ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 25, NO. 5, 2008, 748–756

Effects of Irrigation on Nitrous Oxide, Methane and Carbon Dioxide Fluxes in an Inner Mongolian Steppe

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(Received 26 February 2007; revised 21 February 2008)

ABSTRACT

Increased precipitation during the vegetation periods was observed in and further predicted for Inner Mongolia. The changes in the associated soil moisture may affect the biosphere-atmosphere exchange of greenhouse gases. Therefore, we set up an irrigation experiment with one watered (W) and one unwatered plot (UW) at a winter-grazed *Leymus chinensis*-steppe site in the Xilin River catchment, Inner Mongolia. UW only received the natural precipitation of 2005 (129 mm), whereas W was additionally watered after the precipitation data of 1998 (in total 427 mm). In the 3-hour resolution, we determined nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) fluxes at both plots between May and September 2005, using a fully automated, chamber-based measuring system. N_2O fluxes in the steppe were very low, with mean emissions (±s.e.) of 0.9±0.5 and 0.7±0.5 μg N m^{-2} h^{-1} at W and UW, respectively. The steppe soil always served as a CH_4 sink, with mean fluxes of −24.1±3.9 and -31.1 ± 5.3 μg C m^{-2} h^{-1} at W and UW. Nighttime mean CO_2 emissions were 82.6±8.7 and 26.3±1.7 mg C m^{-2} h^{-1} at W and UW, respectively, coinciding with an almost doubled aboveground plant biomass at W. Our results indicate that the ecosystem CO_2 respiration responded sensitively to increased water input during the vegetation period, whereas the effects on CH_4 and N_2O fluxes were weak, most likely due to the high evapotranspiration and the lack of substrate for N_2O producing processes. Based on our results, we hypothesize that with the gradual increase of summertime precipitation in Inner Mongolia, ecosystem CO_2 respiration will be enhanced and CH_4 uptake by the steppe soils will be lightly inhibited.

Key words: nitrous oxide, methane, carbon dioxide, semi-arid steppe, irrigation, precipitation

Citation: Liu, C. Y., J. Holst, N. Brüggemann, K. Butterbach-Bahl, Z. S. Yao, S. H. Han, X. G. Han, and X. H. Zheng, 2008: Effects of irrigation on nitrous oxide, methane and carbon dioxide fluxes in an Inner Mongolian steppe. *Adv. Atmos. Sci.*, **25**(5), 748–756, doi: 10.1007/s00376-008-0748-3.

1. Introduction

China has about 3.9 million km^2 of grasslands, corresponding to 40% of its land area (Su, 1994; Kang et al., 2007). These grasslands mainly cover areas from the northeastern plain adjacent to Mongolia, to the southern Tibetan Plateau (Kang et al., 2007). The region is characterized by low mean, but highly variable precipitation (Hou and Wulanbater, 2006). Potential evaporation rates exceed the precipitation by 4–5 times (Liang et al., 2003; Bai et al., 2004). It has been reported that precipitation can regulate greenhouse gas (GHG) fluxes well (Verchot et al., 2000; Hellebrand et al., 2003; Davidson et al., 2004; McLain and Martens, 2006). The resulting soil moisture changes directly affect e.g. gas diffusion, the aerobic-anaerobic

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microsite distribution in the soil, substrate availability, C and N turnover rates and thus, influence the microbial production and consumption of GHG (Christensen et al., 2004; Davidson et al., 2004; McLain and Martens, 2006; Holtgrieve et al., 2006; Yahdjian et al., 2006).

Precipitation data over the past 50 years do not show a clear linear pattern for China as a whole, but there are distinctive regional and seasonal trends visible. The summer precipitation significantly increased in the Yangtze River valley, southeastern coast, Inner Mongolia, northwestern China and the north part of northeastern China (Zhang et al., 1994; You et al., 2002; Gemmer et al., 2004; Zhai et al., 2005). In broad parts of Inner Mongolia for instance, the annual precipitation has gradually increased since 1950 (You et al., 2002). Thereby a significant summertime (June–August) precipitation increase by nearly 70% was observed for this province (as well as for the neighbouring Republic of Mongolia) between 1980 to 1998 (Iwao and Takahashi, 2006). Despite lower summer means during the following four years, these limited data are still not sufficient to suppose a reversal of the observed trend. Increasing summer and annual precipitation as well as more frequent extreme precipitation events were also predicted by modelling for this region (Gao et al., 2001; Lal and Harasawa, 2001; Gao et al., 2002; Min et al., 2004; Zhang et al., 2006; IPCC, 2007). Based on a regional climate model, Gao et al. (2001) reported that summer precipitation in China would increase by 19% with the scenario that the atmospheric carbon dioxide (CO_2) concentration was doubled. Min et al. (2004) projected a precipitation increase by 4%–5% (with larger change in summer precipitation) in the 2080s as compared with 1961–1990 over East Asia, using a multi-model ensembles method. IPCC (2007) also predicted a likely increase in annual precipitation by 9% at the end of the 21st century for East Asia with the multiple model data. The significant changes in precipitation frequency, amount and distribution may affect GHG fluxes in the semi-arid steppes of China, which, considering the huge steppe area, may cause a feedback on the global climate change. However, experimental data, evaluating the influences of increased precipitation on GHG fluxes in this region, are still scarce. It was reported that seasonal and inter-annual variations of nitrous oxide (N_2O) fluxes in the steppe of Inner Mongolia were more influenced by the distribution of effective rainfall than by the total precipitation amount (Du et al., 2006). But low measurement frequencies (twice per week to once per month) and likely problems with the accurate determination of N_2O concentrations (as discussed in Holst et al., 2007a) make the evaluation of precipitation effects on GHG exchange highly uncertain.

Therefore, we set up an irrigation experiment to simulate a wet vegetation period at a winter-grazed *Leymus chinensis*-steppe site in Inner Mongolia, China, and conducted continuous, high frequency measurements (3-hour interval) of N_2O, methane (CH_4) and CO_2 fluxes at one watered and one unwatered plot during the vegetation period (May–September) in 2005. Our objective was to characterize the effects of increased water supply on N_2O, CH_4 and CO_2 fluxes in the semi-arid steppe.

2. Materials and methods

2.1 *Experimental site and field treatments*

Our measurements were conducted in the Xilin River catchment, Inner Mongolia, at a so called winter-grazed site (WG01) (43°33.0′N, 116°40.2′E). This site (40 hm^2) was set up for a long-term ecosystem study in 2001 and is under management of the Inner Mongolia Grassland Ecosystem Research Station (IMGERS: 43°37.8′N, 116°42.3′E). Here, grazing is forbidden during growing seasons (May–September), but approximately 4–5 sheep hm^{-2} graze in the daytime between November and April. Before 2001, the area was year-round grazed with an intensity of < 2 sheep hm^{-2} for more than 20 years.

WG01 is covered by a *Leymus chinensis*-steppe, which is a typical semi-arid grassland type in Northern China. *Stipa grandis P. Smirn.* is the most abundant species here. The soil is a calcic chernozem, with a soil organic carbon content of approximately 25.9 ± 4.5 mg g^{-1}, a total N content of 2.72 ± 0.44 mg g^{-1}, a C:N ratio of around 9.5 ± 0.4, a mean bulk density of 1.09 ± 0.08 g cm^{-3} and, a pH of approximately 6.7 ± 0.3 ($\pm$standard deviation) in the uppermost 4 cm (Steffens et al., 2008). More details about the experimental site and further soil characteristics are described by Zhao et al. (2007) and Steffens et al. (2008). In this area, the growing season usually lasts from the end of May to late September (Liang et al., 2001). The mean annual air temperature is 0.7°C (1982–2005), with a monthly mean maximum of 19.0°C in July and a minimum of −21.1°C in January. The total annual precipitation was 166 mm in 2005, of which approximately 80% fell between June and August. During 1982–2005, the total annual precipitation varied between 166 and 507 mm, with a mean of 335 mm. 2005 was the driest year in last two decades (meteorological data by IMGERS).

We set up two treatments to investigate the effects of different water supply on CO_2, CH_4 and N_2O fluxes. One plot (110 m^2) was additionally watered since June 13 (hereinafter referred as W), the other served as a control and only received the natural precipitation (unwatered, UW). Irrigation water was taken from a nearby well of a farmer. We manually irrigated using watering pot during nightfall. W and UW were situated within a relatively flat area and 3–5 m away from each other. In this way, we tried to minimize spatial heterogeneity effects, so that soil conditions and likely water flow patterns can be assumed to be comparable at both plots. The watering followed the rainfall amount and frequency of 1998. The amount of the additional applied water was 298 mm (June: 28 mm; July: 184 mm; August: 78 mm; September: 8 mm), so that the total water supply (by natural precipitation and irrigation) was 427 mm at W during the watering period (13 June–30 September) in 2005. This is approximately 231% higher as compared to UW (129 mm) and 72% higher than the average precipitation during the same periods in 1982–2005 (average: 248 mm, range from 129 to 393 mm; data by IMGERS).

2.2 *Measurement of* CO_2*,* CH_4 *and* N_2O *fluxes*

The biosphere-atmosphere exchange of N_2O, CH_4 and CO_2 was continuously measured from 12 May to 9 September 2005, using a six-chamber automated measuring system as described by Butterbach-Bahl et al. (2004) and Werner et al. (2006). Three chambers were used for each treatment. All chambers were fixed on stainless steel frames, reaching around 10 cm into the soil. To minimize chamber effects, all chambers were moved between alternative positions on a bi-weekly basis. Air samples were automatically taken from the closed measuring chambers. CO_2 concentrations were analyzed using an infrared gas analyzer (LI-COR 820, LICOR, Lincoln, USA). CH_4 and N_2O concentrations were determined with a gas chromatograph (Texas Instruments SRI 8610C, Torrance, CA, USA), equipped with a flame ionization detector (FID) and an electron capture detector (ECD). N_2 (99.999% purity) served as a carrier gas. In order to avoid cross-sensitivity of N_2O and CO_2 inside the ECD cell, a pre-column filled with CO_2-absorbing ascarite (Sigma Aldrich, Munich, Germany) was installed upstream of the detector and renewed weekly. N_2O, CH_4 and CO_2 concentrations were calibrated every 1.5 hours, using a standard gas (Air Liquide, Munich, Germany). Each calculated flux was based upon five gas concentrations determined during a 75-minute chamber enclosure period. After calibration (15 min), all measuring chambers stayed open for 1.5 hours and thus, we obtained a 3-hour flux resolution. Daily mean CH_4 and N_2O fluxes were calculated for each spatial replica as the arithmetic mean of 8 fluxes per chamber, and for each plot as the arithmetic mean of daily mean fluxes at 3 spatial replicas. Due to the sensitive plant response to increased air temperatures inside the closed translucent chambers (photorespiration, stomata closure), CO_2 fluxes were distorted during daytime. Thus, we only present nighttime mean fluxes (2100–0400 LST) for CO_2, which were calculated for each spatial replica as the arithmetic mean of 2 fluxes per chamber, and for each plot as the arithmetic mean of nighttime mean fluxes at 3 spatial replicas.

2.3 *Auxiliary measurements*

The air temperature (30 cm) inside of a chamber was continuously recorded using a PT100 thermocouple, attached to the automated measuring system. Soil moisture contents (0–6 cm) were daily measured at both plots, using a portable Theta Probe (ThetaKit, Delta-T Devices, Cambridge, UK). Daily precipitation and air pressure data were obtained from the meteorological station at IMGERS. Air pressure and air temperature data were used for correcting N_2O, CH_4 and CO_2 fluxes. We also determined the aboveground plant biomass (dry weight) for both plots at the end of the vegetation period (30 September).

2.4 *Statistical analysis*

Software packages SPSS 8.0 (SPSS Inc., Chicago, USA) and Origin 7.0 (Origin Lab Corporation, USA) were used for statistical data analysis. Linear or nonlinear regression was used to describe relationships between soil moisture or air temperature and GHG fluxes. Significance was tested by using an F-test (for regressions) or by using the General Linear Model for Repeated Measures to analyze differences in GHG fluxes between W and UW.

3. Results

There was no significant difference in soil moisture between the two plots until the start of the irrigation on June 13 (Fig. 1a). Afterwards, the soil moisture at W was significantly higher than at UW (volume water content: 18.9 versus 9.0 vol%, $p < 0.01$; Table. 1). Extremely low soil water contents (<3 vol%) occurred at UW for 27 days during the observation period, but never at W (Fig. 1b). The daily mean air temperatures varied between 7.7°C and 35.4°C (Fig. 1c), with a mean (±standard error) of 21.0°C±0.5°C. The high water input at W significantly increased the aboveground plant biomass as compared to UW (302.1±14.5 versus 160.9±26.4 g m^{-2}, $p < 0.01$).

Daily mean N_2O fluxes were close to zero at both plots, showing net emissions as well as net uptake (Fig. 2a). They ranged from −7.4 to 17.3 μg N m^{-2} h^{-1}, without high variations within the measuring period. Before and after the start of the watering, fluxes at

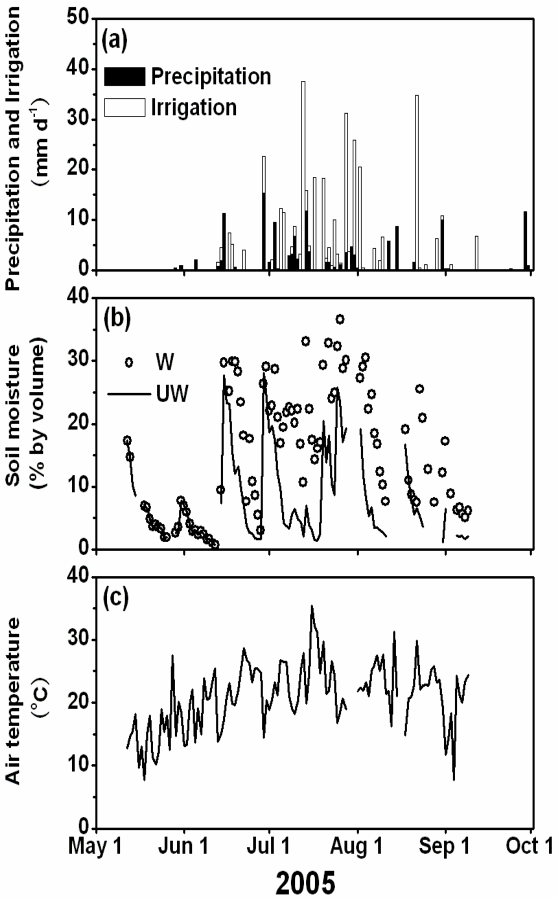

Fig. 1. Temporal course of (a) precipitation and irrigation, (b) soil moisture (0–6 cm soil depth) at the watered (W) and unwatered (UW) plots, (c) air temperature (chamber height: 30 cm).

both plots were not significantly different (Fig. 2a). We observed mean emissions of 1.0±0.9 and 1.3±0.6 μg N m^{-2} h^{-1} at W and UW before 13 June. Afterwards, mean emissions were 0.9±0.5 and 0.7±0.5 μg N m^{-2} h^{-1} at W and UW, respectively, corresponding to 0.08±0.04 and 0.06±0.04 kg N hm^{-2} yr^{-1} (Table 1). We did not find significant correlations between soil moisture or air temperature and daily mean N_2O fluxes for the two plots, despite the fact that both environmental parameters varied over a large range (volume water content: 0.7–36.5 vol%; air temperature: 7.7°C–35.4°C).

The daily mean CH_4 fluxes at both plots were well below zero, and thus, both always functioned as CH_4 sinks during the measuring period (Fig. 2b). The uptake rates ranged from 6.7 to 51.0 μg C m^{-2} h^{-1}, showing a clear temporal variation. During the first week of the measuring period, the uptake rates were low (< 25 μg C m^{-2} h^{-1}). High uptake rates were observed between the end of May and the middle of July. At the end of the measuring period, the uptake rates sharply decreased at UW, whereas they increased at W (Fig. 2b). Before 13 June, the mean uptake was 34.7±4.6 and 35.7±8.9 μg C m^{-2} h^{-1} at W and UW, respectively. Afterwards, the mean uptake was 24.1±3.9 and 31.1±5.3 μg C m^{-2} h^{-1} at W and UW, respectively, corresponding to 2.1±0.3 and 2.7±0.5 kg C hm^{-2} yr^{-1} (Table 1). The uptake rates at W were slightly lower than at UW during the watering period (Fig. 2b). However the differences were not statistically significant. We occasionally (16–19 July, 9–11 August and 25 August–9 September) observed low uptake rates at UW, coinciding with long periods of extreme low soil moisture contents (<3 vol%) (Fig. 1b; Fig. 2b, shaded regions). Excluding these low uptake rates at UW, we found significantly linear correlations between daily mean CH_4 uptake and soil moisture at both plots ($p < 0.001$) (Fig. 3a). Changes of soil moisture explained 41% and 19% of the variations in daily mean uptake at W and UW, respectively. We did not find significant correlations between air temperature

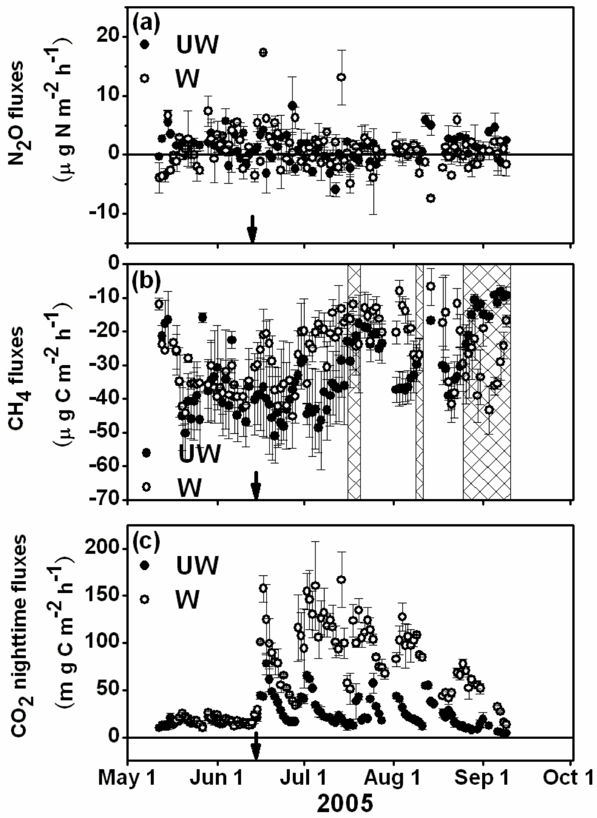

Fig. 2. Temporal course of (a) daily mean N_2O fluxes, (b) daily mean CH_4 uptake and (c) night-time mean CO_2 emissions at the watered (W) and unwatered (UW) plots. The arrow indicates the start of the irrigation. The netted regions show the periods when drought stress inhibited CH_4 uptake at UW.

Table 1. Mean N_2O, CH_4 and CO_2 fluxes at both unwatered (UW) and watered (W) plots during the vegetation periods in 2004 and 2005.

Year	Treatment	Water supply (mm)	Soil moisture (vol%)	N_2O fluxes (μg N m^{-2} h^{-1})	CH_4 fluxes (μg C m^{-2} h^{-1})	CO_2 fluxes (mg C m^{-2} h^{-1})
2005	UW	129	9.0 (0.9)	0.7 (0.5)	−31.1 (5.3)	26.3 (1.7)
			11.0 (1.1)[a]		−35.9 (6.5)[a]	
2004	UW	266	16.7 (0.6)[b]	1.2 (0.1)[c]	−31.1 (5.4)[b]	41.3 (1.7)[d]
2005	W	427	18.9 (1.0)	0.9 (0.5)	−24.1 (3.9)	82.6 (8.7)

[a] Values when drought stress on CH_4 oxidation did not occur. [b]Values adapted from Liu et al. (2007). [c]Values adapted from Holst et al. (2007a). [d]unpublished data. Data without superscript are observed by the study. Values in parentheses indicate standard errors.

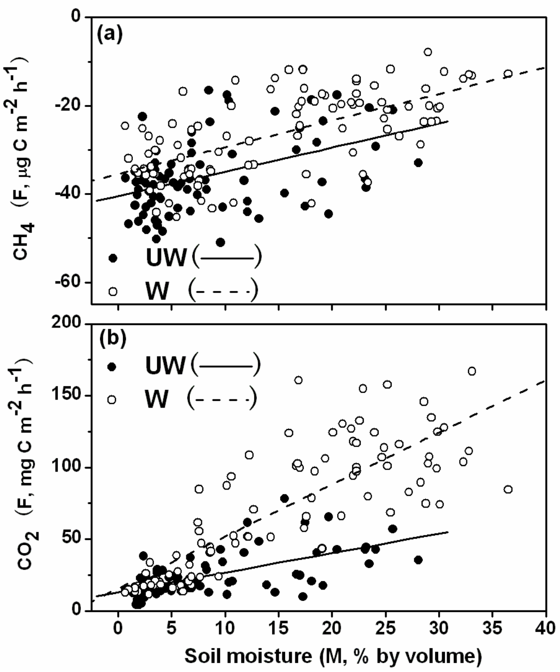

Fig. 3. Correlations of (a) daily mean CH_4 fluxes and (b) night-time mean CO_2 fluxes with soil moisture (0–6 cm) at the watered (W) and unwatered (UW) plots. Fitting lines: (a) $F = -35.5+0.6\,M$ ($n = 94, r^2$=0.41, p <0.001) for W; $F = -40.5 + 0.5\,M$ ($n = 80, r^2 = 0.19, p < 0.001$) for UW. (b) $F = 15.5 + 3.6\,M$ ($n = 90, r^2 = 0.68, p < 0.001$) for W; $F = 13.0 + 1.4\,M$ ($n = 98, r^2 = 0.42, p < 0.001$) for UW. ($F$: CH_4 or CO_2 fluxes; M: soil moisture, % by volume; n: sample number; r: Spearman rank correlation coefficient; p: probability value)

and daily mean CH_4 uptake for both plots.

As expected, we observed CO_2 emissions during night (Fig. 2c). Nighttime mean fluxes ranged from 10.3 to 166.8 mg C m^{-2} h^{-1} at W, and from 4.3 to 78.2 mg C m^{-2} h^{-1} at UW. They showed a clear seasonal pattern at both plots. Low mean emissions (<30 mg C m^{-2} h^{-1}) were determined for more than one month until 15 June, when the first heavy rain event occurred (precipitation > 10 mm d^{-1}). Thereafter, a sharp increase in CO_2 emission was observed, with high emissions between the middle of June and the beginning of August. At the end of the measuring period, CO_2 emissions decreased (Fig. 2c). Before 13 June, nighttime mean emissions were not significantly different between the two plots (18.2 ± 2.0 and 15.9 ± 3.0 mg C m^{-2} h^{-1} for W and UW). During the watering period, emission rates were significantly higher at W than at UW ($p < 0.01$). We observed mean emissions of 82.6 ± 8.7 and 26.3 ± 1.7 mg C m^{-2} h^{-1} at W and UW, respectively, corresponding to 7235.8 ± 762.1 and 2303.9 ± 148.9 kg C hm^{-2} yr^{-1} (Table 1). This corresponds to a difference of 214.1% between W and UW ($p < 0.01$). We found linear correlations between soil moisture and nighttime mean CO_2 emission for both plots ($p < 0.001$) (Fig. 3b). However, the value of each parameter of the regression line for W was higher than that for UW (intercept: 15.5 vs. 13.0 mg C m^{-2} h^{-1}; slope: 3.6 vs. 1.4 mg C m^{-2} h^{-1} 10^{-2}; Square of spearman rank correlation coefficient: 0.68 vs. 0.42, $p < 0.1$). We also found a significant exponential correlation between air temperature and nighttime mean CO_2 emission for W (Fig. 4), whereas such a correlation could not be found in case of UW.

4. Discussion

Previous studies have reported that high precipitation significantly increases N_2O and soil CO_2 emissions and decreases CH_4 uptake in arable lands, forests and pastures (Billings et al., 2000; Verchot et al., 2000; Hellebrand et al., 2003; Davidson et al., 2004). In our study, different water supply (129 and 427 mm) did not result in a significant change in N_2O fluxes. This result is further confirmed by considering the mean flux at WG01 during the vegetation period 2004. Holst et al. (2007a) determined N_2O fluxes at WG01 in the "normal" wet year, 2004 (total precipitation between 13 June and 30 September: 266 mm). As compared with the dry year, 2005, the precipitation was 107%

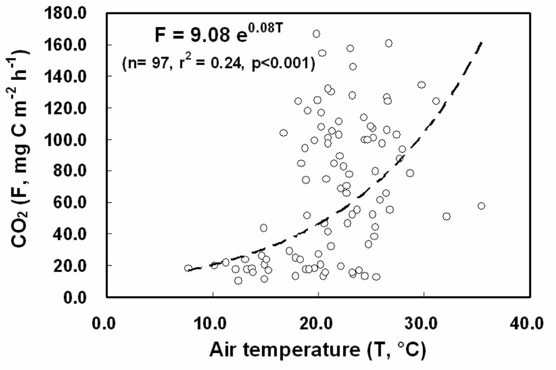

Fig. 4. Correlations of night-time mean CO_2 emissions with air temperature (chamber height: 30 cm) at the watered plot.

higher in 2004. However, the observed N_2O fluxes are not significantly different between the two years (Table 1). Obviously, the precipitation amount did not play a significant role for N_2O emissions during the vegetation periods. Generally, the observed fluxes were always very low at this steppe site as compared to other ecosystems (e.g., Huang et al., 2003; Tang et al., 2006; Gu et al., 2007). Several reasons are to be considered. First, the soil total N content, which almost exclusively consists of organic N (Holst et al., 2007a; Steffens et al., 2008), is quite low in this steppe as compared to many other ecosystems (Huang et al., 2003; Horváth et al., 2006; Hyde et al., 2006). The permanent removal of biomass-N by grazing and the lack of additional N application might partly contribute to the low soil N content. N-deficiency may inhibit microbial N_2O producing process and thus, N_2O fluxes as well as microbial nitrification and denitrification were not sensitive to the changes of temperature or soil moisture. Nitrification is the main source for N_2O production in the semi-arid steppe (Du et al., 2000; Xu-Ri et al., 2003). In our previous work (Holst et al., 2007a), we observed the nitrification rates at WG01 during the growing seasons of the wet year, 2004, and the dry year, 2005. The mean soil moisture content in 2004 was 9.1 vol% higher than in 2005 ($p < 0.01$). However, nitrification rates were not significantly different between the two years (0.8 ± 0.2 and 0.5 ± 0.1 mg N kg^{-1} SDW d^{-1}; SDW: soil dry weight). Secondly, other processes, e.g., plant and microbial NH_4^+-immobilization (Schimel et al., 1986; Del Prado et al., 2006) and, at W, N losses via NH_3 volatilization (Milchunas et al., 1988; Del Prado et al., 2006) might play an important role in this steppe ecosystem and thus, prevent a further turnover of ammonium via N_2O producing processes. Plant immobilization is probably especially high at W, since the aboveground plant biomass almost doubled there as compared to UW (302 and 161 g m^{-2} for W and UW). Thirdly, the N_2O (from atmosphere or soil microbial production) might be consumed by denitrifying bacteria within anaerobic soil microsites, and is then further metabolized to N_2. At high soil NO_3^- concentrations, NO_3^- is preferred to N_2O as an electron acceptor (Singh, 2000). However, N_2O can be an alternative electron acceptor in soils with low NO_3^- contents and high O_2 availability (Robertson et al., 1995; Wrage et al., 2001). Rosenkranz et al. (2006) observed uptake or low emissions of N_2O in a Mediterranean pine forest soil with low NO_3^- content (0–5 cm, < 1 mg N kg^{-1} SDW). The authors assumed that aerobic denitrification consumed N_2O in the soil, which resulted in the net uptake or low emissions. In our case, the soil NO_3^- content (0–6 cm) was also very low (mean during vegetation period: 1.59 ± 0.15 mg N kg^{-1} SDW, Holst et al., 2007a). We suppose that the aerobic N_2O consuming process might also occur in the steppe soil.

Increased water supply slightly decreased CH_4 uptake rates at W, which is probably due to hampered substrate availability for CH_4 oxidation in the soil. It has been reported that gas diffusion rates are 10,000 times slower in water than in air (Boeckx and van Cleemput, 2000) and thus, CH_4 oxidizing bacteria lack of sufficient CH_4 and O_2 supplies in a wet soil. This conclusion is also confirmed by other studies (Hellebrand et al., 2003; Werner et al., 2006). To evaluate the effect of different precipitation amounts on CH_4 uptake in this steppe region, we took, besides the CH_4 data of 2005, uptake rates at WG01 in 2004 (Liu et al., 2007) into our considerations. It is clear that the mean CH_4 uptake does not significantly differ between plots and years, despite the highly varying precipitation (Table 1). One might assume that drought stress, which occurred at UW in 2005 (Fig. 2b), inhibited the physiological activity of CH_4-oxidizers and thus, prevented a higher mean uptake in such a low water input condition. This kind of CH_4 suppression is well known (e.g., Schnell and King, 1996; van den Pol-van Dasselaar et al., 1998; Borken et al., 2006). Under exclusion of these drought stress periods, we observed slightly, but significantly decreased mean uptake rates with increased precipitation ($p < 0.1$) (Table 1). However, the uptake differences are still small (see error bars; Table 1). This almost insignificant effect of even a 300 mm precipitation difference on the CH_4 uptake can be explained with the high evapotranspiration rates in this steppe region. Here, the annual potential evaporation is approximately 1700 mm, five times higher than the annual precipitation (Liang et al., 2003; Bai et al., 2004). Due to the much higher plant biomass at W, the transpiration may also be higher at W as compared to UW. Thus, a significant part of the increased water input is lost by evapotranspiration. In our study, the water input was 231% higher at W as compared to UW, but this only caused a by 110% higher soil moisture at W (corresponds to an increase of 9.9 vol%). The low soil moisture increase is obviously not enough to cause a strong decrease in CH_4 uptake due to gas diffusion inhibition.

Thus, there are two opposite effects of higher precipitation on CH_4 uptake in the steppe. On one hand, higher precipitation will reduce the CH_4 uptake due to gas diffusion inhibition, since clear correlations between uptake rates and soil moisture were also found for our plots. On the other hand, it will reduce the likelihood of drought stress events in this area and thus increase CH_4 uptake during dry periods.

Increased water supply significantly increased the nighttime CO_2 emissions. We observed maximum emissions up to 167 mg C m^{-2} h^{-1}, which were comparable to emissions measured by the eddy covariance technique in this area (Hao et al., 2006). Water is the main limiting factor for the vegetation in the semi-arid Inner Mongolian steppe (Xiao et al., 1995, 1996). Higher water availability resulted in significantly increased aboveground, and certainly also belowground biomass at W as compared to UW (aboveground biomass: 302 versus 161 g m^{-2}), inducing enhanced plant respiration. Higher water availability may also stimulate microbial decomposition rates in semi-arid soils (Yahdjian et al., 2006), and thus the CO_2 production. Therefore, the high nighttime CO_2 emissions at W should be the result of enhanced plant and microbial respiration.

The water amounts, received by UW and W in our study, represent the lower and approximately the upper borders of precipitation in the region during the vegetation periods (1982–2005: 129–393 mm). We observed the different responses of N_2O, CH_4 and CO_2 fluxes to the different water availability. The effects of increased summertime precipitation on N_2O emissions are negligible, probably due to a general lack of substrate availability for N_2O-producing processes in the semi-arid steppe (Holst et al., 2007b). It seems possible that the CH_4 uptake by soils will be lowered with further increasing summertime precipitation. However, the total decrease in sink strength will probably not be very intensive, since the evaporation in this region is very high and increased plant biomass (under higher water availability) will also result in enhanced transpiration. A considerable part of the increased precipitation will get lost by evapotranspiration. Furthermore, the reduced drought stress on CH_4 oxidation in high precipitation conditions will also partly compensate for the reduction. The ecosystem respiration will be enhanced with the increase of water availability. Considering the much higher aboveground plant biomass at W, we also assume that the net ecosystem CO_2 uptake will be facilitated with increasing precipitation.

5. Conclusion

We set up an irrigation experiment and conducted high frequency measurements (at a 3-h interval) to investigate the effects of different water supply on fluxes of N_2O, CH_4 and CO_2, since increasing precipitation was observed and further predicted for the Inner Mongolian steppe region. Increased water supply significantly increased nighttime CO_2 emissions and lightly inhibited CH_4 uptake, whereas effects on N_2O fluxes were not detectable. Higher water availability in this semi-arid region is positive for plant growth and microbial activity, and therefore resulted in an enhanced CO_2 respiration. The CO_2 sink strength may also increase during the vegetation period since the aboveground plant biomass was significantly higher under high water supply in this area. The reduction of CH_4 uptake in the high precipitation case was not intensive, due to high evaporation and likely enhanced transpiration rates under wetter conditions. The reduction may also be partly compensated by reduced drought stress on CH_4 oxidation in the high precipitation scenario. The missing response of N_2O fluxes to different water supplies is attributed to N substrate deficiency for N_2O-producing processes and N_2O consuming by aerobic denitrification.

Acknowledgements. This study was supported by the German Research Foundation (DFG, Research Unit No. 536, "Matter fluxes in grasslands of Inner Mongolia as influenced by stocking rate", MAGIM) (BU 1173/6-2) and the National Natural Science Foundation of China (NSFC) (Grant Nos. 40425010, 40331014). We thank the staff of Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP–CAS) and Institute for Meteorology and Climate Research, Atmospheric Environmental Research (IMK–IFU), Karlsruhe Research Centre for their technical assistance in the field and laboratory.

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