Drought-induced reduction in methane fluxes and its hydrothermal sensitivity in alpine peatland

Haidong Wu Equal first author, 1, 2, 3 , **Liang Yan** Equal first author, 1, 2, 3 , **Yong Li** 1, 2, 3 , **Kerou Zhang** 1, 2, 3 , **Yanbin Hao** 4 , **Jinzhi Wang** 1, 2, 3 , **Xiaodong Zhang** 1, 2, 3 , **Zhongqing Yan** 1, 2, 3 , **Yuan Zhang** 4 , **Xiaoming Kang** Corresp. 1, 2, 3

[1] Institute of Wetland Research, Chinese Academy of Forestry, Beijing, China

[2] Beijing Key Laboratory of Wetland Services and Restoration, Beijing, China

[3] Sichuan Zoige Wetland Ecosystem Research Station, Tibetan Autonomous Prefecture of Aba, China

[4] University of Chinese Academy of Science, Beijing, China

Corresponding Author: Xiaoming Kang
Email address: xmkang@ucas.ac.cn

Accurate estimation of CH_4 fluxes in alpine peatland of the Qinghai-Tibetan Plateau under extreme drought is vital for understanding the global carbon cycle and predicting future climate change. However, studies on the impacts of extreme drought on peatland CH_4 fluxes are limited. To study the effects of extreme drought on CH_4 fluxes of the Zoige alpine peatland ecosystem, the CH_4 fluxes during both extreme drought treatment (D) and control treatment (CK) were monitored using a static enclosed chamber in a control platform of extreme drought. The results showed that extreme drought significantly decreased CH_4 fluxes in the Zoige alpine peatland by 31.54% (P<0.05). Extreme drought significantly reduced the soil water content (SWC) (P<0.05), but had no significant effect on soil temperature (Ts). Under extreme drought and control treatments, there was a significant negative correlation between CH_4 fluxes and environmental factors (Ts and SWC), except Ts, at a depth of 5cm (P<0.05). Extreme drought reduced the correlation between CH_4 fluxes and environmental factors and significantly weakened the sensitivity of CH_4 fluxes to SWC (P<0.01). Moreover, it was found that the correlation between subsoil (20 cm) environmental factors and CH_4 fluxes was higher than with the topsoil (5, 10 cm) environmental factors under the control and extreme drought treatments. These results provide a better understanding of the extreme drought effects on CH_4 fluxes of alpine peatland, and their hydrothermal impact factors, which provides a reliable reference for peatland protection and management.

Drought-induced reduction in methane fluxes and its hydrothermal sensitivity in alpine peatland

Haidong Wu[1¶], Liang Yan[1¶], Yong Li[1], Kerou Zhang[1], Yanbin Hao[2], Jinzhi Wang[1], Xiaodong Zhang[1], Zhongqing Yan[1], Yuan Zhang[2], Xiaoming Kang[1*]

[1] Institute of Wetland Research, Chinese Academy of Forestry, Beijing, China; Beijing Key Laboratory of Wetland Services and Restoration, Beijing, China; Sichuan Zoige Wetland Ecosystem Research Station, Tibetan Autonomous Prefecture of Aba, China

[2] University of Chinese Academy of Science, Beijing, China

[¶] These authors contributed equally to this work

Corresponding Author:
Xiaoming Kang[1*]
Institute of Wetland Research, Chinese Academy of Forestry, Beijing, China
Email address: xmkang@ucas.ac.cn (X.K)

Abstract

Accurate estimation of CH_4 fluxes in alpine peatland of the Qinghai-Tibetan Plateau under extreme drought is vital for understanding the global carbon cycle and predicting future climate change. However, studies on the impacts of extreme drought on peatland CH_4 fluxes are limited. To study the effects of extreme drought on CH_4 fluxes of the Zoige alpine peatland ecosystem, the CH_4 fluxes during both extreme drought treatment (D) and control treatment (CK) were monitored using a static enclosed chamber in a control platform of extreme drought. The results showed that extreme drought significantly decreased CH_4 fluxes in the Zoige alpine peatland by 31.54% (P<0.05). Extreme drought significantly reduced the soil water content (SWC) (P<0.05), but had no significant effect on soil temperature (Ts). Under extreme drought and control treatments, there was a significant negative correlation between CH_4 fluxes and environmental factors (Ts and SWC), except Ts, at a depth of 5cm (P<0.05). Extreme drought reduced the correlation between CH_4 fluxes and environmental factors and significantly weakened the sensitivity of CH_4 fluxes to SWC (P<0.01). Moreover, it was found that the correlation between subsoil (20 cm) environmental factors and CH_4 fluxes was higher than with the topsoil (5, 10 cm) environmental factors under the control and extreme drought treatments. These results provide a better understanding of the extreme drought effects on CH_4 fluxes of alpine peatland, and their hydrothermal impact factors, which provides a reliable reference for peatland protection and management.

Keywords: extreme drought; alpine peatland; CH_4 fluxes; hydrothermal sensitivity

Introduction

In recent years, due to the aggravation caused by human activities, the global atmospheric and water cycle pattern has been significantly changed, resulting in an increasing frequency and intensity of global extreme climate events [1-4]. Recent studies have indicated that the occurrence of extreme drought events can significantly change the water and heat conditions of the ecosystem, affecting the physiological state of plants and activities of soil microbes, triggering changes in the soil structure and function, and breaking the original carbon balance of the ecosystem, which in turn can aggravate the intensity and frequency of extreme drought events on a global scale [5-8]. However, research on extreme drought is still concentrated in arid and semi-arid grasslands at present, and research on peatland is relatively rare [6-7,9]. As an important global carbon pool, peatlands are carbon-rich ecosystems that cover just 3% of the Earth's land surface, but they store one-third of the soil carbon [10-11]. As such, peatlands play an important role in the global carbon cycle and mitigation of climate change [12].

The alpine peatland ecosystem, on account of its special altitude, presentsa higher sensitivity to climate change [13]. Additionally, with low temperatures and anoxia all year round, peatlands have sequestered large amounts of carbon in the soil [14-15]. However, when disturbed by external conditions, the source and sink of CH_4 in the alpine peatland ecosystem can be significantly altered [16]. As one of the main greenhouse gases, the warming potential of CH_4 is 23 times than that of CO_2, and changes in the CH_4 content in the atmosphere can have a significant impact on the trend and intensity of global climate change [17-18]. However, the dynamics of CH_4 in alpine peatland ecosystems and its response to extreme drought are poorly understood and lack quantified analyses. Therefore, accurate quantification of alpine peatland CH_4 fluxes under extreme drought conditions at various spatial and temporal scales is crucial and necessary for fully understanding the climate change process.

The Zoige plateau, located in the northeast of the Qinghai-Tibet plateau, is the region with the highest organic carbon reserves in China and one of the largest plateau peatlands in the world, thus playing an important role in the global carbon cycle [19]. As such, this region could potentially have a significant impact on regional climate change [20]. However, due to the warming and drying trends that have occurred over the past 30 years, the surface water level of the Zoige peatland has decreased substantially, which directly alters the pattern of CH_4 fluxes in this area [21-24]. Moreover, changes in precipitation and atmospheric temperatures, as well as the effects of decreased water levels, serve to increase the level of uncertainty regarding the magnitude of the CH_4 fluxes occurring in many ecosystems [24-25]. Therefore, to improve our understanding of the CH_4 dynamics occurring in the Zoige alpine peatland, the effects of temperature and precipitation variability under extreme drought conditions should be studied simultaneously.

In recent years, researchers have found that CH_4 uptake is strongly controlled by soil moisture, as soil temperature only has a minor influence on CH_4 fluxes measured at the Tasmania Ecological Research site [26]. Daily observations of CH_4 fluxes in nine different types of swamps in northern Finland have shown that the average CH_4 emission is significantly correlated with the average groundwater level [27]. Related research has also indicated that the yield of CH_4 is lower under drought conditions in peatlands [28]. Moreover, frequent extreme drought events in recent years have been increasing, and these events have clearly had a profound impact on CH_4 fluxes in the Zoige peatland [29-30]. However, data regarding the changes in CH_4 fluxes in the Zoige peatland under extreme drought are limited.

Therefore, the accurate estimation of CH_4 fluxes and the factors impacting their dynamics will help quantify the interactions and feedback occurring between extreme drought events and the alpine peatland ecosystem. In this study, we observed the CH_4 fluxes and environmental factors at the Zoige peatland in a controlled experiment of extreme drought with the hope of estimating the drought effects on CH_4 fluxes, and we identified the environmental variables affecting these fluxes under continuous drought stress. The results provide an important scientific basis to accurately evaluate the contribution of alpine peatland CH_4 towards global climate change and will also help support peatland conservation.

Materials & Methods

2.1. Site description

The experiment was conducted in Zoige county in the eastern Tibetan Plateau (33.79° N, 102.95° E) at an altitude of 3430 m (Figure 1a). The mean annual temperature is 1.1 °C, and mean annual precipitation is 648.5 mm, with 80% falling during the growing season from June to September. The mean monthly temperature ranges from 1 °C (January) to 11 °C (July). The experiment was established in a frigid temperate zone steppe dominated by herbaceous marshes and composed mainly of *Carex meyeriana*, *Carex muliensis*, and *Kobresia tibetica*. The main soil type was marshy peat, with the soil pH is between 6.8-7.2 in localized areas [31]. The depth of peat in the vertical profile of this site is in general 1.2 m. Field experiments were approved by the Institute of Wetland Research.

2.2. Experiment design and data collection

Based on the local rainfall data for the past 50 years, we defined daily rainfall ≥ 3 mm as ecologically effective precipitation [32]. During the flourishing period of the growth season, we selected 32 days as the duration of non-ecologically effective precipitation (drought days) and simulated extreme drought over this period of plant growth [33]. The area of the plot was 20 m × 20 m, and extreme drought treatment (D) and control treatments (CK) were set up, independently, with each treatment consisting of three (2 m × 2 m) repetition plots (Figure 1b). We buried iron sheets in the soil about 1 m deep around each treatment to prevent the lateral flow of soil water. A stainless-steel base (50 cm × 50 cm × 20 cm) was placed at the sampling point and inserted into the ground at a depth of 10 cm. Before each measurement, we filled the groove of stainless steel with water to ensure the airtightness of the measurement (Figure 1c). For the extreme drought treatment, we used a magnesium-aluminum alloy shelter (length × width

× height; 2.5 m × 2.5 m × 1.8 m) to simulate drought, and the light transmittance of the shelter was more than 90%. The gas in the controlled plot was monitored under natural conditions.

A fast greenhouse gas analyzer (DLT-100, Los Gatos Research, USA) was used to monitor CH_4 fluxes, at a data acquisition frequency of 1 Hz. A TZS-5X thermometer was used to monitor the air temperature (Ta) and soil temperature (Ts), and a TDR 300 was used to measure the SWC. A box (50 cm × 50 cm) was connected with the fast greenhouse gas analyzer. There were two small holes 2 cm in diameter at the top of the box, which were closed with rubber plugs. There was a small hole in each rubber plug for the insertion of two gas conduits (intake pipe and outlet pipe) with a length of 20 m and an inner diameter about 4mm. The box was connected to an intake pipe and an outlet pipe with a length of about 20 m. To ensure the gas in the box could be quickly mixed and evenly distributed, two small fans (10 cm in diameter) were set at the top of the box. Each sampling point was measured in a sealed transparent box or dark box for 2 min, and the measured data from the dark box were used to ascertain the CH_4 fluxes. The drought treatment started on July 15, 2017, and end on August 16, 2017. The measurements were taken at three periods of one day (first: 9:00- 10:00, second: 12:00-13:00, third: 14:00- 15:00). For the measurement of aboveground biomass, 50 cm × 50 cm quadrats were randomly chosen in each experimental plot, and all plants within the quadrats were cut to ground level. After the dust was removed, the plant material was oven dried to constant weight at 70 °C. Belowground biomass was collected by digging soil pits at the same locations where the aboveground biomass had been removed at the sampling depths of 0-20 cm and 20-40 cm. Soils containing root biomass were placed in 40-mesh nylon bags and taken back to the laboratory, where the roots were carefully washed and then oven dried to a constant weight at 70 °C. A soil drill was used to sample the soil via multi-point sampling and mixing. The soil organic matter (SOC) was determined using a potassium dichromate volumetric method [33], total carbon (TC) was determined by the elemental analyzer [34], and total nitrogen (TN) was determined via the Kjeldahl method [35].

2.3. Data analysis

The formula used for calculating the greenhouse gas fluxes [36] was:

$$F_c = \frac{\partial C'}{\partial t} \times \frac{M}{V_0} \times \frac{P}{P_0} \times \frac{T_0}{T_0 + t} \times \frac{H}{100} \times 3600 \qquad (1)$$

Where Fc is the gas fluxes (mg C/ (m2·h)); M is the molar mass of gas (g/mol); V_0 is the standard molar volume of gas (22.4 L/mol); P/P_0 is the measurement of pressure to standard air pressure; T_0 is the absolute temperature (273.15 °C); t is the average value of the measured temperature in the box (°C); and H is the static height (cm). Importantly, the measured data were analyzed by linear regression to calculate the linear slope of the gas concentration relative to the time of observation.

Repeated-measure ANOVA with Duncan's multiple-range tests were performed to examine the main and interaction effects of date, treatment and block on the differences in CH_4 fluxes and environmental factors in 2017 (SPSS, Chicago, IL, USA). A one-way ANOVA analysis was performed to examine the properties (above and below ground biomass, TC, TN, SOC) at different depths in 2017 (SPSS, Chicago, IL, USA). To further evaluate the relationship of CH_4 fluxes and environmental factors, a correlation matrix analysis between CH_4 fluxes and environmental factors was conducted (Origin 2017, USA). The slopes of those linear relationships were analyzed and compared by SMA (Standardized Major Axis) regression analysis, using the SMATR (Standardized Major Axis Tests and Routines) package [37]. R v3.5.1 with the corrplot package was used for the correlation analysis [38].

Results

3.1. Climate during the experiment period

During the experiment period (32 d), 14 precipitation events occurred in Zoige, with 6 days including ecologically effective precipitation events (≥3 mm). The daily precipitation ranged from 0.1 mm to 20.6 mm (Figure 2) and the average precipitation was 1.9 mm. The total precipitation was 58.9 mm in the control treatment and 0 mm in the extreme drought treatment during the experimental period. The precipitation mainly occurred in early August, and a transient rainfall occurred at the end of the treatment period. The highest and lowest daily temperatures were 15.3 °C and 8.4 °C, respectively, and the average temperature was 12.9 °C during the treatment period.

3.2. Effects of extreme drought on CH_4 fluxes

From the end of June to the middle of July, there was a transition period between a weak CH_4 sink and a weak CH_4 source of the Zoige peatland (Figure 3a). The emission of CH_4 from the Zoige peatland reached a maximum around August 16. During the pre-drought period, the ecosystem functioned as a CH_4 sink, and during the extreme drought and post-drought periods, the ecosystem functioned as a net CH_4 source (Figure 3b). Compared to the control treatment, extreme drought significantly decreased the CH_4 fluxes of the Zoige peatland ecosystem by 31.54% ($P<0.05$, Figure 3b, Table 1) in the drought period, and there was no significant change in the pre and post-drought periods of the experiment under the extreme drought and control treatment ($P>0.05$). Additionally, the difference of CH_4 fluxes between the control and drought reached the highest value at the peak of plant growth (Figure 3c). The extreme drought significantly decreased SWC at depths of 5, 10, and 20 cm ($P<0.05$), but there was no significant influence of the extreme drought on Ts at depths of 5, 10, or 20 cm ($P>0.05$, Table 1).

3.3. Effects of extreme drought on plant biomass and soil physicochemical properties

The extreme drought treatment significantly decreased the aboveground biomass of the Zoige alpine peatland ecosystem by 42.75% ($P<0.05$, Figure 4a). The extreme drought treatment significantly decreased the belowground biomass by 59.73% and 59.65% at a depth of 0-10 cm and 10-20 cm, respectively ($P<0.05$, Figure 4b). Under both treatments, the root mass of the subsoil (10-20 cm) was higher than that of the topsoil (0-10 cm) (Figure 4b). Subsoil (20 cm) SWC was higher than that of the topsoil (5, 10 cm) (Figure 4c). Significant differences in TC and TN between the two treatments were observed at a depth of 10-20 cm ($P<0.05$, Figure 4d-e), but there was no significant difference in TC or TN between the extreme drought treatment and control treatment at depths of 0-10 cm ($P>0.05$, Figure 4d-e). There was also no significant difference in SOC at depths of 0-10 and 10-20cm (*P*>0.05, Figure 4f). The organic matter (TC, TN, and SOC) of the subsoil was lower than that of the top soil (Figure 4d-f).

3.4. Relationship between CH_4 fluxes and environmental factors

The regression analysis showed that the Ts at the depth of 10 and 20 cm had a significantly negatively relationship with CH_4 fluxes between the two treatments ($P<0.05$, Figure 5b-c), as the CH_4 fluxes gradually decreased as the Ts increased. The correlation between the subsoil (20 cm) temperature and CH_4 fluxes was higher than it was with the topsoil (5, 10 cm) temperature between the two treatments (Figure 5a-c). The dynamics of the CH_4 fluxes correlated well with that of the SWC, both in the extreme drought and control treatments (Figure 5d-f). The SWC at depths of 5 ($P<0.01$), 10 ($P<0.01$), and 20 ($P<0.01$) cm was negatively correlated with the CH_4 fluxes under the extreme drought and control treatments (Figure 5d-f). The correlation between the subsoil (20 cm) water content and CH_4 fluxes was higher than it was with the topsoil (5, 10 cm) water content between the two treatments. Moreover, there was a significant difference in the slopes of the SWC at depths of 5, 10, and 20 cm between the control and drought treatments ($P_{slope}<0.01$, Figure 5d-f). The slope of the CH_4 fluxes under the extreme drought treatment was lower than that under the control treatment relative to the SWC. The correlation of CH_4 fluxes to SWC was higher than it was relative to Ts (Figure 5a-f).

The correlation matrix analysis between CH_4 fluxes and the different environmental factors at depths of 5, 10, and 20 cm were negative under the two treatments. The correlation between CH_4 fluxes and subsoil (20 cm) environmental factors (SWC and Ts) was higher than that with the topsoil (5, 10 cm) environmental factors (Figure 6a-d). The extreme drought decreased the correlation between the Ts and CH_4 fluxes (Figure 6a-b), and the extreme drought decreased the correlation between the SWC and CH_4 fluxes (Fig 6c-d). There was a stronger relationship between the SWC and CH_4 fluxes than between the Ts and CH_4 fluxes (Figure 6a-d).

Discussion

The influence of extreme drought in relation to the variation of CH_4 fluxes has been recognized in earlier studies [30,39-43]. For instance, CH_4 fluxes measured by the eddy covariance method at Mer Bleue bog in Canada suggested that the total CH_4 emitted during the growing season with extreme drought was less than that during the previous wetter year [44]. Meanwhile, three drought scenarios (gradual, intermediate, and rapid transition into drought) at 18 freshwater wetlands investigated in Everglades National Park, USA revealed that more CH_4 was emitted than net carbon uptake could offset as the relative humidity increased [45]. Our study used a control experiment to simulate an extreme drought event for the reason that the controlled experiment had better consistency in soil and vegetation conditions. We analyzed the effects of extreme drought on CH_4 fluxes and the relationship between CH_4 fluxes and environmental factors in a typical alpine peatland. The results clearly showed that extreme drought significantly decreased the CH_4 fluxes of the peatland ecosystem (Figure 3b), which was consistent with previous studies [43-46]. With the decrease of SWC and anaerobic degree, the transition from anaerobic environment to aerobic environment decreased the generation of methane and increased the thickness of the oxide layer, and the produced methane was oxidized by more methanogens [47-49]. Extreme drought can also decrease the anaerobic environment of CH_4 production and reduce the activity of methanogenic bacteria and anaerobic microsites, thus, decreasing the emission of CH_4 [49-51].

Extreme drought also had potential effects on different soil physical and chemical properties [52-55]. Across the observed content of the soil organic matter, our results indicated that the soil content of TN, TC, and SOC in the control treatment were higher than that under extreme drought (Figs 4d-f). As previously reported, one possible explanation for this observation is that drought might alter the distribution and transformation of carbon in the soil via the movement of water and solutes through the pore matrix; thus, this might result the decrease of these matters [54]. Additionally, with the vegetation coverage up to 90% and abundant rainfall during the growing season in the Zoige alpine peatland, the large amount of methanol released from dead plants will provide the substrate for methanogens, but the active conditions for methanogens changes with the changing water conditions of the alpine peatland, resulting in reduced CH_4 emission [55]. Our results also found that the soil contents of TN, TC, and SOC of the subsoil (20 cm) were lower than that of the topsoil (5, 10 cm) (Figure 4d-f). In contrast, our results also showed that there was a higher belowground biomass in the subsoil (Figure 4b) than the topsoil. Moreover, a higher SWC in the subsoil (20 cm) was found relative to the topsoil (Figure 4c), and this might have been because plants will allocate more roots to absorb more water and nutrients in deeper soils, thus leading to a decreased SWC and soil organic matter [56].

Some prior studies have reported that environmental factors, including Ts and SWC, might influence CH_4 fluxes [57-59]. Across the study period, our results found that Ts had a significant negative relationship with CH_4 fluxes under control treatments at depth of 10 and 20 cm in the Zoige peatland ecosystem, with the CH_4 fluxes decreasing with the increasing of Ts (Figure 5b-c). This negative relationship was in agreement with several studies [60-62], which suggested that CH_4 oxidation rates increased faster with increasing temperature when compared to CH_4 production, leading to the decrease of CH_4 fluxes. In addition, the alpine peatland is low-temperature and anoxic all year round, but the oxygen content and temperature are increased greatly in the peak period of plant growth, which provides an environment for methane oxidation and enhances the activity of methane oxidative bacteria [58]. Additional results from this study indicated that the correlation between subsoil (20 cm) Ts and CH_4 fluxes was better than with the topsoil (5, 10 cm) Ts under these two treatments. This might have been due to the subsoil not being easily disturbed by changes in the external environment, making it more suitable for the survival of microorganisms related to methane production and oxidation [62]. Another founding in this research was that extreme drought decreased the correlation of CH_4 fluxes and Ts (Figure 6a-b). One possible explanation for this could be that extreme drought releases sulfate into the soil solution, and this increase could stimulate sulfate-reducing bacteria, which could compete with methanogens for access to organic substrates that might sever to reduce the influence of Ts on CH_4 fluxes [63].

In addition to Ts, CH_4 fluxes are sensitive to the SWC, and previous studies have shown a strong relationship between the water table and CH_4 emissions [63]. Here, we compared the relationship between CH_4 fluxes and the SWC at different depths and found that there was a significant negative relationship between CH_4 fluxes and SWC in the Zoige peatland ecosystem (Figure 5). This might have been due to the increase of SWC hindering the diffusion of CH_4 into soil pores [64]. By comparing the slope of CH_4 fluxes under extreme drought and control treatments, we found that extreme drought significantly decreased the sensitivity of CH_4 fluxes towards the SWC (Figure 5d-f). A possible explanation for this could be that extreme drought significantly decreased the SWC and changed the hydrothermal conditions of the soil, which could affect the production and oxidation of CH_4 fluxes [65,67]. CH_4-oxidizing microorganisms are able to be retrained under extreme drought conditions, resulting in a higher CH_4 consumption during a drought, which could lead to the observed decreased sensitivity [66]. In addition, we found a better correlation between CH_4 fluxes and subsoil SWC than for topsoil (Figure 6c-d). This might be due to the correlation of CH_4 emissions and the concentration of CH_4 dissolved in the pore water, which was controlled by rhizospheric oxidation of CH_4 driven by plant photosynthesis [68]. With more water, the subsoil could provide a beneficial environment for higher methanogen activity [69]. However, a detailed analysis of the microbes and enzyme data is needed to explore these possible mechanisms in the future studies.

Conclusions

We found that the condition of extreme drought significantly decreased the CH_4 fluxes in the Zoige peatland on the Tibetan Plateau. The Ts and SWC had negative relationships with CH_4 fluxes under the extreme drought and control treatments. Extreme drought decreased the correlation of the CH_4 fluxes relative to the SWC and weakened the sensitivity of CH_4 fluxes towards the SWC. The correlation coefficient between the subsoil (20 cm) environmental factors and CH_4 fluxes were higher than it was with the topsoil (5, 10 cm) environmental factors under the extreme drought and control treatments. These findings indicated that extreme drought might reduce the contributions of CH_4 emissions from high-altitude peatland into the atmosphere and decrease the global warming potential. However, the mechanism of CH_4 fluxes affected by extreme drought remains unclear. As such, our further work will focus on the response of soil enzyme activity and soil microorganisms to extreme drought events and the coupling of microbial process and macroscopic phenomenon.

Acknowledgements

This work was supported by the National Nonprofit Institute Research Grant (CAFYBB2017QB009), the National Key Research and Development Program of China (Grant No. 2016YFC0501804), and the National Natural Science Foundation of China (Grant No. 41701113, 41877421, 31770511).

References

1. IPCC. Climate change 2013: the physical science basis. U.K. Cambridge: Cambridge University Press 2013.
2. Kreyling, J.; Wenigmann, M.; Beierkuhnlein, C.; Jentsch, A. Effects of extreme weather events on plant productivity and tissue die-back are modified by community composition. Ecosystems 2008, 11, 752-763.
3. Kang, X.M.; Yan, L.; Cui, L.J.; Zhang, X.D.; Hao, Y.B.; Wu, H.D.; Zhang, Y.; Li, W.; Zhang, K.R.; Yan, Z.Q.; Li, Y.; Wang, J.Z. Reduced carbon dioxide sink and methane source under extreme drought condition in an alpine peatland. Sustainability 2018, 10, 4285.
4. Thakur, M.P.; Reich, P.B.; Hobbie, S.E.; Stefanski, A.; Rich, R.; Rice, K.E.; Eddy, W.C.; Eisenhauer, N. Reduced feeding activity of soil detritivores under warmer and drier conditions. Nat Clim Change 2017.
5. Reichstein, M.; Bahn, M.; Ciais, P.; Frank, D.; Mahecha, M.; Seneviratne, S.I.; Zscheischler, J.; Beer, C.; Buchmann, N.; Frank, D.C.; Papale, D.; Ramming, A.; Smith, P.; Thonicke, K.; Van der Velde, M.; Vicca, S.; Walz, A.; Wattenbach, M. Climate extremes and the carbon cycle. Nature 2013, 500, 287-295.
6. Bloor, J.M.G.; Bardgett, R.D. Stability of above-ground and below-ground processes to extreme drought in model grassland ecosystems: Interactions with plant species diversity and soil nitrogen availability. Perspectives in Plant Ecology Evolution and Systematics 2012, 14, 0-204.
7. Beierkuhnlein, C.; Thiel, D.; Jentsch, A.; Willner, E.; Kreyling, J. Ecotypes of European grass species respond differently to warming and extreme drought. Journal of Ecology 2011, 99, 703-713.
8. Hao, Y.B.; Cui, X.Y.; Wang, Y.F.; Mei, X.R.; Kang, X.M.; Wu, N.; Luo, P.; Zhu, D. Predominance of precipitation and temperature controls on ecosystem CO_2 exchange in Zoige alpine wetlands of southwest China. Wetlands 2011, 31(2), 13-422.
9. Yin, Y.; Liu, H.Y.; Liu, G.; Hao, Q.; Wang, H.Y. Vegetation responses to mid-Holocene extreme drought events and subsequent long-term drought on the southeastern Inner Mongolian Plateau, China. Agricultural & Forest Meteorology 2013, 178-179, 3-9.
10. Dargie, G.C.; Lewis, S.L.; Lawson, I.T.; Mitchard, E.T.A.; Page, S.; Bocko, Y.E.; Suspense, I.A. Age, extent and carbon storage of the central Congo Basin peatland complex. Nature 2017, 542, 86-90.
11. Page, S.E.; Rieley, J.O.; Banks, C.J. Global and regional importance of the tropical peatland carbon pool. Global Change Biology 2011, 17, 798-818.
12. Wu, J. Response of peatland development and carbon cycling to climate change: a dynamic system modeling approach. Environmental Earth Sciences 2012, 65, 141-151.
13. Mclaughlin, J.; Webster, K. Effects of climate change on peatlands in the far north of ontario, canada: A synthesis. Arctic, Antarctic, and Alpine Research, 2014, 46(1), 84-102.

14. van Bellen, S.; Garneau, M.; Booth, R. K. Holocene carbon accumulation rates from three ombrotrophic peatlands in boreal Québec, Canada: impact of climate-driven ecohyrological change. The Holocene 2011, 21, 1217–1231.
15. Bunbury, J.; Finkelstein, S.A.; Bollmann, J. Holocene hydro-climatic change and effects on carbon accumulation inferred from a peat bog in the Attawapiskat River watershed, Hudson Bay Lowlands, Canada. Quaternary Research, 2012, 78(2), 275-284.
16. Webster, K.L.; McLaughlin, J.W.; Kim, Y.; Packalen, M.; Li, C.S. Modelling carbon dynamics and response to environmental change along a boreal fen nutrient gradient. Ecological Modelling, 2013, 248, 148–164.
17. Reichstein, M.; Bahn, M.; Ciais, P.; Frank, D.; Mahecha, M.D.; Seneviratne, S.I.; Zscheischler, J.Z.; Beer, C.; Buchmann, N.; Frank, D.C.; Papale, D.; Ramming, A.; Smith, P.; Thonicke, K.; Van der velde, M.; Vicca, S.; Walz, A.; Wattenbach, M. Climate extremes and the carbon cycle. Nature,2013,500(7462).
18. Soren, N.M.; Sejian, V.; Malik, P.K. Enteric methane emission under different feeding systems. Springer 2015.
19. Wang, M.; Liu, Z.G.; Ma, X.H.; Wang, G.D. Division of organic carbon reserves of peatlands in China. Wetland Sciences 2012, 10(2), 156-163.
20. Kang, X.M.; Wang, Y.F.; Chen, H.; Tian, J.Q.; Cui, X.Y.; Rui, Y.C.; Zhong, L.; Kardol, P.; Hao, Y.B.; Xiao, X.M. Modeling carbon fluxes using multi-temporal MODIS imagery and CO_2 eddy flux tower data in Zoige alpine wetland, south-west China. Wetlands 2014, 34, 603-618.
21. Rydin, H.; Jeglum, J.K. The biology of peatlands. Economic Botany 2006, 1-400.
22. Yang, G.; Chen, H.; Wu, N.; Tian, J.Q.; Peng, C.H.; Zhu, Q.A.; Zhu, D.; He, Y.X.; Zheng, Q.Y.; Zhang, C.B. Effects of soil warming, rainfall reduction and water table level on CH_4, emissions from the Zoige peatland in China. Soil Biol Biochem 2014, 78, 83-89.
23. Gorham, E. Northern Peatlands: Role in the carbon cycle and probable responses to climatic warming. Ecol Appl 1991, 1, 182-195.
24. Chen, W.W.; Zheng, X.H.; Chen, Q.; Wolf, B.; Butterbach-Bahl, K.; Bruggemann, N.; Lin, S. Effects of increasing precipitation and nitrogen deposition on CH_4 and N_2O fluxes and ecosystem respiration in a degraded steppe in Inner Mongolia, China. Geoderma 2013, 192, 335-340.
25. Blankinship, J.C.; Brown, J.R.; Dijkstra, P.; Allwright, M.C.; Hungate, B.A. Response of terrestrial CH_4 uptake to interactive changes in precipitation and temperature along a climatic gradient. Ecosystems 2010, 13, 1157-1170.
26. Fest, B.J.; Nina, H.N.; Tim, W.; Griffith, D.W.T.; Livesley, S.J.; Arndt, S.K. Soil methane oxidation in both dry and wet temperate eucalypt forests shows a near-identical relationship with soil air-filled porosity. Biogeosciences 2017, 14, 467-479.
27. Huttunen, J.T.; Nykänen, H.; Turunen, J.; Martikainen, P.J. Methane emissions from natural peatlands in the northern boreal zone in Finland, Fennoscandia. Atmos Environ 2003, 37, 147-151.

28. Freeman, C.; Nevison, G.B.; Kang, H.; Hughes, S.; Reynolds, B.; Hudson, J.A. Contrasted effects of simulated drought on the production and oxidation of methane in a mid-wales wetland. Soil Biol Biochem 2002, 34, 61-67.
29. Chen, H.; Wu, N.; Gao, Y.H.; Wang, Y.F.; Luo, P.; Tian, J.Q. Spatial variations on methane emissions from Zoige alpine wetlands of southwest China. Sci Total Environ 2009, 407, 1097-1104.
30. Wang, D.X.; Ding, W.X.; Wang, Y.Y. Influence of major environmental factors on difference of methane emission from Zoige plateau and Sanjiang plain wetlands. Wetland Science 2003.
31. Zhou, W.C.; Duoerji, S.; Cui, L.J.; Wang, Y.F.; Li, W. Effects of fencing and grazing on the emissions of CO_2 and CH_4 in Zoige peatland, East Qinghai-Tibetan plateau. Ecology & Environmental Sciences 2015.
32. Hao, Y.B.; Kang, X.M.; Cui, X.Y.; Ding, K.; Wang, Y.F.; Zhou, X.Q. Verification of a threshold concept of ecologically effective precipitation pulse: from plant individuals to ecosystem. Ecol Inform 2012, 12, 23-30.
33. Wang, H.T.; He, X.D.; Gao, Y.B.; Lu, J.G.; Xue, P.P. Density in artemisia ordosica successional community in response to spatial heterogeneity of soil moisture and organic matter. Journal of Plant Ecology 2007, 31, 1145-1153.
34. Sokolova, O.V.; Vorozhtsov, D.L. Development of rapid method for determining the total carbon in boron carbide samples with elemental analyzer. Russian Journal of Applied Chemistry 2014, 87, 1640-1643.
35. Nozawa, S.; Hakoda, A.; Sakaida, K.; Suzuki, T.; Yasui, A. Method performance study of the determination of total nitrogen in soy sauce by the Kjeldahl method. Analytical Sciences the International Journal of the Japan Society for Analytical Chemistry 2005, 21(9):1129-1132.
36. Wickland, K.P.; Striegl, R.G.; Mast, M.A.; Clow, D.W. Carbon gas exchange at a southern Rocky Mountain wetland, 1996~1998. Global Biogeochem Cycles 2001, 15, 321~335.
37. Warton, D.I.; Wright, I.J.; Falster, D.S.; Westoby, M. Bivariate line-fitting methods for allometry. Biological Reviews 2006, 81, 259-291.
38. Svetnik, V.; Liaw, A.; Tong, C.; Wang, T. Application of Breiman's random forest to modeling structure-activity relationships of pharmaceutical molecules. Multiple Classifier Systems, 5th International Workshop 2004.
39. Harriss, R.; Sebacher, D.I.; Day, F.P. Methane flux in the Great Dismal Swamp. Nature. 1982, 297, 673-674.
40. Borken, W.; Davidson, E.A.; Savage, K.; Sundquist, E.T.; Steudler, P. Effect of summer throughfall exclusion, summer drought, and winter snow cover on methane fluxes in a temperate forest soil. Soil Biol Biochem 2006, 38, 1388-1395.
41. Stiehl-Braun, P.A.; Hartmann, A.A.; Kandeler, E.; Buchmann, N. Interactive effects of drought and N fertilization on the spatial distribution of methane assimilation in grassland soils. Glob Change Biol 2011, 17, 2629-2639.

42. Hartmann, A.A.; Buchmann, N.; Niklaus, P.A. A study of soil methane sink regulation in two grasslands exposed to drought and N fertilization. Plant Soil 2011, 342, 265-275.
43. Goodrich, J.P.; Campbell, D.; Schipper, L.A.; Clearwater, M. Summer drought leads to reduced net CO_2 uptake and CH_4 fluxes in a New Zealand peatland. AGU Fall Meeting Abstracts 2013.
44. Brown, M.; Humphreys, E.; Roulet, N.T.; Moore, T.R.; Lafleur, P. Divergent effects of drought on peatland methane emissions. AGU Fall Meeting Abstracts 2013.
45. Malone, S.L.; Starr, G.; Staudhammer, C.L.; Ryan, M.G. Effects of simulated drought on the carbon balance of everglades short-hydroperiod marsh. Glob Change Biol 2013, 19, 2511-2523.
46. Korres, N.E.; Norsworthy, J.K.; Burgos, N.R.; Oosterhuis, D.M. Temperature and drought impacts on rice production: An agronomic perspective regarding short- and long-term adaptation measures. Water Resources & Rural Development 2017, 9, 12-27.
47. Smith, K.A.; Ball, T.; Conen, F.; Dobbie, K.E.; Massheder, J.; Rey, A. Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes. European Journal of Soil Science 2003, 54, 779–791.
48. Webster, K.L.; McLaughlin, J.W.; Kim, Y.; Packalen, M.S.; Li, C.S. Modelling carbon dynamics and response to environmental change along a boreal fen nutrient gradient. Ecological Modelling 2012, 248, 148–164.
49. Tiemeyer, B.; Borraz, E.A.; Augustin, J.; Bechtold, M.; Beetz, S.; Beyer, C.; Drosler, M.; Ebli, M.; Eickenscheidt, T.; Fiedler, S.; Forster, C.; Freibauer, A.; Giebels, M.; Glatzel, S.; Heinichen, J.; Hoffmann, M.; Hoper, H.; Jurasinski, G.; Leiber-Sauheitl, K.; Peichl-Brak, M.; Robkopf, N.; Sommer, M.; Zeitz, J. High emissions of greenhouse gases from grasslands on peat and other organic soils. Glob Change Biol 2016, 22, 4134-4149.
50. Tian, J.Q.; Zhu, Y.B.; Kang, X.M.; Dong, X.Z.; Li, W.; Chen, H.; Wang, Y.F. Effects of drought on the archaeal community in soil of the Zoige wetlands of the Qinghai–Tibetan plateau. Eur J Soil Biol 2012, 52, 84-90.
51. O'Connell, C.S.; Ruan, L.L.; Silver, W.L. Drought drives rapid shifts in tropical rainforest soil biogeochemistry and greenhouse gas emissions. Nat Commun 2018, 9, 1348.
52. Fenner, N.; Freeman, C. Drought-induced carbon loss in peatlands. Nat Geosci 2011, 4, 895-900.
53. Yuste, J.C.; Peñuelas, J.; Estiarte, M.; Garcia-Mas, J.; Mattana, S.; Ogaya, R.; Pujol, M.; Sardans, J. Drought-resistant fungi control soil organic matter decomposition and its response to temperature. Glob Change Biol 2011, 17, 1475-1486.
54. Smith, A.P.; Bond-Lamberty, B.P.; Tfaily, M.M.; Todd-Brown, K.E.; Bailey, V.L. The destabilization of protected soil organic carbon following experimental drought at the pore and core scale. AGU Fall Meeting Abstracts 2015.
55. Jiang, N.; Wang, Y.F.; Dong, X.Z. Methanol as the primary methanogenic and acetogenic precursor in the cold Zoige wetland at Tibetan Plateau. Microbial Ecology 2010, 60(1):206-213.

56. Johnson, D.M.; Sherrard, M.E.; Domec, J.C.; Jackson, R.B. Role of aquaporin activity in regulating deep and shallow root hydraulic conductance during extreme drought. Trees 2014, 28, 1323-1331.
57. Morishita, T.; Hatano, R.; Desyatkin, R.V. CH_4 flux in an alas ecosystem formed by forest disturbance near Yakutsk, Eastern Siberia, Russia. Soil Science & Plant Nutrition 2003, 49, 369-377.
58. Wei, D.; Xu, R.; Wang, Y.H.; Wang, Y.S.; Liu, Y.W.; Yao, T.D. Responses of CO_2, CH_4 and N_2O fluxes to livestock exclosure in an alpine steppe on the Tibetan Plateau, China. Plant Soil 2012, 359, 45-55.
59. Krause, K.; Niklaus, P.A.; Schleppi, P. Soil-atmosphere fluxes of the greenhouse gases CO_2, CH_4 and N_2O in a mountain spruce forest subjected to long-term N addition and to tree girdling. Agr Forest Meteorol 2013, 181, 61-68.
60. Conrad, R. Soil microorganisms as controllers of atmospheric trace gases (H_2, CO, CH_4, OCS, N_2O, and NO). Microbiol Rev 1996, 60, 609-640.
61. Butterbach-Bahl, K.; Papen, H. Four years continuous record of CH_4-exchange between the atmosphere and untreated and limed soil of a N-saturated spruce and beech forest ecosystem in Germany. Plant Soil 2002, 240, 77-90.
62. Koch, O.; Tscherko, D.; Kandeler, E. Seasonal and diurnal net methane emissions from organic soils of the eastern Alps, Austria: effects of soil temperature, water balance, and plant biomass. Arct Antarct Alp Res 2007, 39, 438-448.63. Dowrick, D.J.; Freeman, C.; Lock, M.A.; Reynolds, B. Sulphate reduction and the suppression of peatland methane emissions following summer drought. Geoderma 2006, 132, 384-390.
64. Luan, J.W.; Liu, S.R.; Wu, J.H.; Wang, M.; Yu, Z. The transient shift of driving environmental factors of carbon dioxide and methane fluxes in Tibetan peatlands before and after hydrological restoration. Agr Forest Meteorol 2018, 250–251, 138-146.
65. Borken, W.; Matzner, E. Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. Glob Change Biol 2010, 15, 808-824.
66. Einola, J.K.M.; Kettunen, R.H.; Rintala, J.A. Responses of methane oxidation to temperature and water content in cover soil of a boreal landfill. Soil Biol Biochem 2007, 39, 1156-1164.
67. Wu, X.; Yao, Z.; Brüggemann, N.; Shen, Z.Y.; Wolf, B.; Dannenmann, M.; Zheng, X.; Butterbach-Bahl, K. Effects of soil moisture and temperature on CO_2 and CH_4 soil–atmosphere exchange of various land use/cover types in a semi-arid grassland in Inner Mongolia, China. Soil Biol Biochem 2010, 42, 773-787.
68. Ding, W.; Cai, Z.; Tsuruta, H. Diel variation in methane emissions from the stands of carex lasiocarpa and deyeuxia angustifolia in a cool temperate freshwater marsh. Atmospheric Environment 2004, 38, 181-188.
69. Tian, J.Q.; Chen, H.; Wang, Y.F.; Zhou, X.Q. Methane production in relation with temperature, substrate and soil depth in Zoige wetlands on Tibetan Plateau. Acta Ecologica Sinica 2011, 31, 121-125.

Table 1(on next page)

Table 1. Results (P value) of effects of CH_4 fluxes, Ts5, Ts10, Ts20, SWC5, SWC10 and SWC20 on block, date, drought, date*drought and date*block in 2017.

Ts 5/10/20, soil temperature at depth of 5, 10 and 20 cm; SWC 5/10/20, soil water content at depth of 5, 10 and 20 cm.

	CH_4 fluxes	Ts5	Ts10	Ts20	SWC5	SWC10	SWC20
Block	0.679	0.960	0.999	0.900	0.072	0.066	0.034
Date	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Drought	0.015	0.624	0.617	0.499	0.023	0.034	0.033
Date*Drought	<0.001	0.775	0.960	0.937	0.354	0.883	0.499
Date*Block	0.006	0.623	0.994	0.947	0.100	0.790	0.793

Figure 1

Figure 1.

(a) Zoige peatland in the eastern part of the Tibetan Plateau with the location of the study site, Sichuan province. (b) The picture of experiment site. (c) The zoning schematic map of experiment plot.

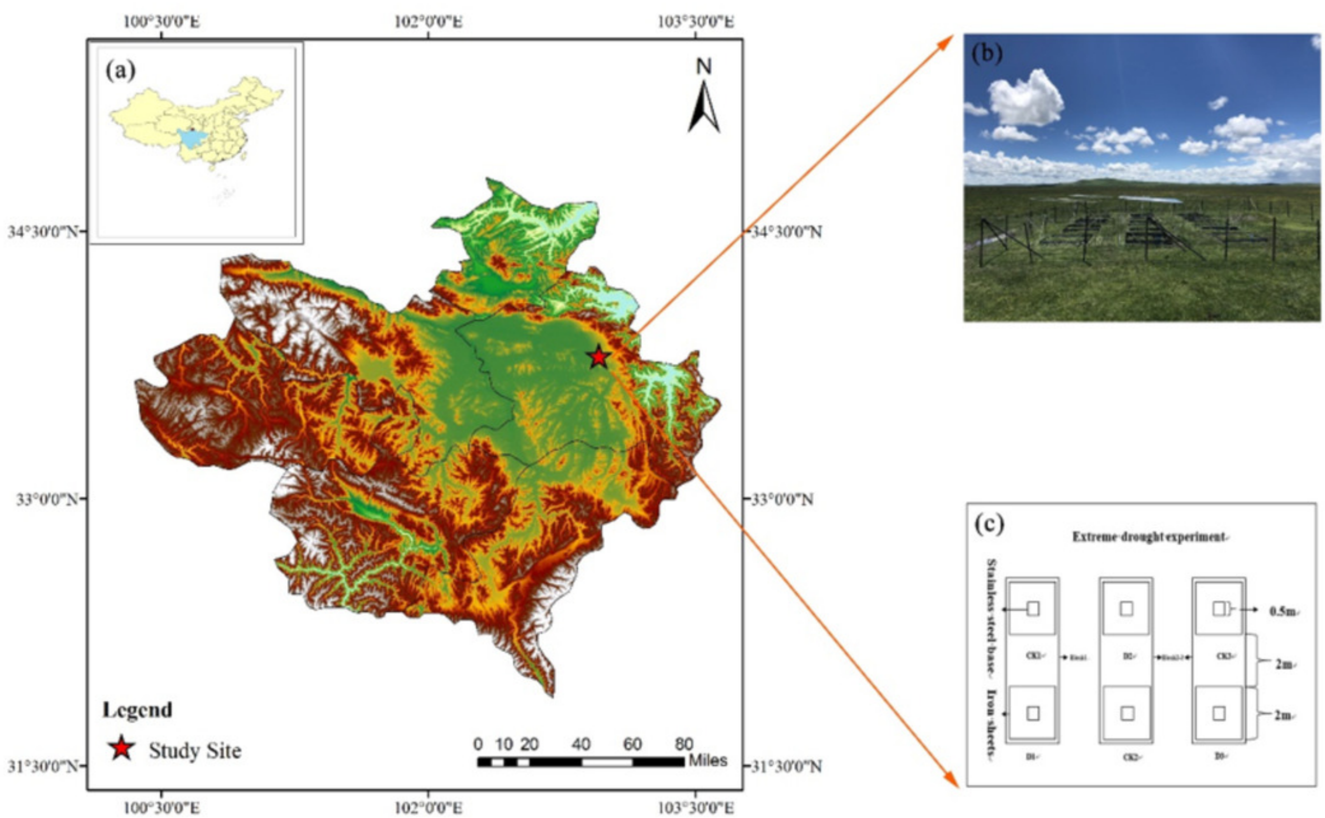


Figure 2

Figure 2.

Daily average precipitation and temperature of Zoige peatland during the experimental period in 2017. Point-line chart and histogram indicate temperature and precipitation respectively

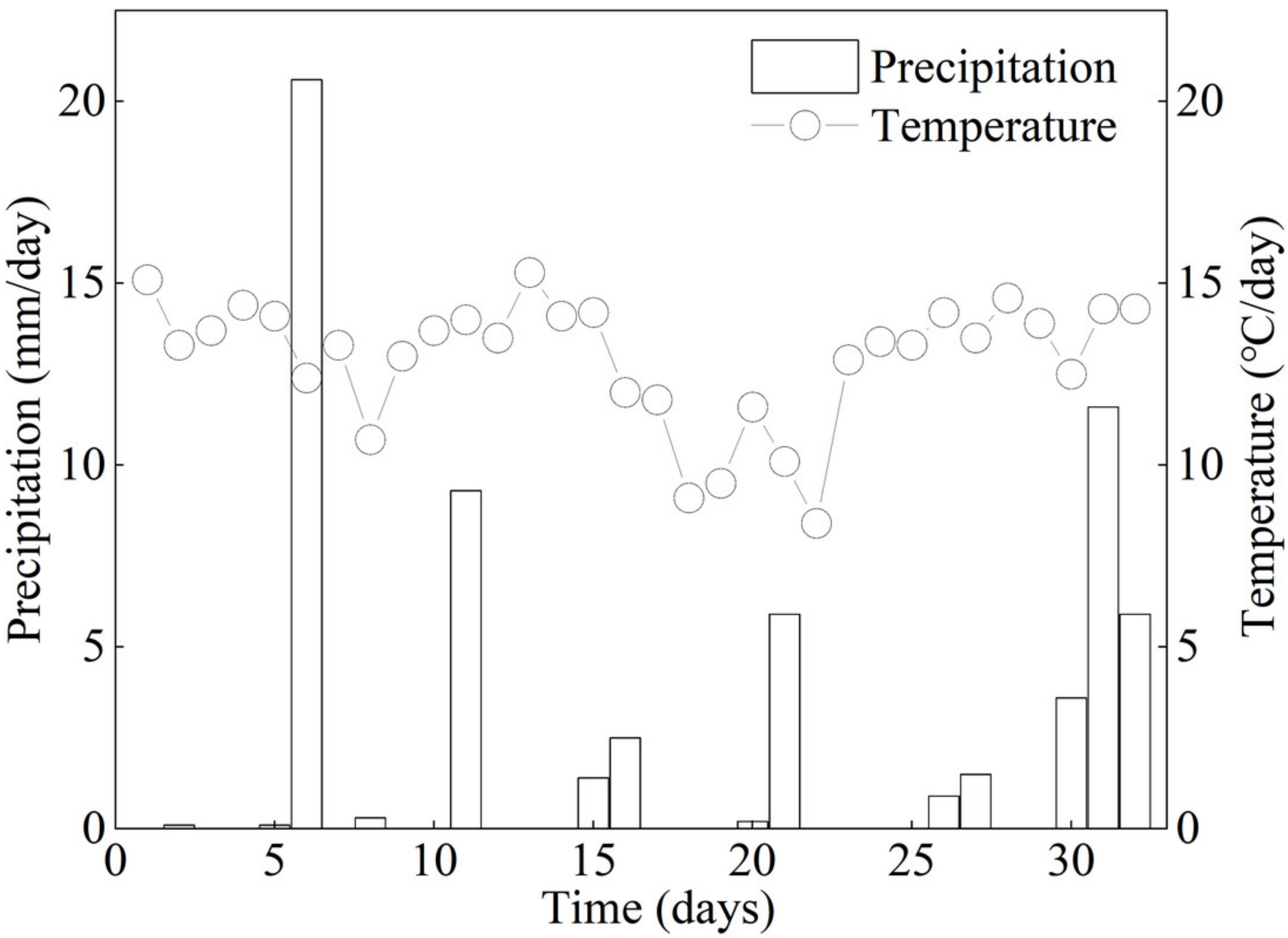


Figure 3

Figure 3.

(a) Effects of extreme drought on CH_4 fluxes in 2017. (b) The total mean value at different periods. (c) The difference value between the extreme drought and control treatments. Bars show ± SE (n=3). The arrows indicate the dates of the experiment. *: statistically significant at *P*<0.05. CK, control; D, extreme drought.

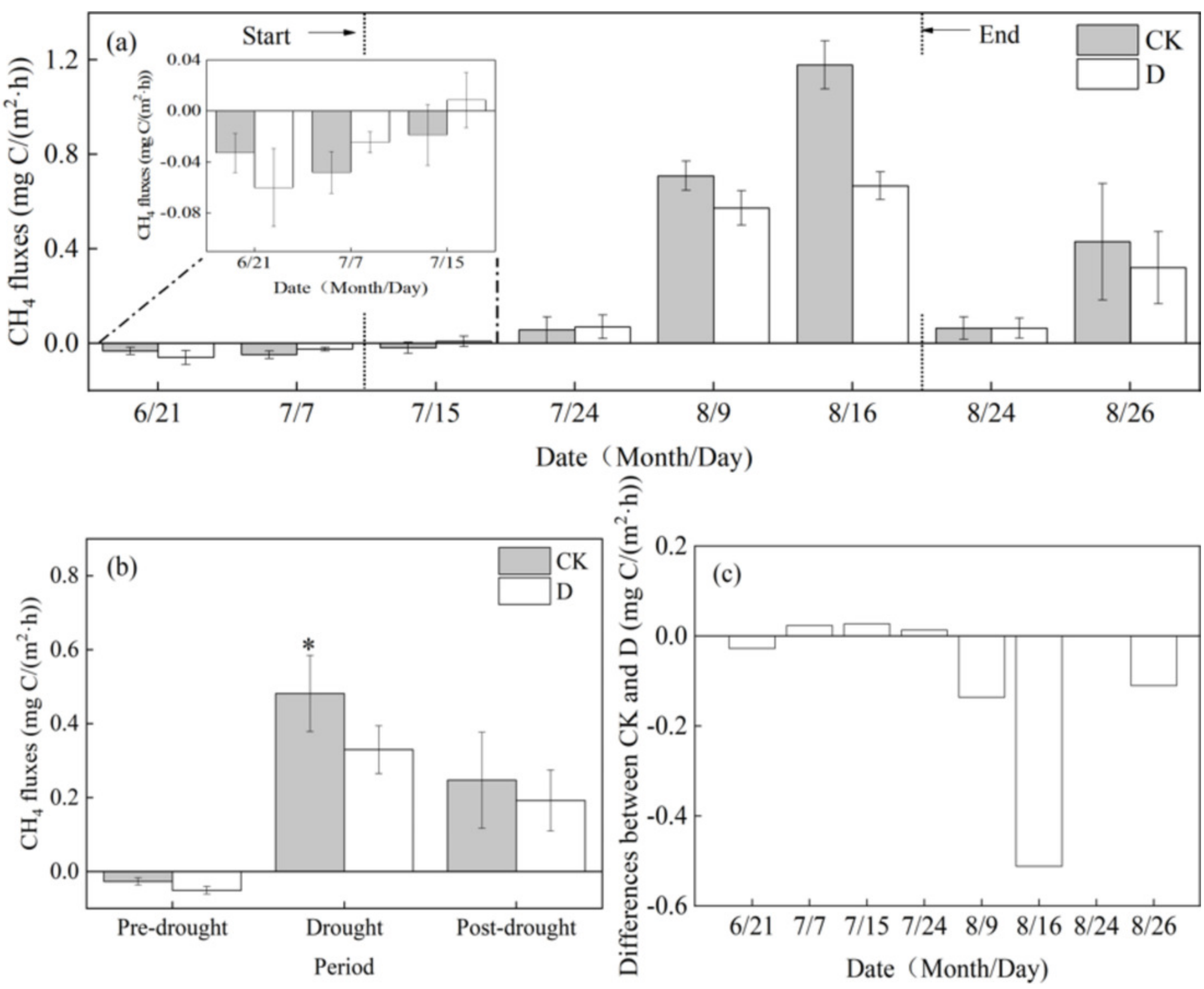


Figure 4

Figure 4.

(a) The impacts of extreme drought on aboveground biomass. (b) The impacts of extreme drought on belowground biomass. (c) The impacts of extreme drought on SWC at depths of 5, 10 and 20cm. (d) The effects of extreme drought on total nitrogen in the different soil layers. (e) The effects of extreme drought on total carbon in the different soil layers. (f) The effects of extreme drought on soil organic carbon in the different soil layers.

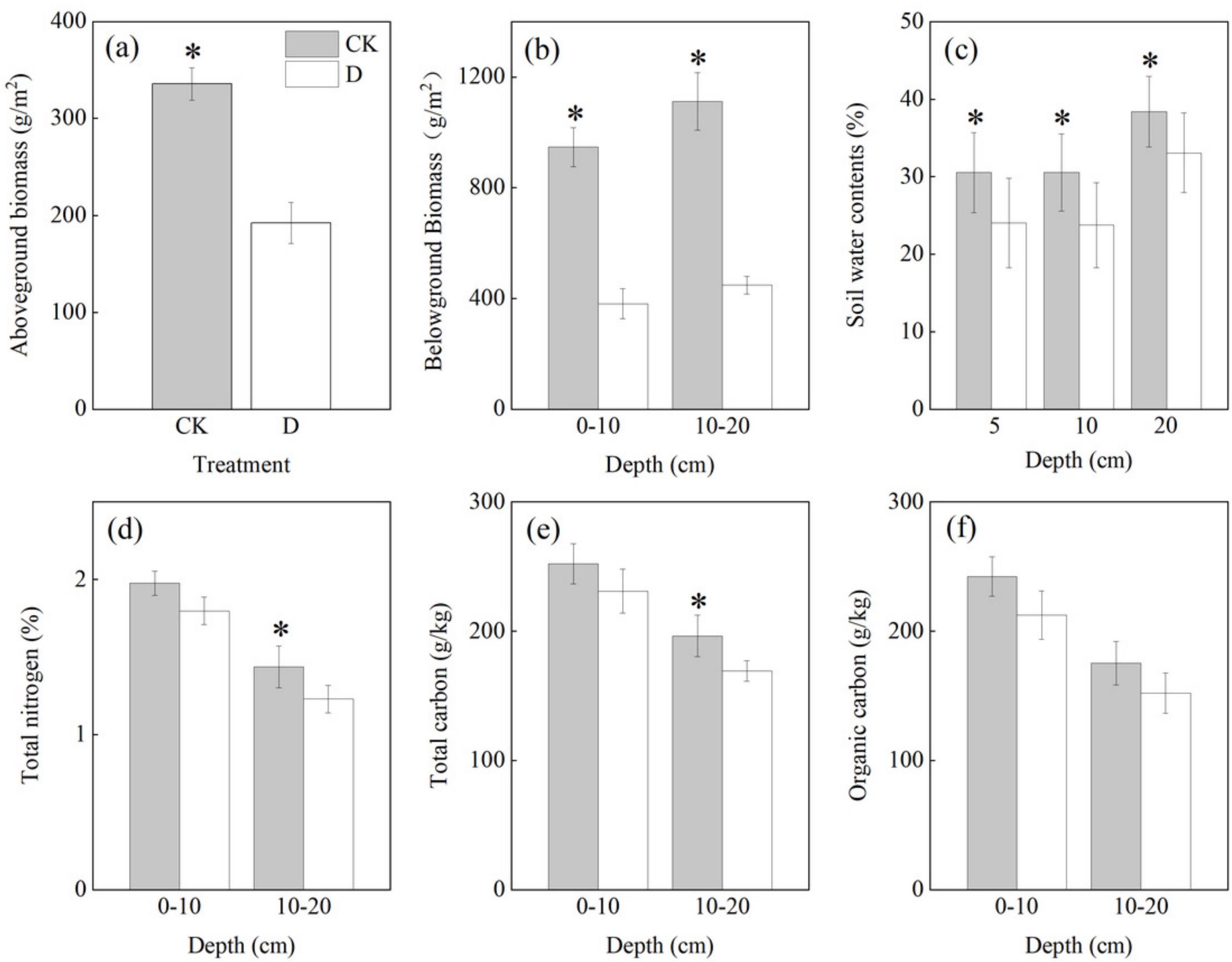


Figure 5

Figure 5.

Relationships between CH_4 fluxes and (a) 5 cm, (b) 10 cm, and (c) 20 cm soil temperature, and the relationships between CH_4 fluxes and (d) 5 cm, (e) 10 cm, and (f) 20 cm SWC in the different treatments. CK, control; D, extreme drought. *P*<0.05 indicates a significant difference between CH_4 fluxes and environment factors (Ts, SWC). P_{slope}<0.05 indicates a significant difference in the slopes between control and drought treatment.

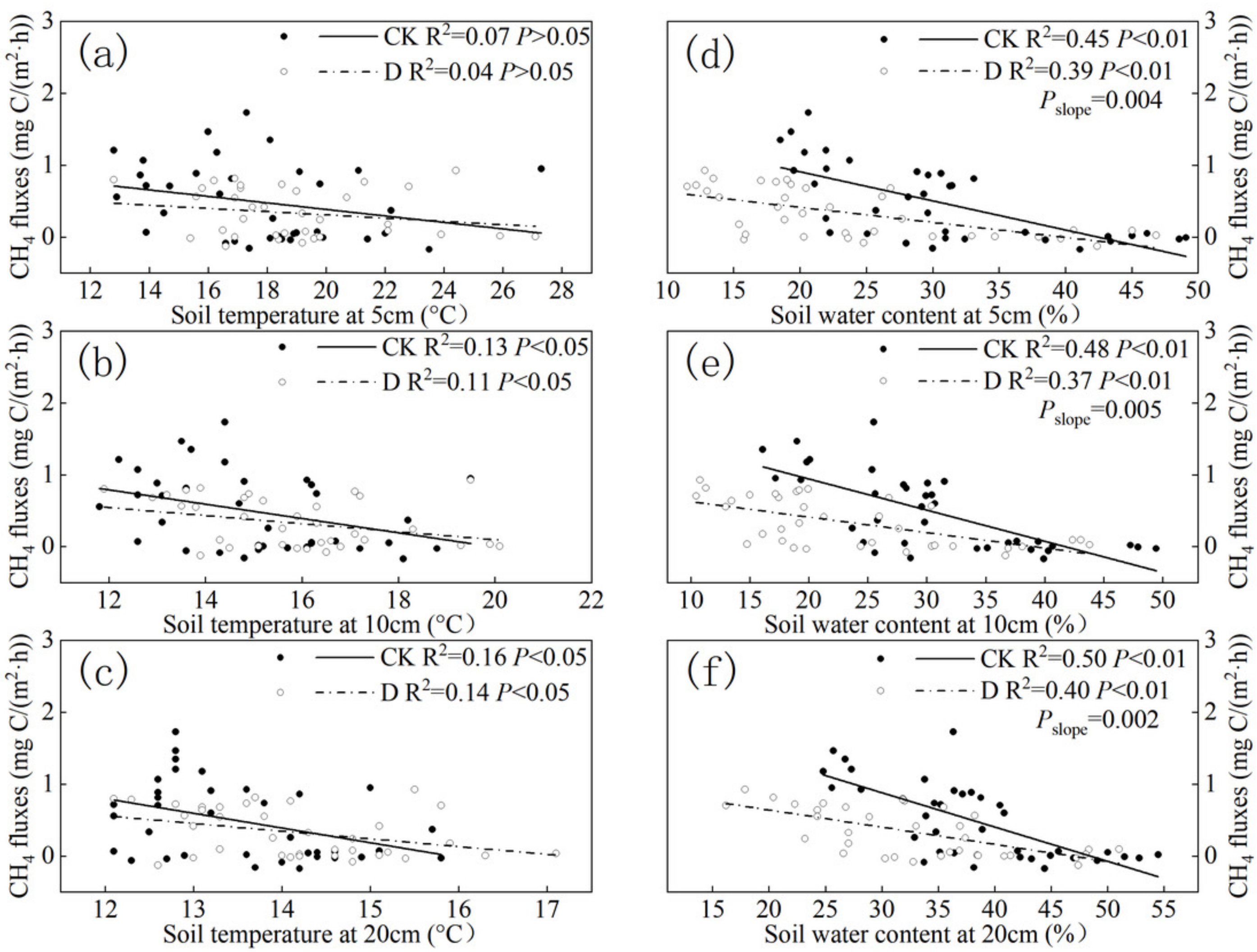
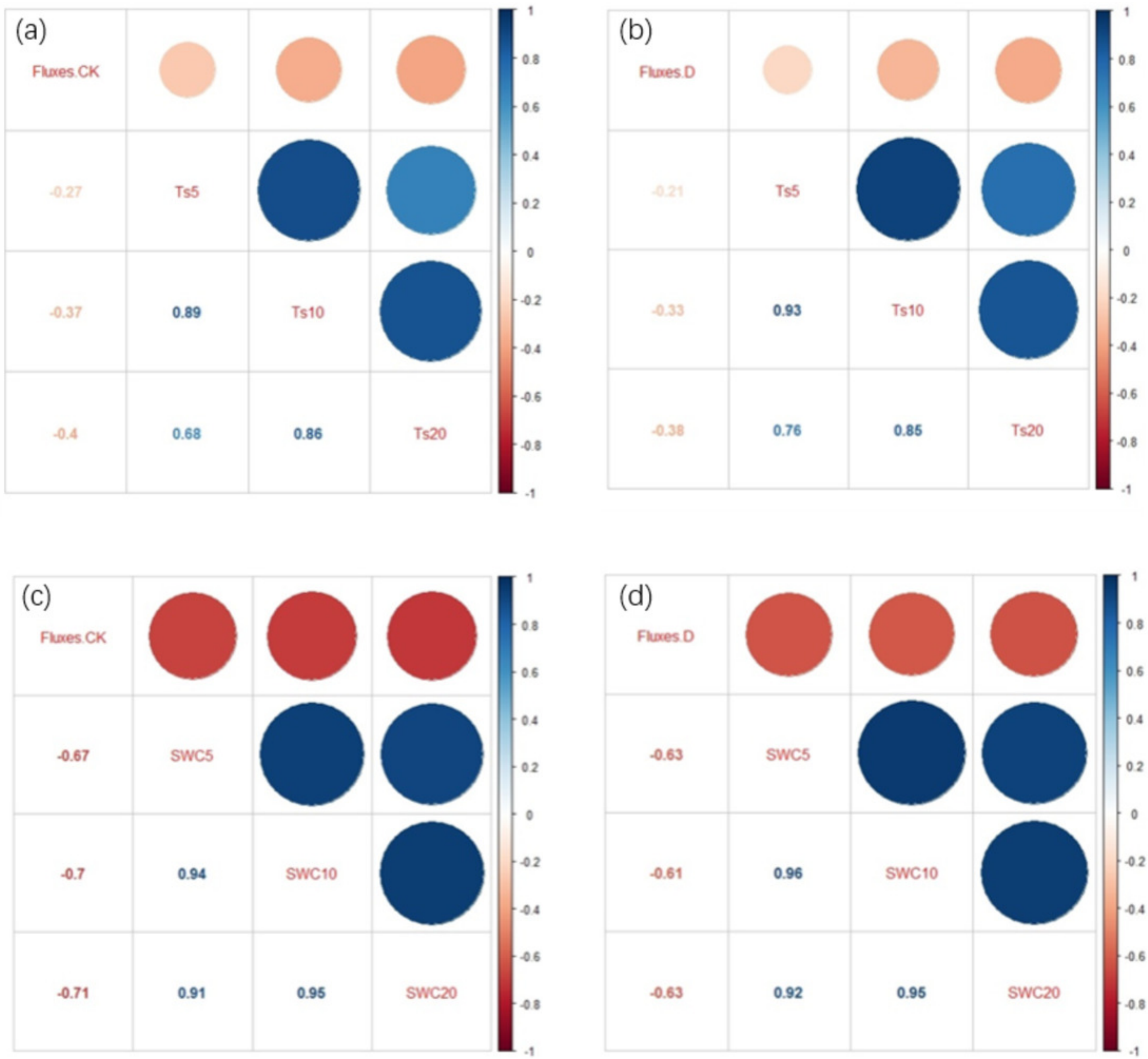


Figure 6

Figure 6.

(a) Correlation coefficient matrix for CH_4 fluxes and Ts in the control treatment. (b) Correlation coefficient matrix of CH_4 fluxes and Ts in the extreme drought treatment. (c) Correlation coefficient matrix between CH_4 fluxes and SWC in the control treatment. (d) Correlation coefficient matrix between CH_4 fluxes and SWC in the extreme drought treatment. Fluxes. CK, fluxes in control; Fluxes. D, fluxes in extreme drought; Ts (5, 10, and 20 cm), soil temperature at a depth of 5, 10, and 20 cm; SWC (5, 10, and 20 cm), soil water content at a depth of 5, 10, and 20 cm. Light and dark red represent the degree of negative correlation. Light and dark blue represent the degree of positive correlation.


(a)
Fluxes.CK
-0.27
Ts5
-0.37
0.89
Ts10
-0.4
0.68
0.86
Ts20
(b)
Fluxes.D
-0.21
Ts5
-0.33
0.93
Ts10
-0.38
0.76
0.85
Ts20
(c)
Fluxes.CK
-0.67
SWC5
-0.7
0.94
SWC10
-0.71
0.91
0.95
SWC20
(d)
Fluxes.D
-0.63
SWC5
-0.61
0.96
SWC10
-0.63
0.92
0.95
SWC20