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Response of soil respiration to experimental warming in a highland barley of the Tibet

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Abstract

Highland barley is an important dominant crop in the Tibet and the croplands of the Tibet are experiencing obvious climatic warming. However, information about how soil respiration will respond to climatic warming in the highland barley system is still lacking. A field warming experiment using infrared heaters with two warming magnitudes was conducted in a highland barley system of the Tibet in May 2014. Five daily cycles of soil respiration was measured using a CO_2 flux system (Li-8100, Li-COR Biosciences, Lincoln, NE, USA) during the period from early June to early September in 2014. The high and low experimental warming significantly increased soil temperature by 1.98 and 1.52 °C over the whole study period, respectively. The high experimental warming significantly decreased soil moisture. Soil respiration and its temperature sensitivity did not significantly change under both the high and low experimental warming. The response of soil respiration to experimental warming did not linearly correlate with warming magnitudes because a greater experimental warming resulted in a higher soil drying. Our findings suggested that clarifying the response of soil CO_2 production and its temperature sensitivity to climatic warming need consider water availability in the highland barley system of the Tibet.

Keywords: Infrared radiator, Soil moisture, Temperature sensitivity, Tibetan Plateau, Warming magnitude

Background

The global surface temperature is predicted to increase by 1.0–3.7 °C by the end of this century and the Tibetan Plateau, "the Third Pole of the Earth", is one of the most sensitive regions to climatic warming (Fu et al. 2015; IPCC 2013). To better understand and predict the effect of such warming on alpine ecosystems, many warming experiments are performed; however, no studies are conducted in agricultural ecosystems on the Tibetan Plateau (Zhang et al. 2015). The croplands are experiencing obvious warming on the Tibetan Plateau (Shen et al. 2014) and about 80 % of the population lives in the cropland areas of the Tibet (Yang et al. 1996). These suggest that it remains unclear about how alpine agricultural ecosystems respond to future climatic warming on the Tibetan Plateau.

The Tibetan Plateau is one of the domestication centers of cultivated barley and the planting area of highland barley accounts for approximately 43 % of the grain crop area on the Tibetan Plateau (Dai et al. 2012; Zhao et al. 2015). Highland barley, the only crop which is grown at high altitudes, is one of the dominant crops on the Tibetan Plateau and is an important staple food of the Tibetan people (Wang et al. 2013). Highland barley can be made into a variety of conventional foods, such as fried noodles (i.e. zanba), wine, and health food due to its high beta-glucan (Zhang et al. 2002). The highland barley ecosystem is one sensitive system to climatic warming considering the significant relationship between the potential productivity of highland barley and air temperature (Zhao et al. 2015). However, no studies demonstrate the warming effects on highland barley ecosystem under controlled warming on the Tibetan Plateau. Therefore, it remains unclear about how highland barley system responds to future climatic warming on the Tibetan Plateau.

Soil respiration (R_s) is one primary component of the carbon cycling in terrestrial ecosystems (Rustad et al. 2001). Soil temperature is one of the most important abiotic factors affecting R_s (Raich and Schlesinger 1992). Soil respiration generally increases exponentially with increasing soil temperature and the Q_{10} is often used to evaluate the temperature sensitivity of R_s (Lin et al. 2011; Raich and Schlesinger 1992). The response of R_s and its temperature sensitivity to climatic warming are different among different terrestrial ecosystems with regard to vegetation types and climatic conditions. For example, the effects of experimental warming on R_s are negative in a semi-arid grassland in Inner Mongolia, China (Liu et al. 2009), positive in a cropland at the southern Germany (Reth et al. 2009) or neutral in an alpine meadow in the Northern Tibet (Shen et al. 2015). The Q_{10} of R_s shows a negative correlation with experimental warming in a temperate agricultural ecosystem in Germany (Poll et al. 2013), positive in a subtropical cropland in China (Liu et al. 2012) or neutral in an alpine meadow in the Northern Tibet (Shen et al. 2015). Soil moisture (SM) is another one of the most important abiotic factors influencing R_s, especially in arid and semi-arid ecosystems (Liu et al. 2009; Shen et al. 2015). SM can not only directly affect R_s, but also influence the Q_{10} of R_s (Lin et al. 2011; Shen et al. 2015). SM can also dampen the effect of soil temperature on R_s (Liu et al. 2009; Shen et al. 2015).

No studies discuss the response of R_s to climatic warming under controlled warming condition in agricultural ecosystems on the Tibetan Plateau. Therefore, it is still rudimentary about how climatic warming will affect R_s in the alpine croplands on the Tibetan Plateau. In this study, a field warming experiment using infrared heaters was conducted in a highland barley system of the Tibet. The main objective of this study was to analyze the response of R_s to warming.

Methods

Study area

The study area (91°21′E, 29°41′N, 3688 m above sea level) is located at the Lhasa Agro-ecosystem Research Station, Tibet Autonomous Region in China. Mean annual air temperature is 7.9 °C and mean annual precipitation is around 425 mm, with more than 90 % concentrated in the period from June to September (He et al. 2011). The annual air temperature was 8.5 °C and annual precipitation was 642.4 mm in 2014. That is, it is a warmer and wetter year (2014).

Experimental design

The experimental soils have been used for crop planting since 1970s. Infrared heaters were used to increase temperature during the whole study period from May 26 to September 14 in 2014. There were three warming treatments with three replicates: the control (CK), low (1000 W) and high (2000 W) warming treatments with a total of nine 2 m × 2 m experimental plots. A 165 cm × 15 cm infrared heater (Kalglo Electronics Inc., Bethlehem, PA, USA) was suspended approximately 1.7 m above the ground in the center of each 2 m × 2 m plot. There was approximately 6–7 m distance between plots.

The highland barley was sown in May 26, 2014 and harvested in September 14, 2014. There was approximately 0.25 m between seeding rows and the seeding was 18.75 g m^{-2}. There were no highland barley outside the 2 m × 2 m plot and there were no other vegetation types within each 2 m × 2 m plot. There were approximately 1150 plants per 2 m × 2 m plot.

Soil temperature and soil moisture monitor

Soil temperature (T_s) and SM sensors were set a depth of 0.05 m in the center of each plot. For each plot, the two sensors were connected to a data logger (HOBO weather station, Onset Computer, Bourne, MA, USA). The measurements were taken every minute, and the data was processed to provide an average every 5 min.

Soil respiration measurements

A CO_2 flux system (LI-8100, LI-COR Biosciences, Lincoln, NE, USA) with a 20 cm diameter opaque survey chamber was used to measure R_s (Fu et al. 2014). A polyvinyl chloride (PVC) collar (diameter, 20 cm; height, 5 cm) was inserted about 2–3 cm into the soil in the center of each plot (the soil temperature and soil moisture sensors were just beneath the PVC collar) in May 2014. The PVC collar was left the same place during the whole study period. The soil temperatures and moistures were consistent with those beneath the chambers. We started to measure R_s in May 2014. The opaque survey chamber was manually mounted on the PVC collar in each plot for the measurement of R_s. Daily cycles of R_s measurements were generated from 8:00 to 8:00 on June 5–6 (approximately 3–4 days after sprouting), July 26–27 (approximately flag leaf stage), August 6–7 (approximately blooming stage), August 26–27 (approximately waxy ripeness stage) and September 6–7 (from yellow ripeness stage to full ripeness stage). The measuring interval was 2 and 3 h during the daytime (8:00–20:00) and nighttime (20:00–8:00), respectively.

Statistical analysis

A repeated-measures ANOVA with experimental warming as the between subject factor and measuring date and time as the within subject factors was conducted for R_s. Duncan multiple comparisons were performed among the three warming treatments.

Exponential regression analyses were conducted between R_s and T_s, whereas linear regression analyses were conducted between R_s and SM for each treatment. For each treatment, a stepwise multiple regression analysis was used to analyze the relationships between R_s and T_s and SM, before which natural-logarithm transformations were made for R_s and SM.

We analyzed the sensitivity of R_s to soil temperature for each treatment using all measurement data according to

$$R_s = ae^{bT_s}, \tag{1}$$

where a is the intercept of R_s when T_s is 0 °C (i.e. the R_s value when T_s is 0 °C), and b reflects the temperature sensitivity of R_s (Shen et al. 2015). The b values were used to calculate the respiration quotient (Q_{10})

$$Q_{10} = \frac{R_{t+10}}{R_t} = e^{10b} \tag{2}$$

where t is a given reference soil temperature, R_{t+10} and R_t are the R_s values when soil temperature is $t + 10$ and t ℃, respectively.

To decrease the disturbance of SM on Q_{10} of R_s, we also chose data to compare the Q_{10} of R_s among the three treatments by the two following rules: (1) there were no correlations between R_s and T_s when SM <0.17 m^3 m^{-3} for the high warming treatment. The R_s was obviously suppressed when SM <0.17 m^3 m^{-3} for the low warming treatment. Therefore, only measuring data when SM >0.17 m^3 m^{-3} were used; and (2) measuring date and time was consistent among the three treatments. That is, 26 groups of measured R_s, T_s and SM were used for each treatment.

All the statistical analyses were performed using the SPSS software (version 16.0; SPSS Inc., Chicago, IL, USA).

Results

Compared to the control, the low and high warming treatments significantly increased daily average T_s by 1.52 and 1.98 °C, respectively, over the whole study period (Fig. 1). The high warming treatment significantly decreased daily average SM by 16.1 % (−0.03 m^3 m^{-3}) over the whole study period (Fig. 1).

There were significantly temporal variations of R_s (Table 1; Fig. 2). The average R_s rates were 4.31, 5.41 and 4.85 μmol CO_2 m^{-2} s^{-1} for the control, low and high warming treatments over the five measuring dates, respectively. There were no significant differences of R_s among the three warming treatments (Table 1).

Soil respiration significantly increased with increasing T_s (Fig. 3a–f). There was no significant effect of experimental warming on the apparent Q_{10} values when all the

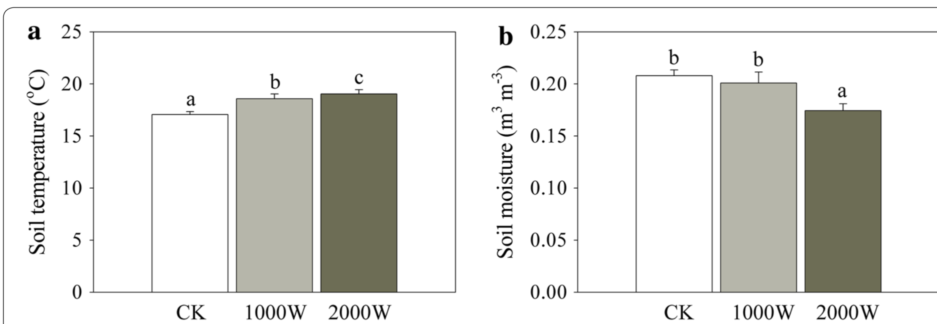

Fig. 1 Effects of experimental warming on **a** soil temperature and **b** soil moisture over the whole study period in a highland barley of the Tibet. CK: the control, 1000 W: the low warming treatment, and 2000 W: the high warming treatment

Table 1 Repeated measures ANOVA for the main and interactive effects of experimental warming (W), measuring date (D) and time (T) on soil respiration (R_s, μmol CO_2 m^{-2} s^{-1}) in a highland barley of the Tibet ($n = 3$)

Model	*df*	*F*	*p*
W	2, 6	0.99	0.43
D	4, 24	20.82	<0.001
T	10, 60	42.38	<0.001
W × D	8, 24	1.36	0.26
W × T	20, 60	0.57	0.72
D × T	40, 240	3.76	<0.05
W × D × T	80, 240	0.76	0.63

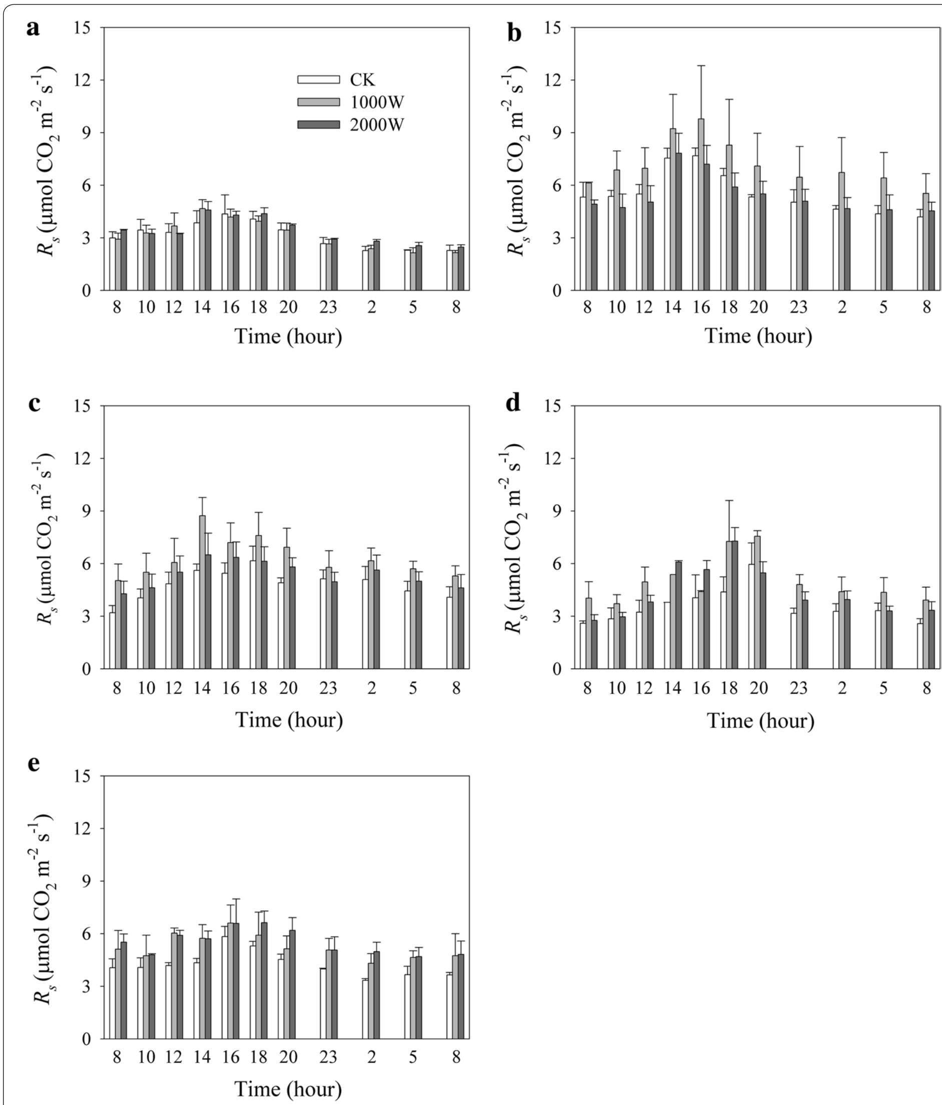

Fig. 2 Effects of experimental warming on soil respiration (R_s) in a highland barley of the Tibet (mean ± SE, $n = 3$). **a** June 5–6, **b** July 26–27, **c** August 6–7, **d** August 26–27, and **e** September 6–7 in 2014. CK: the control, 1000 W: the low warming treatment, and 2000 W: the high warming treatment

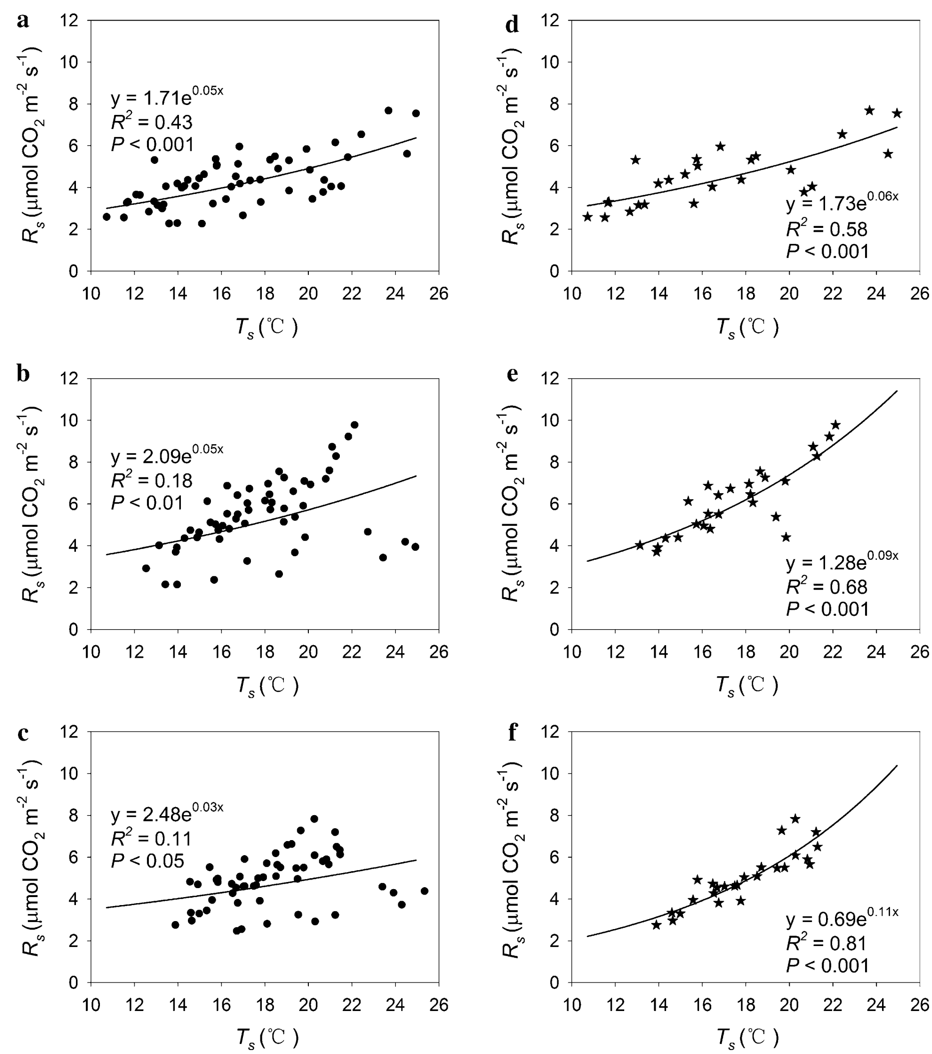

Fig. 3 Relationship between soil respiration (R_s) and soil temperature (T_s) across all measuring data for **a** the control, **b** low warming treatment and **c** high warming treatment; and data included when soil moisture was >0.17 m^3 m^{-3} and the measuring data and time were consistent among the three treatments for **d** the control, **e** low warming treatment and **f** high warming treatment

measuring data were used (control: 1.70; low warming treament: 1.65; high warming treament: 1.41). In contrast, there was significant effect of experimental warming on the Q_{10} of R_s when only the 26 groups data were used ($df = 2, 75$; $F = 5.84$; $p < 0.01$). In detail, the low and high warming treatments significantly increased the Q_{10} by approximately 0.67 and 1.22, while there was a negligible difference between the low and high warming treatments. The experimental warming-induced change of R_s significantly increased with that of SM (Fig. 4).

Stepwise regression analyses indicated that the variation of R_s was explained by T_s for the control plots, but explained by SM for the high warming treatment (Table 2). Soil temperature and SM together explained the variation of R_s for the low warming treatment (Table 2). However, the partial correlation between R_s and SM was larger than that between R_s and T_s for the low warming treatment (Table 2).

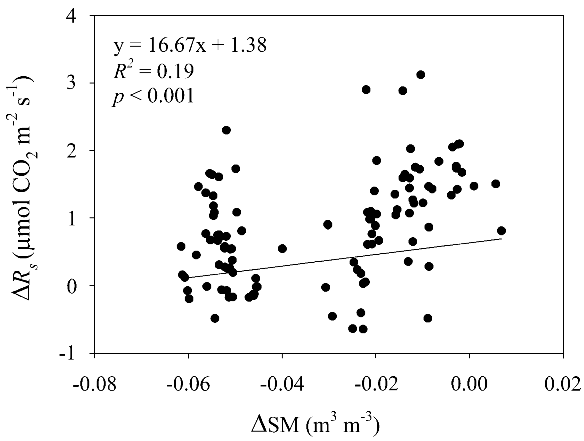

Fig. 4 Relationship between the change of soil respiration (ΔR_s) and the change of soil moisture (ΔSM) caused by the low and high warming treatment

Table 2 Stepwise multiple regression analyses between soil respiration (R_s) and soil temperature (T_s) and soil moisture (SM), showing changes in the regression coefficient, significance probability (p), coefficient of determination (R^2) and partial correlation coefficient

Treatment	Coefficient	R^2	Partial correlation	p
CK				
Constant	0.54			<0.001
T_s	0.05	0.43	0.65	<0.001
1000 W				
Constant	5.27			<0.001
T_s	0.06	0.24	0.75	<0.001
SM	2.88	0.57	0.88	<0.001
2000 W				
Constant	5.43			<0.001
SM	2.20	0.39	0.62	<0.001

Natural logarithm transformations were made for R_s and SM prior to regression analysis. CK: the control, 1000 W: the low warming treatment, and 2000 W: the high warming treatment. T_s and SM coincided with R_s

Discussion

For the first time to our knowledge, this study quantified the warming effects on R_s and its temperature sensitivity in agricultural ecosystems of the Tibetan Plateau. Our finding that experimental warming did not significantly change R_s in this highland barley system was in line with our one previous study performed in alpine meadows of the Northern Tibet (Shen et al. 2015). However, there were significant positive responses of R_s to experimental warming in the alpine meadow of the Haibei station (Lin et al. 2011) and the Songpan County (Shi et al. 2012), an alpine steppe of the Northern Tibet (Lu et al. 2013) and forest ecosystems (Xu et al. 2010) on the Tibetan Plateau. These findings implied that the alpine ecosystems on the Tibetan Plateau did not always show a positive response of R_s to climatic warming. These results also indicated that the effect of climatic warming on R_s varied with not only ecosystems but also regions on the Tibetan Plateau. Compared to alpine grasslands and forests, the soil CO_2 production of alpine agricultural ecosystem may have a lower response to climatic warming on the Tibetan Plateau. Our finding was also not in line with some previous studies which demonstrated that experimental warming significantly increased R_s in temperate and subtropical croplands (Liu et al. 2012; Reth et al. 2009). This phenomenon implied that alpine agricultural soil may not always have higher temperature sensitivity than temperate and subtropical agricultural soils.

In this study, the no significant response of R_s to experimental warming was most likely due to the experimental warming-induced soil drying (Table 2; Fig. 3). A meta-analysis showed that drying had a significant negative effect on R_s (Wu et al. 2011). Experimental warming-induced soil drying suppressed the effect of increased temperature on R_s in croplands (Poll et al. 2013; Wall et al. 2013), alpine and temperate grasslands (Liu et al. 2009; Shen et al. 2015). Soil drying can suppress soil microbial activity and microbial respiration (Fu et al. 2012; Liu et al. 2009), and plant photosynthesis and primary production (Fu et al. 2013; Xu et al. 2013), all of which are positively correlated with R_s (Fu et al. 2014; Iqbal et al. 2010). The finding that the effect of experimental warming on R_s did not correlate with warming magnitudes may be attributed to the finding that a higher experimental warming resulted in a greater soil drying in our study system.

Different from many previous studies which exhibited experimental warming significantly decreased temperature sensitivity of soil respiration (Luo et al. 2001; Poll et al. 2013; Suseela and Dukes 2013; Zhou et al. 2012), experimental warming did not significantly affect the temperature sensitivity of R_s across all the measuring data in this highland barley system (Fig. 3a–c). In contrast, when the disturbance of SM was dampened (i.e. when SM >0.17 m^3 m^{-3}), experimental warming significantly increased the temperature sensitivity of R_s in this highland barley system (Fig. 3d–f). Soil respiration did not significantly correlate with soil temperature when SM was smaller than 0.17 m^3 m^{-3} for the high warming treatment. Similarly, the temperature sensitivity of R_s declined with drought in a New England old-field ecosystem (Suseela and Dukes 2013) and increased with increasing SM in an alpine meadow in the Northern Tibet (Shen et al. 2015). Therefore, soil water availability affected the temperature sensitivity of soil respiration and the negligible response of temperature sensitivity derived from all the measuring data may be due to soil drying caused by experimental warming.

Conclusions

Experimental warming-induced soil drying masked the effect of increased soil temperature on soil respiration in the highland barely system. Water availability will be a limited factor for the carbon emission of alpine agricultural soil under climatic warming on the Tibetan Plateau. The alpine soil may not show a positive feedback to climatic warming, which contrasted with the finding as most of previous studies have suggested on the Tibetan Plateau.

Authors' contributions

Z-MZ and GF designed the study; Z-XS provided valuable suggestions about the data analysis. GF wrote the first draft of the manuscript, aided by Z-XS and Z-MZ, while they contributed substantially to revisions. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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