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Different responses of CO_2, CH_4, and N_2O fluxes to seasonally asymmetric warming in an alpine grassland of Tianshan Mountains

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Abstract:

An experiment was conducted to investigate the effect of seasonally asymmetric warming on CO_2, CH_4, and N_2O fluxes in alpine grassland of Tianshan Mountains of Central Asia, from October 2016 to September 2019. Our results indicated that the CO_2, CH_4 and N_2O fluxes varied in the range 0.56−98.03 mg C m^{-2} h^{-1}, -94.30–0.23 μg C m^{-2} h^{-1}, and -1.28–10.09 μg N m^{-2} h^{-1}, respectively. The CO_2 and N_2O fluxes were negatively correlated with soil temperature, but the CH_4 fluxes decreased with the increase in temperature. Furthermore, the variation in greenhouse gas flux under seasonally asymmetric warming was different between the growing season (June to September) and the non-growing season (October to May). In addition, the response rates of CO_2 and N_2O fluxes to temperature increases was significantly reduced due to warming throughout the year. Warming during the growing season led to a significant decrease in the response rate of CO_2 flux to temperature increases. However, warming during the non-growing season caused a significant increase in the response rate of

CO_2 flux to temperature increases. The response rate of CH_4 flux was insensitive to temperature increase under seasonally asymmetric warming. Thus, the main finding of our results was that seasonally asymmetric warming resulted in different responses in the fluxes of individual greenhouse gases to rising temperatures in the alpine grassland.

Keywords: Greenhouse gas flux; Extreme climatic event; Temperature sensitivity; Warming of open-top chamber

1. Introduction

Since the industrial revolution, human activities have intensified global warming. The global surface temperature increased by about 0.85°C from 1880 to 2012, and it is expected that the surface temperature will increase by about 1.1–6.4°C by the end of this century (IPCC, 2007; IPCC, 2013). Moreover, the fastest climate warming occurs in the middle latitude of the northern hemisphere, with an average warming rate greater than 0.4°C per decade (Ji et al., 2014). The rise in atmospheric temperature is not continuous on the temporal scale, but there is asymmetrical warming during the seasons and between daytime and nighttime (Peng et al., 2013; Xia et al., 2014). The 3th assessment report of the Inter-Governmental Panel on Climate Change (IPCC) proposed that, against the backdrop of global warming, the temperature change will show that the warming amplitude in winter is greater than that in summer, and the warming amplitude at high latitude is greater than that at low latitude (IPCC, 2001). In addition, the 4th assessment report of IPCC further clarified that the warming rate in winter is much higher than that in the summer, and confirmed that the warming shows asymmetric trends on a seasonal scale (Easterling et al., 1997; IPCC, 2007).

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in the atmosphere are the three major greenhouse gases (GHGs) in the atmosphere that directly cause global climate warming, and their contributions to global warming are 20 %, 60 %, and 6 % (IPCC, 2007; IPCC, 2013), respectively. At present, most studies focus on the influence of annual warming on GHG flux in terrestrial ecosystems (Li et al., 2011; Keenan et al., 2014; Yang et al., 2014). Nevertheless, data on the influence of asymmetric warming on the GHG flux on a temporal scale is scarce. A study of the Alaskan tundra found that the increase in summer temperature significantly increased the CO_2 flux in the growing season by about 20% (Natali et al., 2011). Compared with the effect of increased temperature in winter on the CO_2 flux in the growing season, the CO_2 flux in the nongrowing season increased by 50 % (Natali et al., 2011). Studies have shown that the response of soil CH_4 absorption rates to temperature increases in alpine meadows of the Qinghai-Tibet Plateau were not consistent seasonally, with CH_4 absorption in the nongrowing season being more sensitive to temperature (increasing by 162%) than the corresponding value in the growing season (Lin et al., 2015). The study on the alpine grassland ecosystem indicated that the response of N_2O flux to warming showed clear seasonal differences, with the N_2O flux in the growing season showing significant differences between the warming treatments, whereas the response of N_2O flux to the warming treatments in November was not obvious (Cantarel et al., 2012).

In summary, the GHG flux in terrestrial ecosystems shows significant interannual, seasonal and diurnal variations, and its response to warming also varies in different temporal scales. After long-term uniform warming, the biotic and abiotic factors have adapted to the temperature increase, and the GHG flux response to increasing temperature is reduced, compared with that in the early stage of warming. Moreover, climate warming is often unstable, most of it occurring as extreme events (Jentsch et al., 2007). The heterogeneity of warming may change the adaptability of GHG fluxes to warming, and thus affect the carbon and nitrogen cycles in terrestrial ecosystems. Therefore, more uniform (continuous) heating experiments are carried out, and the research results may underestimate the impact of global change on GHG emissions in terrestrial ecosystems, making it impossible to accurately grasp the changed law of GHG flux. Therefore, the current short communication will help to evaluate the uncertainty with respect to GHG flux in response to increasing temperatures against the backdrop of global climate change, by carrying out seasonally asymmetrical warming studies in alpine grasslands.

2. Materials and methods

The experiment was conducted from October 2016 to September 2019 at the Bayinbuluk Grassland Ecosystem Research Station, Chinese Academy of Sciences (42°52.76′ ~ 42°53.17′ N, 83°41.90′ ~ 83°43.12′ E, 2460 m above sea level), which is located in the southern Tianshan mountains of Central Asia, Xinjiang Uygur Autonomous Region of China. The mean annual temperature was -4.8°C per decade, with the lowest monthly temperature in January (-27.4 °C) and the highest in July

(11.2 °C), and the annual precipitation amounted to 265.7 mm, with 78.1% occurring during the growing season, from June to September (Geng et al., 2019). Variations in soil temperature are shown in Fig. S1. Ungrazed since 2005, all the plots were dominated by *Stipa purpurea*, *Festuca ovina*, *Oxytropis glabra*, and *Potentilla multifida*. The soil was subalpine steppe soil, and the parent material of the soil was Loess.

There were four simulated treatments using open-top chambers: warming throughout the year (AW), warming in the nongrowing season (October to May) only (NGW), warming in the growing season (June to September) only (GW) and no warming (NW). Three replicate plots were established for each treatment, each plot measuring 1 m × 1 m, with a 3-m wide buffer zone between adjacent plots, making a total of 12 plots.

CO_2, N_2O, and CH_4 fluxes were measured using static chambers that were made of PVC tube with the dimensions of diameter 0.25 m and height 0.17 m in all 12 plots. Gas samples were collected from the headspace of each static chamber at 0, 10, 20, and 30 min after closing the chamber between 12:00 and 14:00 (GMT+8). Gas samples were collected once or twice a week. Concentrations of individual gases in samples were measured using a gas chromatograph (GC) (Agilent 7890A; Agilent Technologies, Santa Clara, CA, USA). Fluxes were calculated according to Chen et al. (2013).

Effects of seasonally asymmetric warming on CO_2, N_2O, and CH_4 fluxes were analyzed by two-way repeated-measures analysis of variance (ANOVA). One-way

ANOVA was used to compare soil temperature differences. General linear analyses were used to identify significant linear correlations and regressions between soil temperature variation and responses of CO_2, CH_4, or N_2O fluxes. The natural logarithm of the response ratio (RR) was used to reflect the effects of seasonally asymmetric warming on alpine grassland GHG fluxes (Hedges et al., 1999). The RR is the ratio of the mean value of the chosen variable in the warming group ($\overline{W_t}$) to that in the control group (NW; $\overline{W_c}$), and is an index of the effect of seasonally asymmetric warming on the corresponding variable (Eq. 1). All statistical analyses were conducted using SPSS (version 20.0) (IBM, Armonk, NY, USA) with statistically significant difference threshold set at $P < 0.05$.

$$RR = \ln\left(\frac{\overline{W_t}}{\overline{W_c}}\right) = \ln\left(\overline{W_t}\right) - \ln\left(\overline{W_c}\right) \qquad (1)$$

3. Results

Our study showed that the CO_2, CH_4, and N_2O fluxes in the alpine grassland varied in the range of 0.56–98.03 mg C m^{-2} h^{-1}, -94.30–0.23 μg C m^{-2} h^{-1}, and -1.28–10.09 μg N m^{-2} h^{-1}, respectively, from October 2016 to September 2019 (Fig. 1). Compared with the control group (NW), the CO_2 flux decreased by 7.5% and 4.0% in the growing and nongrowing seasons, respectively, under AW and decreased by 2.4% and 8.5% under GW in the growing and nongrowing seasons, respectively. However, compared with the control group, the CO_2 flux under NGW increased by 7.9% and 10.5% in the growing season and nongrowing season, respectively, averaged over the 3 years (Fig. S2 a). The AW temperature change induced a 6.4% increase in CH_4 flux in the growing season and a 3.8% decrease in the nongrowing season. The GW

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treatment resulted in 7.1% and 10.2% increases in CH_4 flux in the growing and nongrowing seasons, respectively. On the contrary, the NGW generated a 10.6% and 9.2 % decrease in CH_4 flux in the growing and nongrowing seasons, respectively (Fig. S2 b). The AW and NGW treatments resulted in 5.8% and 2.2 % decreases in N_2O flux in the growing season, and 101.9% and 192.3% increases in N_2O flux in the nongrowing season, respectively. Compared with the control, NW group, the N_2O flux increased by 29.7% and decreased by 24.4% under GW in the growing season and nongrowing season, respectively (Fig. S2 c).

The results of two-way repeated measures ANOVA showed significant interannual CO_2 flux in the growing season ($P < 0.05$, Fig. 1 a), while the CH_4 flux under warming treatment exhibited extremely significant differences in the growing season ($P < 0.01$, Fig. 1 b), whereas the interannual N_2O flux showed significant difference in both the growing and the nongrowing seasons ($P < 0.05$, Fig. 1 c). Under the four warming treatments, CO_2 flux and soil temperature were significantly positively linearly correlated ($P < 0.05$, Fig. S3 a), whereas CH_4 flux showed significantly decreasing trends with increasing soil temperature ($P < 0.05$, Fig. S3 b). On the other hand, the N_2O flux showed a significantly positive linear correlation with soil temperature, but only under NGW ($P < 0.05$, Fig. S3 c).

4. Discussion

Our study found that the response rate of CO_2 flux to temperature significantly decreased with the increase in soil temperature (ΔST_{AW} and ΔST_{GW}) under AW and GW treatments, respectively (Figure 2 a, c; $P < 0.05$). This finding indicated that the

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response of CO_2 flux to soil temperature became less and less sensitive with warming throughout the year (or growing season) in the alpine grasslands. On the contrary, NGW significantly increased the response rate of CO_2 flux to temperature change (ΔST_{NGW}), indicating that warming in the non-growing season amplified the sensitivity of CO_2 flux to temperature change (Figure 2 b, $P < 0.05$). In addition, Zou et al. (2018) showed that the soil fluxes of CO_2 increased exponentially with temperature, but warming decreased the temperature sensitivity by 23% at the grassland. Furthermore, Natali et al. (2011) also confirmed that compared with the CO_2 flux in the growing season, the CO_2 flux in the non-growing season was more sensitive to the temperature increase.

In addition, seasonally asymmetric warming did not significantly affect the response rate of CH_4 flux to temperature increase (Figure 2 d-f, $P > 0.05$). However, Wu et al. (2020) deemed that experimental warming was stimulating soil CH_4 uptake in the grasslands of the Tibetan Plateau. The results of research on alpine meadows of the Qinghai-Tibet Plateau showed that the CH_4 absorption in the non-growing season being more sensitive to temperature than the corresponding value in the growing season (Lin et al., 2015). Furthermore, Hu et al. (2016) suggested that asymmetrical responses of CH_4 fluxes to warming and cooling should be taken into account when evaluating the effects of climate change on CH_4 uptake in the alpine meadow on the Tibetan plateau. The latest research confirmed that warming in the Arctic had been more apparent in the non-growing season than in the typical growing season (Bao et al., 2020). Hereby, Bao et al. (2020) found that the CH_4 emissions during spring thaw and autumn freeze contribute to about a quarter of annual total CH_4 emissions.

Furthermore, with the increase in soil temperature variation, the response rate of N_2O flux significantly decreased gradually under AW treatment (Figure 2 g, $P < 0.05$). Our results suggested that the response to temperature increase of N_2O flux was insensitive due to warming occurring throughout the year. Another study has shown that whole-day or whole-year warming treatment significantly enhanced N_2O emissions, but daytime, nighttime or short-season warming did not have significant effects (Li et al., 2019). Additionally, Cantarel et al. (2010) suggest that the N_2O flux of cool and upland grasslands may be driven primarily by responses to elevated temperature under projected future climate conditions.

5. Conclusions

In summary, the effect of seasonally asymmetrical warming on CO_2 flux was obvious, with the GHG flux being able to adapt to continuous warming, resulting in a reduced response rate of GHG flux to temperature increase. Warming in the nongrowing season increased the temperature dependence of GHG flux. Thus, we believe that the study of climate change should pay greater attention to warming in the nongrowing season, so as not to underestimate the greenhouse effect of the GHG flux in alpine grasslands.

Data availability

The measured CO_2, CH_4 and N_2O fluxes and soil temperature and soil water content data are available in Zenodo (http://doi.org/10.5281/zenodo.4244207).

Author contributions

GYM, LYY and MA conceive the research question, designed the study approach, led the field survey, ensured data curation and conducted formal analysis. YP and LKH assisted with data collection and analysis. GYM wrote the first draft of the paper, and all co-authors contributed to writing review and editing.

Competing interests

The authors declare that they have no conflicts of interest.

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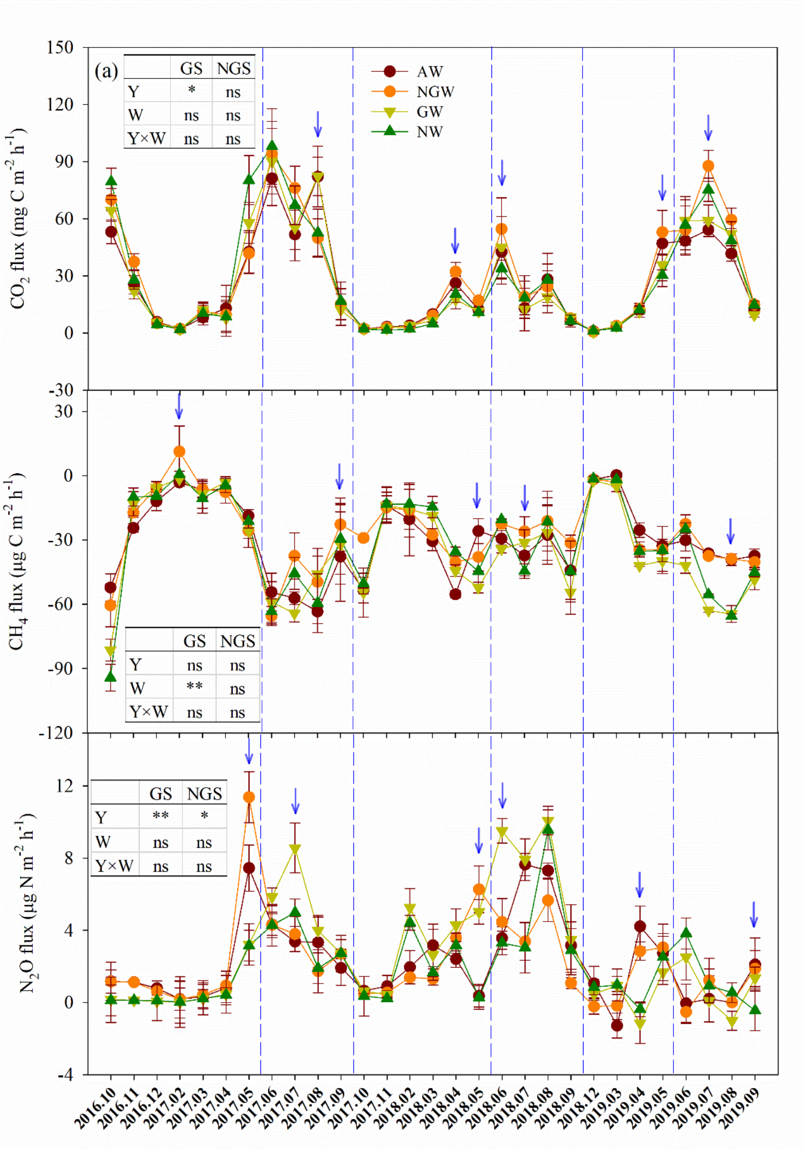

Figure 1 Monthly variation of a). CO₂, b). CH₄ and c). N₂O fluxes under the four treatments from October 2016 to September 2019. AW, warming throughout the year; NGW, warming in the nongrowing season only; GW, warming in the growing season only; NW, non-warming., The blue arrows indicate obvious warming effects. The data points represent mean ± standard error, SE. The tables illustrate the tests of

significance for year (Y) and warming (W) on CO_2, CH_4 and N_2O fluxes by two-way repeated-measures analysis of variance (ANOVA) in the growing season (GS) and the non-growing season (NGS), respectively; $^{*}P < 0.05$; $^{**}P < 0.01$; ns, no significant. AW, warming throughout the year; NGW, warming in the non-growing season only; GW, warming in the growing season only; NW, non-warming.

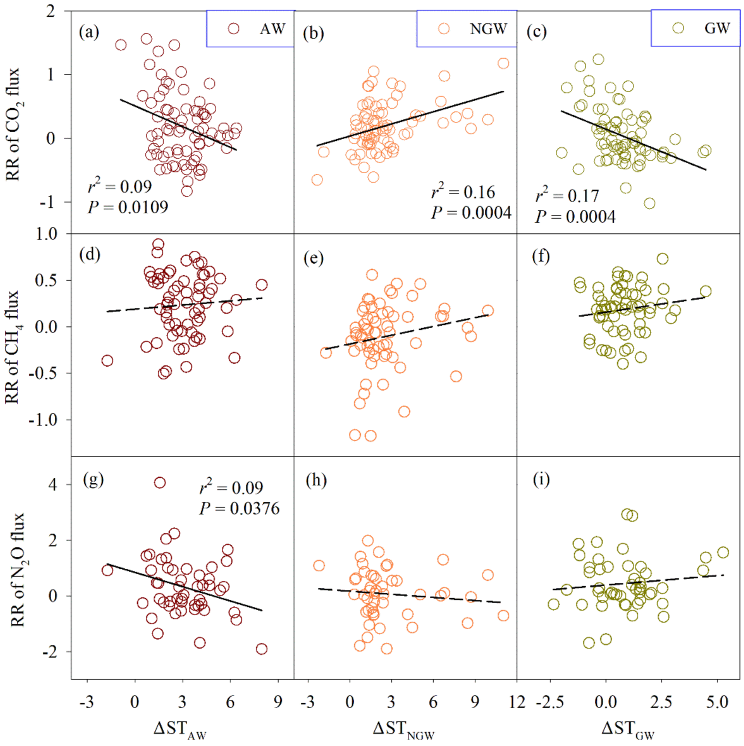

Figure 2 Response of variations in CO_2, CH_4, and N_2O fluxes to changes in soil temperature under AW, NGW and GW conditions in the alpine grassland, from 2016 to 2019. RR, the natural logarithm of the response ratio of the mean value of the chosen variable in the warming group to that in the control (NW) group. ΔST_{AW}, soil temperature of AW minus that of NW. ΔST_{CW}, soil temperature of NGW minus that of NW. ΔST_{WW}, soil temperature of GW minus that of NW. AW, warming throughout

the year; NGW, warming in the nongrowing season only; GW, warming in the growing season only; NW, non-warming.