replications per treatment. Both the Lhasa Agroecosystem Research Station and the village leaders gave us permission to conduct our study on their land. All the plants we used were planted by the experimental staff on the station.

Biomass, microclimate and R_s measurements

We sampled aboveground and belowground portions of naked barley on August 16, 2016, and rinsed any residual soil off with water. Then, the plant sample was dried at a constant temperature of 65°C for 48 h; the weight of the aboveground vegetation was the aboveground biomass, and the weight of the root was the underground biomass.

We measured soil moisture (SM) and temperature (T_s) (5 cm) during the whole research period in 2015–2016. In the center of each plot, we set T_s and SM sensors at a depth of 0.05 m. For each plot, the data of the two sensors was exported via the data logger (HOBO weather station, Onset Computer, Bourne, MA, USA). Data were measured every minute and processed to provide an average value every 5 minutes.

We used LI-8100 (LI-COR Biosciences, Lincoln, NE, USA) to measure daily cycles of R_s during the entire research period in 2015–2016. The R_s observation interval was 2 h during the daytime (8:00 to 20:00) and 3 h and during the nighttime (20:00 to 8:00). A previous study [29] has shown the sample setting of the R_s measuring equipment.

Statistical analyses

We evaluated the impacts of warming and the observation date on R_s using repeated-measures ANOVA. We used an independent sample t-test to compare the seasonal mean soil respiration for the two growing seasons under the four treatments. We explored exponential correlations between R_s and T_s using the Eq 1 and Q_{10} of R_s using the Eq 2 according to previous studies [29, 31].

$$R_s = ae^{bT_s}, \quad (1)$$

$$Q_{10} = e^{10b} \quad (2)$$

We performed natural-logarithm transformations between R_s and SM and then analyzed the correlations between R_s , T_s and SM using a multiple stepwise regression analysis. We calculated R_s and Q_{10} for the full day (8:00–8:00), day (8:00–20:00), and night (20:00–8:00), and compared R_s and Q_{10} of three periods among the 'C', 'DW', 'NW' and 'DW+NW' treatments with Student-Newman-Keuls multiple comparisons.

All statistical analyses were performed in the SPSS software (version 22.0; SPSS Inc., Chicago, IL, USA).

Results

Impacts of DW, NW and DW+NW treatments on T_s , SM and the correlations between R_s and T_s

The comparisons of T_s , SM and the correlations between R_s and T_s among the C, DW, NW and DW+NW treatments are illustrated in Figs 1 and 2. The DW, NW and DW+NW

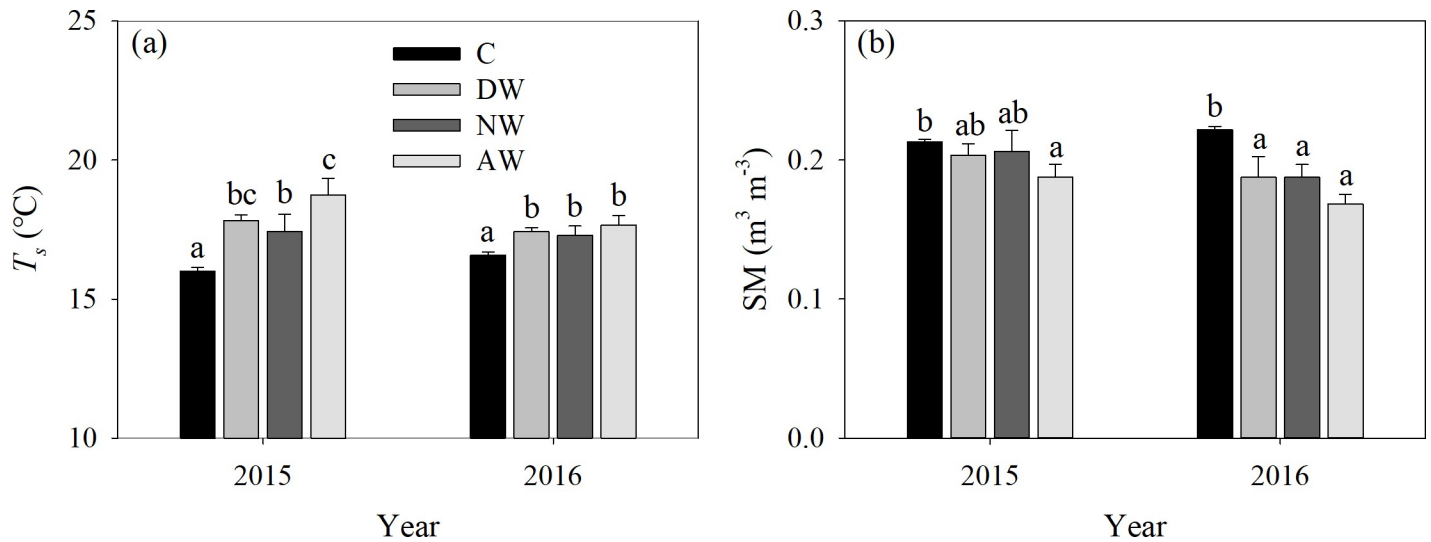


Fig 1. Comparison of soil temperature and soil moisture among diverse warming treatments. (a) is soil temperature (T_s) and (b) is soil moisture (SM) among diverse warming treatments in 2015 and 2016. C: control; DW: daytime warming; NW: nighttime warming; DW+NW: daytime plus nighttime warming.

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treatments dramatically raised T_s by 1.33, 1.07 and 1.91°C in 2015–2016; by 1.83, 1.44 and 2.74°C in 2015; and by 0.84, 0.71 and 1.08°C in 2016, all respectively. The DW, NW and DW+NW treatments dramatically decreased SM by 0.02, 0.02 and 0.04 $\text{m}^3 \text{m}^{-3}$ in 2015–2016 and by 0.03, 0.03 and 0.05 $\text{m}^3 \text{m}^{-3}$ in 2016, respectively. The DW+NW treatment dramatically decreased SM by 0.02 $\text{m}^3 \text{m}^{-3}$ in 2015, while the DW and NW treatments did not dramatically modify SM. R_s increased exponentially with increasing T_s (Fig 2). The p -values of all equations are significant ($p < 0.001$); the exponential equation provides a good fit for the relationship between temperature and soil respiration.

Impacts of DW, NW and DW+NW treatments on R_s , temperature sensibility and plant biomass

The main impact of the observation date and its interaction impact with warming on R_s of the all-day treatment were remarkable. While the main impact of warming on R_s was insignificant, there was a significant difference in soil respiration intensity between different stages of the growing seasons in 2015 and 2016 (Table 1). Through Student-Newman-Keuls multiple comparison, we found R_s of all-day treatment among the C, DW, NW and DW+NW treatments had no significant difference. The comparisons of R_s among the C, DW, NW and DW+NW treatments are illustrated in Fig 3, while the comparison of the seasonal mean soil respiration for the two growing seasons under the four treatments is illustrated in Fig 4. Through an independent sample t-test, it was found that there was no significant difference in seasonal mean soil respiration between the two years.

The effects of the four treatments (C, DW, NW and DW+NW) on daytime and nighttime soil respiration showed no significant difference (Fig 5A). The effects of four treatments (C, DW, NW and DW+NW) on the daytime and nighttime Q_{10} were different, while those on the daytime Q_{10} had no significant difference; Compared with the C treatment, DW, NW and DW+NW had significant inhibitory effects on the nighttime Q_{10} , with all treatments having no significant difference between them. From the all-day Q_{10} , only C and DW showed a significant difference (Fig 5B). From Fig 2, the b values of Eq 1 can be used to calculate the Q_{10} value. The b values obtained by fitting the four treatments were 0.053, 0.044, 0.051, 0.045. The

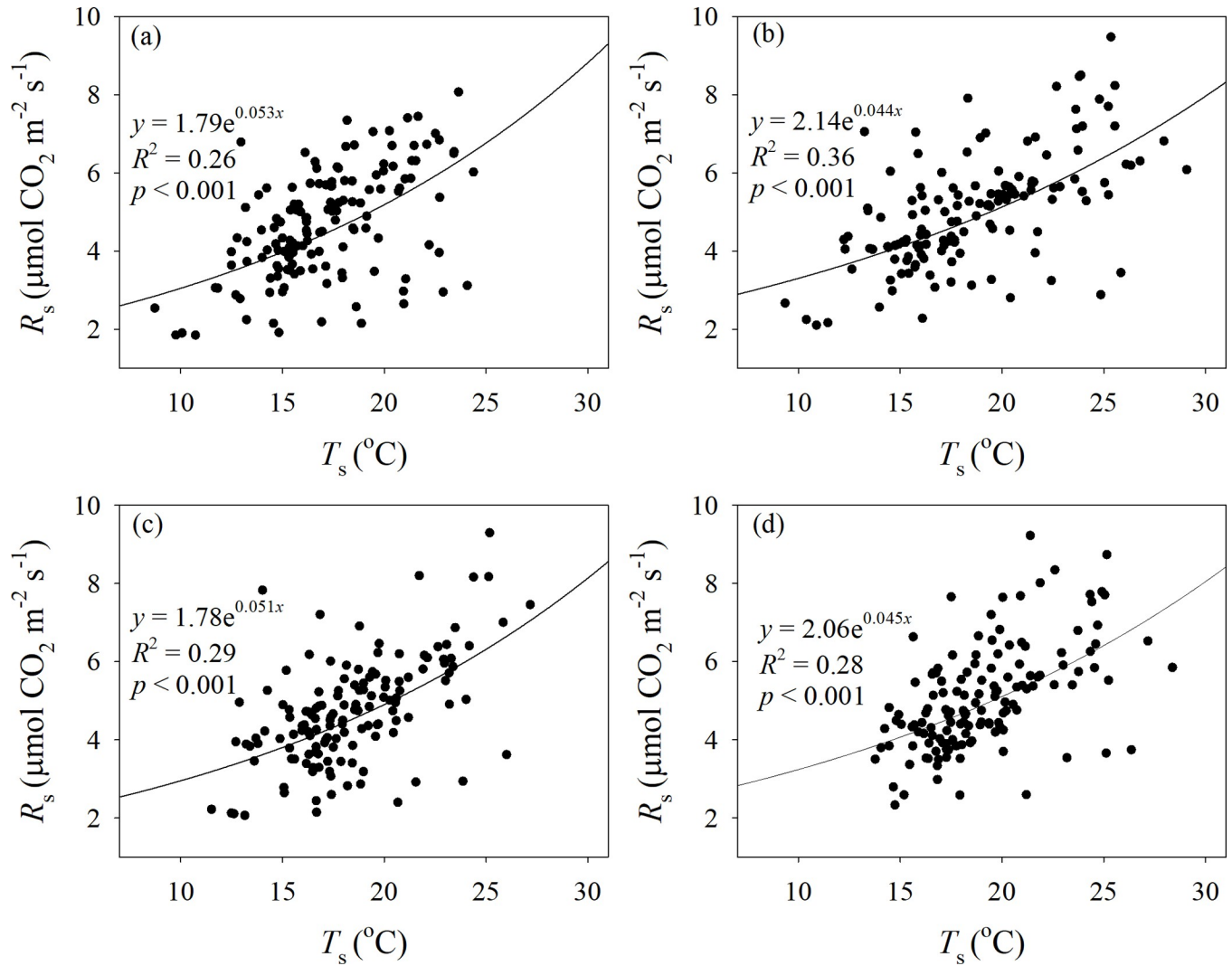


Fig 2. Relationships between R_s and T_s . R_s : soil respiration. T_s : soil temperature. (a) control, (b) daytime warming, (c) nighttime warming and (d) daytime plus nighttime warming.

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difference between the C and DW treatments was the largest, consistent with the multiple comparison results of all-day Q_{10} between the four treatments (Fig 5B). The DW, NW and DW+NW treatments had negligible impacts on plant biomass (Fig 6).

Table 1. Repeated-measures ANOVA was used to estimate the main and interaction impacts of warming (W) and observation date (D) on soil respiration (R_s) during the growing seasons in 2015 and 2016.

Year	Model	F	p
2015	W	0.79	0.525
	D	42.93	<0.001
	W×D	3.58	<0.001
2016	W	1.67	0.226
	D	93.75	<0.001
	W×D	2.54	0.036

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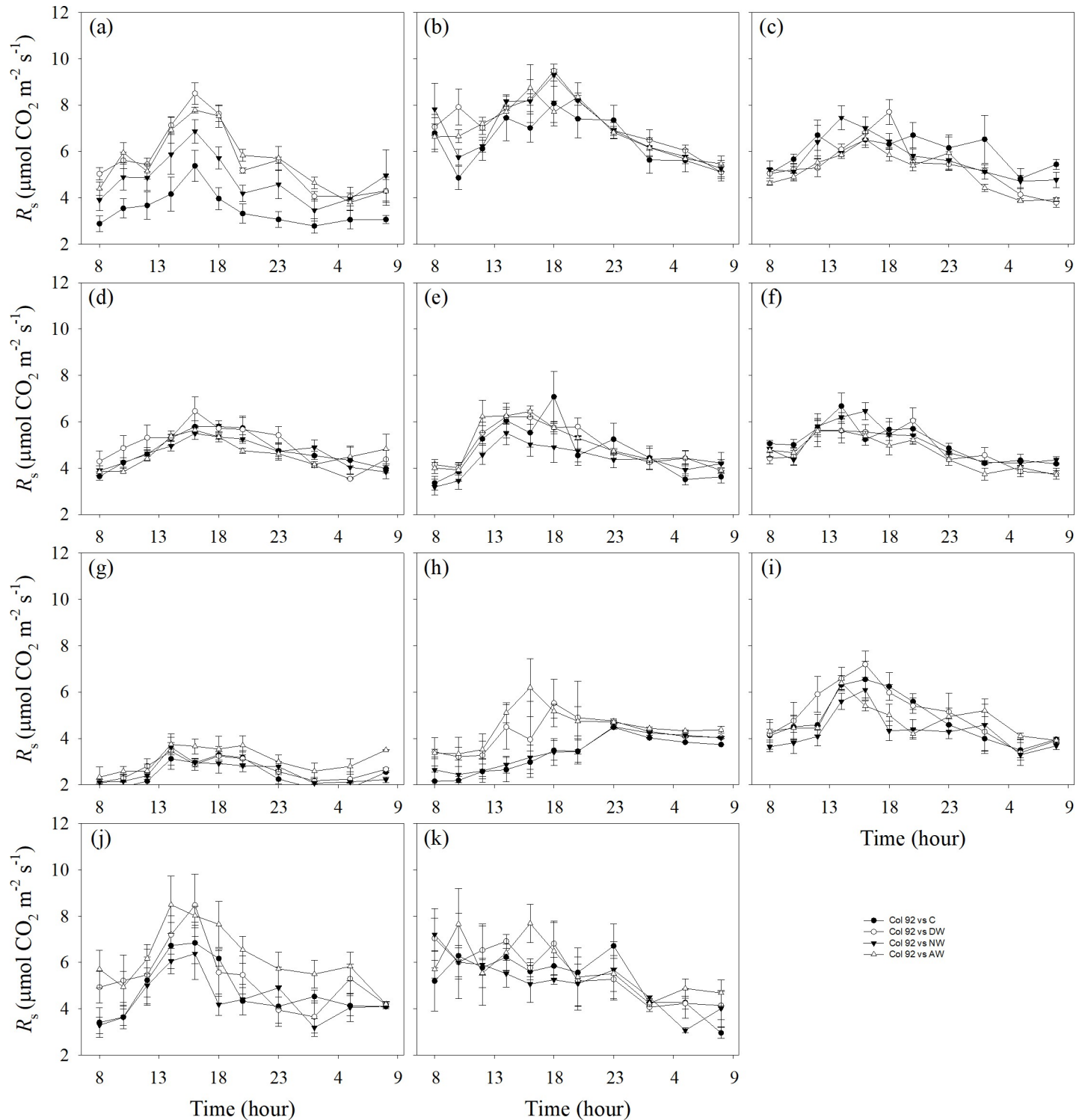


Fig 3. Comparison of R_s among diverse warming treatments in different months. R_s : soil respiration (a) May 25–26, 2015, (b) June 16–17, 2015, (c) June 30–July 1, 2015, (d) July 16–17, 2015 (e) July 30–31, 2015, (f) August 14–15, 2015, (g) May 6–7, 2016, (h) June 12–13, 2016, (i) July 16–17, 2016, (j) July 27–28, 2016 and (k) August 10–11, 2016. C: control; DW: daytime warming; NW: nighttime warming; DW+NW: daytime plus nighttime warming.

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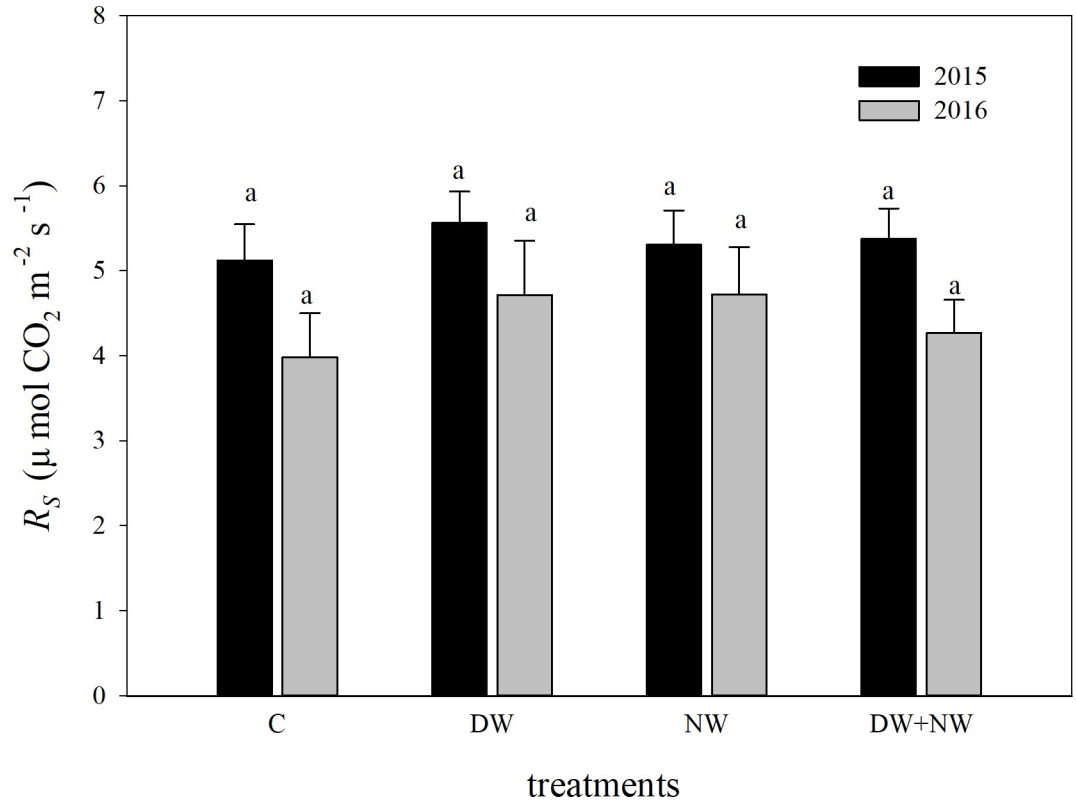


Fig 4. Comparison of the mean R_s for the two growing seasons under the four treatments. R_s : soil respiration. C: control; DW: daytime warming; NW: nighttime warming; DW+NW: daytime plus nighttime warming.

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Correlations between R_s and temperature sensibility, and T_s , and SM

The correlations between R_s , T_s and SM are shown in Table 2. All p -values were significant ($p < 0.001$) based on different interpretation variables for the equation under different treatments. After the stepwise regression, SM did not enter the equation and T_s explicated the

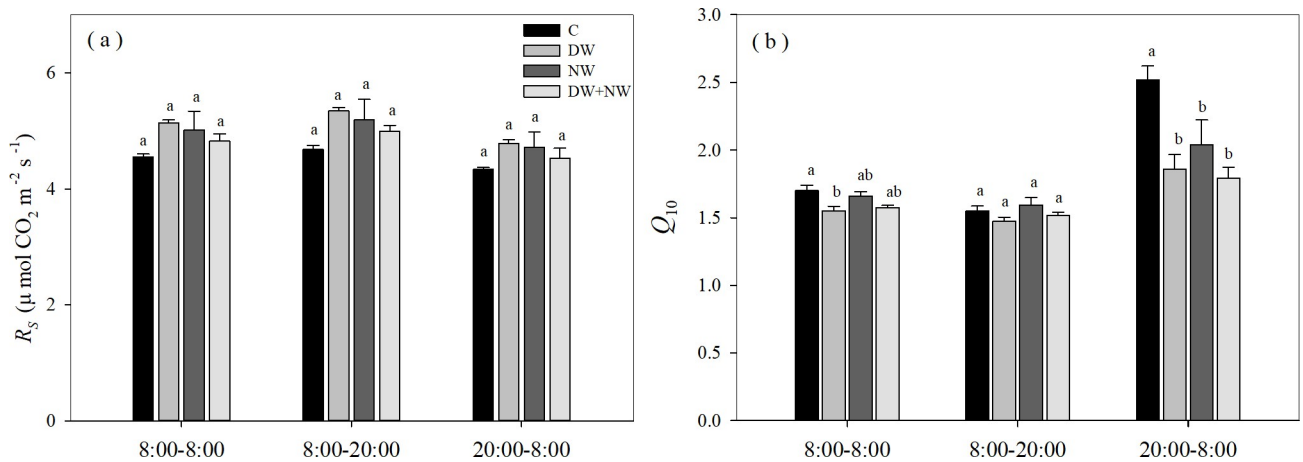


Fig 5. Comparison of four treatments in the R_s and Q_{10} of three time periods. R_s : soil respiration. Q_{10} : temperature sensibility of soil respiration. The four treatments were C: control; DW: daytime warming; NW: nighttime warming; and DW+NW: daytime plus nighttime warming. The three time periods were 8:00–8:00, 8:00–20:00, and 20:00–8:00.

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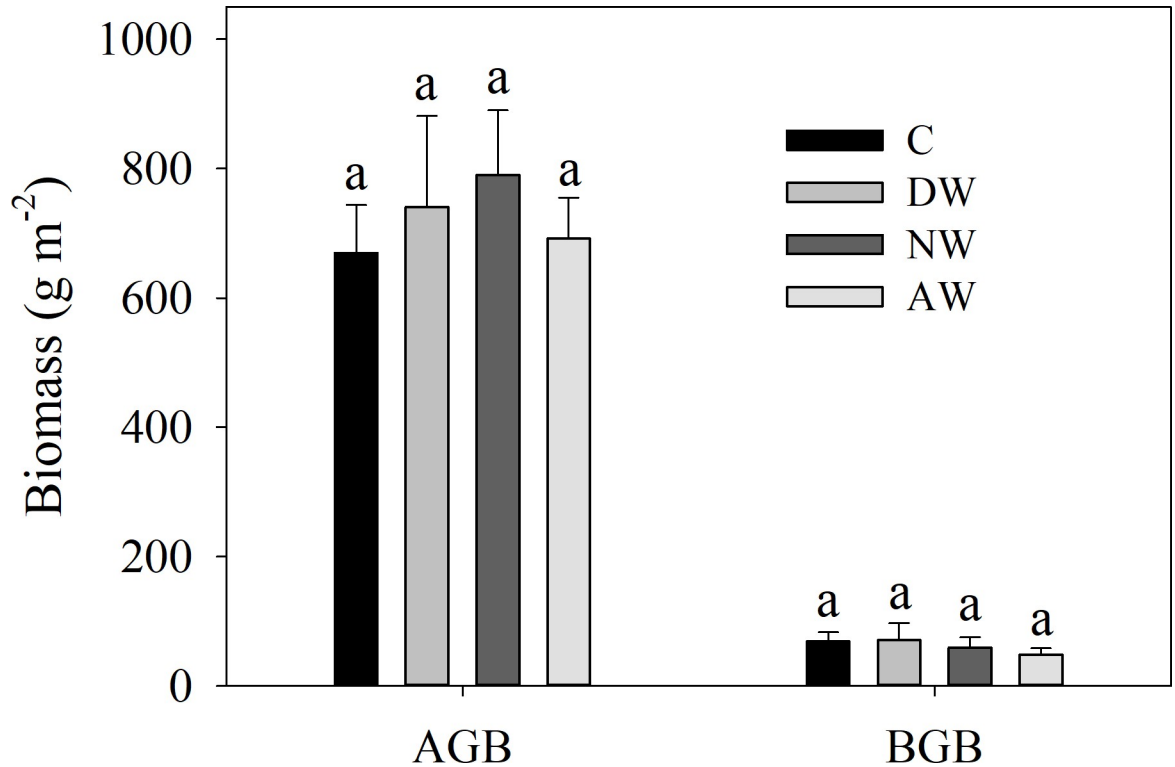


Fig 6. Comparison of AGB and BGB among diverse warming treatments in 2016. AGB: aboveground biomass; BGB: belowground biomass. C: control; DW: daytime warming; NW: nighttime warming; DW+NW: daytime plus nighttime warming.

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change of R_s under the C treatment, whereas T_s and SM jointly explained the change in R_s under the DW, NW and DW+NW treatments. The regression equations are: $y = 0.05x_1 + 0.59$, $y = 0.04x_1 + 0.31x_2 + 1.26$, $y = 0.05x_1 + 0.37x_2 + 1.18$, $y = 0.05x_1 + 0.16x_2 + 0.98$ (x_1 is T_s , x_2 is SM, y is R_s). Partial correlation coefficients of T_s with respect to the C, DW, NW and DW+NW treatments were 0.05, 0.62, 0.59, and 0.54, respectively; those of the SM with respect to the DW, NW and DW+NW treatments were 0.09, 0.19, and 0.05, respectively; and those between R_s

Table 2. Multiple stepwise regressions between soil respiration (R_s) and soil temperature (T_s) and moisture (SM).

Treatment		Regression coefficient	R^2	Partial correlation coefficient	p
C	Constant	0.59			<0.001
	T_s	0.05	0.25	0.50	<0.001
DW	Constant	1.26			<0.001
	T_s	0.04	0.35	0.62	<0.001
	SM	0.31	0.09	0.36	<0.001
NW	Constant	1.18			<0.001
	T_s	0.05	0.28	0.59	<0.001
	SM	0.37	0.19	0.51	<0.001
DW+NW	Constant	0.98			<0.001
	T_s	0.05	0.27	0.54	<0.001
	SM	0.16	0.05	0.25	0.003

C: control; DW: daytime warming; NW: nighttime warming; DW+NW: daytime plus nighttime warming.

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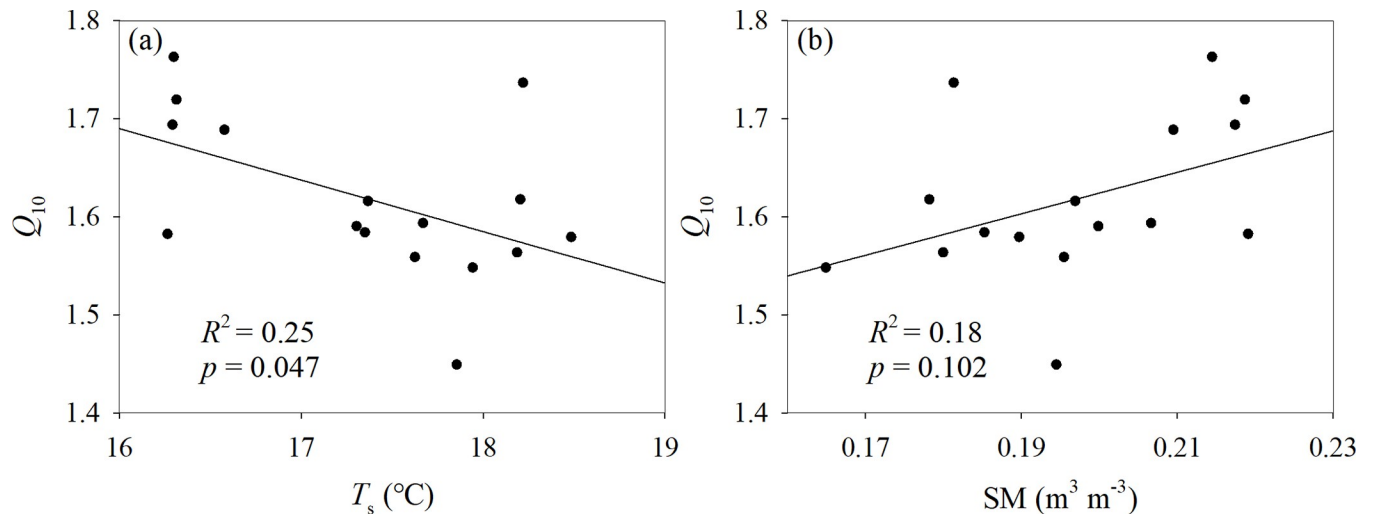


Fig 7. Relationships between Q_{10} and T_s and relationships between Q_{10} and SM. (a): Relationships between the temperature sensibility (Q_{10}) of soil respiration and soil temperature (T_s) (b): Relationships between the temperature sensibility (Q_{10}) of soil respiration and soil moisture (SM).

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and T_s exceeded those between R_s and SM of the DW, NW and DW+NW treatments. Compared with SM, T_s can better explain the change in R_s . The Q_{10} value decreased significantly with increasing T_s across all the experimental plots, while the Q_{10} value only tended to increase with increasing SM (Fig 7).

Discussion

We have discovered that the degree of soil drought produced by the DW+NW treatment was substantially larger than that by the DW and NW treatments, which possibly originated from the fact that the DW+NW treatment brought about a larger increase in T_s than did the DW and NW treatments [29, 31, 32, 35]. Our findings suggest that diurnal unsymmetrical warming will not always trigger unsymmetrical results on plant biomass in cold and high-altitude districts, which is possibly due to unsuitable increase in T_s , warming-induced decline in SM and an increase in plant respiration [32, 35–40]. Our findings suggest that warming can modify the relative impacts of T_s and SM on R_s in cold and high-altitude districts [29, 31, 41].

Vegetation growth and soil microorganism activity are strongly influenced by low temperatures [8, 10, 42, 43], thus rise in temperature is estimated to amplify R_s in cold and high-altitude districts [8]. However, several previous studies noted that rise in temperature had no effect on R_s in agroecological systems and cold and high-altitude meadows in the Qinghai-Xizang Plateau [29, 32, 44], a result which was additionally supported by this study. All of these findings entailed that R_s most likely has no significant response to warming in cold and high-altitude districts. Our findings did not follow the lines of earlier meta-analyses which showed that R_s increased during the warming treatments [45, 46].

We have discovered that the Q_{10} of R_s between the DW and NW treatments were diverse, and moreover, that DW and NW treatments can lead to differing effects in the daytime and nighttime Q_{10} . This indicated that Q_{10} was not only related to the different ecosystems and the magnitude of temperature increase, but different warming methods as well. The all-day Q_{10} values were 1.69, 1.55, 1.66 and 1.58 for the C, DW, NW and DW+NW treatments, respectively. Compared with C treatment, DW and NW Q_{10} values decreased by 9% and 2%, respectively, but the DW + NW Q_{10} decreased by 7% indicating that the impact of DW and NW was not a simple additive relationship. As can be understood from Fig 5, DW significantly reduced

all-day Q_{10} values, while NW and DW+NW had no significant change; this further proves that these two processes were not simple additive relationships. We even speculated that DW and NW may have antagonistic effects; as a consequence, the asymmetry of daytime and nighttime rises in temperature will possibly bring about unsymmetrical results for the temperature sensibility of R_s in cold and high-altitude rural soils.

Q_{10} can be used to reflect the relationship with temperature, as its value is closely related to temperature. From Fig 7, it can be seen that Q_{10} is negatively correlated with temperature, which is consistent with previous studies[47–49]. Kirschbaum[50] analyzed the results of different studies and found that Q_{10} was very high at low temperatures and relatively stable at high temperatures. Luo [51] found that the Q_{10} value of the treatment without warming was significantly higher than the Q_{10} value of the experimental warming treatment in a study on a cold and high-altitude grassland in North America. Moreover, we found that the Q_{10} value of soil respiration during daytime treatment was lower than that of nighttime (Fig 5B), which further confirmed the negative correlation between temperature and Q_{10} .

The minor differences of R_s among the C, DW, NW and DW+NW treatments are possibly due to the following reasons. First, there were minor differences of BGB among the C, DW, NW and DW+NW treatments, and R_s was positively correlated with BGB [52]. Next, although the DW+NW treatment brought about a larger rise in T_s , it triggered more soil drought than did the DW and NW treatments which in turn was able to lessen the impact of rise in temperature on R_s . Third, the warming degrees of the DW, NW and DW+NW treatments possibly did not reach the optimum temperature which could lead to maximum increase in R_s [32]. Lastly, only the DW treatments, not the NW and DW+NW treatments, dramatically lowered the Q_{10} of R_s , which in turn was able to weaken the impact of rise in temperature on R_s [53].

Conclusions

This study explored how diurnal unsymmetrical warming was able to modify R_s and temperature sensibility of R_s in an agroecological system within the Qinghai-Xizang Plateau during two growing seasons in 2015–2016. The R_s differences among the C, DW, NW and DW+NW treatments were able to be neglected. The effects of DW, NW and DW+NW treatments on Q_{10} of R_s during daytime and nighttime were different; they both had no effects on daytime soil respiration sensitivity, but significant inhibitory effects on nighttime soil respiration sensitivity. Moreover, we speculate that DW and NW have antagonistic effects on Q_{10} of R_s .

Through warming experiments, we found that the soil respiration under the diurnal unsymmetrical warming has different sensitivities while the magnitude of warming caused by global warming differed between day and night. The experiment explores the effects of the asymmetric warming mechanism on soil respiration, providing a theoretical basis for better simulation and prediction of soil respiration so as to better explain the response and feedback of terrestrial ecosystems' carbon cycle to global climate change.

Supporting information

S1 Data. Four treatments in the soil respiration of three time periods.

(XLSX)

S2 Data. Four treatments in the Q_{10} -value of three time periods.

(XLSX)

S3 Data. Soil temperature among diverse warming treatments.

(XLSX)

S4 Data. Soil moisture among diverse warming treatments.
(XLSX)

S5 Data. AGB and BGB among diverse warming treatments in 2016.
(XLSX)

S6 Data. The mean R_s for the two growing seasons under the four treatments.
(XLSX)

Author Contributions

Data curation: Zhiming Zhong, Guangyu Zhang, Haorui Zhang.

Formal analysis: Zhiming Zhong, Guangyu Zhang, Haorui Zhang.

Funding acquisition: Zhiming Zhong, Guangyu Zhang, Haorui Zhang.

Investigation: Zhiming Zhong, Guangyu Zhang, Haorui Zhang.

Methodology: Zhiming Zhong, Guangyu Zhang, Haorui Zhang.

Project administration: Zhiming Zhong, Guangyu Zhang, Haorui Zhang.

Resources: Zhiming Zhong, Guangyu Zhang, Haorui Zhang.

Software: Zhiming Zhong, Guangyu Zhang, Haorui Zhang.

Supervision: Zhiming Zhong, Guangyu Zhang, Haorui Zhang.

Validation: Zhiming Zhong, Guangyu Zhang, Haorui Zhang.

Visualization: Zhiming Zhong, Guangyu Zhang, Haorui Zhang.

Writing – original draft: Zhiming Zhong, Guangyu Zhang, Haorui Zhang.

Writing – review & editing: Zhiming Zhong, Guangyu Zhang, Haorui Zhang.

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