J Arid Land (2014) 6(6): 717–724
doi: 10.1007/s40333-014-0070-0
jal.xjegi.com; www.springer.com/40333

Fluxes of methane, carbon dioxide and nitrous oxide in an alpine wetland and an alpine grassland of the Tianshan Mountains, China

GuiXiang HE[1,3], KaiHui LI[1*], XueJun LIU[1,2], YanMing GONG[1], YuKun HU[1]

[1] Key Laboratory of Biogeography and Bioresource in Arid Land, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China;
[2] College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China;
[3] University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: Methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) are known to be major greenhouse gases that contribute to global warming. To identify the flux dynamics of these greenhouse gases is, therefore, of great significance. In this paper, we conducted a comparative study on an alpine grassland and alpine wetland at the Bayinbuluk Grassland Eco-system Research Station, Chinese Academy of Sciences. By using opaque, static, manual stainless steel chambers and gas chromatography, we measured the fluxes of CH_4, N_2O and CO_2 from the grassland and wetland through an *in situ* monitoring study from May 2010 to October 2012. The mean flux rates of CH_4, N_2O and CO_2 for the experimental alpine wetland in the growing season (from May to October) were estimated at 322.4 μg/(m^2•h), 16.7 μg/(m^2•h) and 76.7 mg/(m^2•h), respectively; and the values for the alpine grassland were –88.2 μg/(m^2•h), 12.7 μg/(m^2•h), 57.3 mg/(m^2•h), respectively. The gas fluxes showed large seasonal and annual variations, suggesting weak fluxes in the non-growing season. The relationships between these gas fluxes and environmental factors were analyzed for the two alpine ecosystems. The results showed that air temperature, precipitation, soil temperature and soil moisture can greatly influence the fluxes of CH_4, N_2O and CO_2, but the alpine grassland and alpine wetland showed different feedback mechanisms under the same climate and environmental conditions.

Keywords: alpine wetland; alpine grassland; CH_4; N_2O; CO_2; Tianshan Mountains

Citation: GuiXiang HE, KaiHui LI, XueJun LIU, YanMing GONG, YuKun HU. 2014. Fluxes of methane, carbon dioxide and nitrous oxide in an alpine wetland and an alpine grassland of the Tianshan Mountains, China. Journal of Arid Land, 6(6): 717–724. doi: 10.1007/s40333-014-0070-0

Methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) are dominant greenhouse gases (Wan et al., 2013), contributing to about 60%, 20% and 6% of the global warming potential, respectively (IPCC, 2007). Identifying the sources and sinks of greenhouse gases (GHGs) in terrestrial ecosystems has become an important global research concern (Dalal and Allen, 2008; Schrier-Uijl et al., 2010; Merbold et al., 2013). Wetlands regulate the biogeochemical cycling, play a significant role in the global carbon budget and have a great potential for the exchange of greenhouse gases with the atmosphere (Bonneville et al., 2008). Under cool and waterlogged anaerobic conditions, high- latitude wetlands have moderate decomposition rates relative to rates of primary productivity (Trumbore et al., 1999; Hirota et al., 2006). Carbon dynamics in high-latitude wetland ecosystems are thought to respond dramatically to climate changes, such as the temperature and precipitation changes that are predicted to occur under global warming conditions (Oechel et al., 1993).

As a typical temperate arid alpine grassland,

---

[*]Corresponding author: KaiHui LI (E-mail: likh@ms.xjb.ac.cn)

Received 2013-08-23; revised 2013-11-17; accepted 2014-01-20

Bayinbuluk alpine grassland is the second largest of its kind in China. Recently, a number of studies in CH_4, N_2O and CO_2 fluxes have been conducted on grasslands and wetlands (Ma et al., 2012; Morse et al., 2012; Merbold et al., 2013), yet few researches have considered the alpine grasslands and wetlands of the Tianshan Mountains in Xinjiang (Li et al., 2012). In order to verify the dynamic fluxes of these gases in alpine wetlands and grasslands, we conducted a series of comparative studies, which will deepen our understanding of greenhouse gas emission processes in alpine wetland and grassland ecosystems. In this paper, we focused on the following two aspects: (1) to compare the variance between the alpine grassland and alpine wetland in CH_4, N_2O and CO_2 fluxes; and (2) to analyze the impact of meteorological (temperature, precipitation) and environmental variables (air temperature, soil temperature and soil water content at 10-cm depth) on CH_4, N_2O and CO_2 fluxes.

1 Materials and methods

1.1 Study area

Our study was conducted in the Bayinbuluk Grassland Eco-system Research Station, Chinese Academy of Sciences, which is situated on the southern slope (2,500 m asl) of the Tianshan Mountains, Xinjiang Uygur autonomous region of China. We established our sample plots in an alpine grassland and wetland in the Bayinbuluk region at 42°52.83′N, 83°42.12′E and 42°53.02′N, 83°43.28′E, respectively. The average annual precipitation reaches 265.7 mm, with 78.1% occurring in the growing season. The annual average temperature is –4.8°C, with a lowest monthly value of –27.4°C in January and a highest monthly value of 11.2°C in July. Soil freezing–thawing processes occur regularly from early April to early May and from early October to early November. These processes last about one month for each period.

1.2 Methods

Flux measurements were conducted in two typical alpine ecosystems (an alpine wetland and alpine grassland) of the Tianshan Mountains, which were grazed under a grazing intensity of 4.3 sheep/hm^2. The wetland, which is seasonally inundated, is dominated by *Carex melantha*. The grassland is dominated by *Stipa purpurea.* Air samples were collected in a stainless steel airtight chamber with opaque materials at the top (50 cm×50 cm×10 cm). The external surface of each chamber was covered with white plastic foam to minimize the impact of direct radiative heating during sampling. Four replicated chambers were used at each site. Gas from the chamber was sampled at intervals of 0, 15 and 30 minutes and after that the chamber was closed and transferred immediately into a pre-evacuated 50-mL air bag using a 60-mL plastic syringe (Hede Inc., Dalian, China). Over the three-year period from 2010 to 2012, CH_4, N_2O and CO_2 fluxes were sampled four times each month during the growing season (May–October) and twice each month during the non-growing season (November–April), with the exception of several winter months when samples were not collected due to extremely cold weather conditions. CH_4, N_2O and CO_2 concentrations of the gas samples (stored in specific air bags) were analyzed by gas chromatography (Agilent 4890D, Agilent Technologies, Wilmington, DE) within one week. The calculation of CH_4, N_2O and CO_2 fluxes were done according to the description of Zhang et al., (2005). Average gas fluxes and standard errors were calculated from four replicates for each site.

Air temperature (T_{air}), soil temperature at 10-cm depth (T_{soil}) and soil water content (SWC) at 10-cm depth were monitored when gas samples were collected. The calculation of average gas fluxes and statistical analysis were carried out with SPSS 12.0 for Windows (SPSS Inc., Chicago, IL) and SigmaPlot version 10 (SyStat Software Inc., San Jose, CA). Linear regression analysis was used to identify significant positive or negative correlations between environmental variables and CH_4, N_2O and CO_2 fluxes.

2 Results

2.1 Meteorological environment

Seasonal dynamics of both precipitation and air temperature produced one-peak patterns, which were higher in the growing season and lower in the non-growing season (Fig. 1). The annual precipitations in 2010, 2011 and 2012 were 389.9, 337.5 and 264.4 mm, respectively. Similar with precipitation, there were some differences in average annual or seasonal air temperature among 2010, 2011 and 2012. For all the three years, minimum monthly average temperatures were observed in January. The minimum monthly average temperature in 2011 (–33.5°C) was significantly lower than those in 2010 (–23.9°C) and 2012 (–25.3°C). All maximum monthly average temperatures were observed in August. The maximum monthly average temperature in 2012 (16.4°C) was higher than those in 2011 (14.6°C) and 2010 (11.5°C).

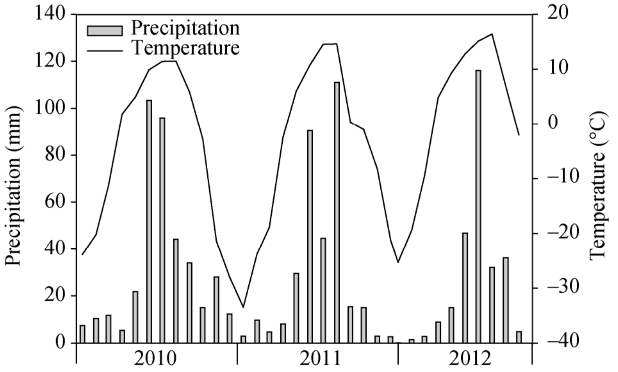

Fig. 1 Monthly mean precipitation and monthly mean air temperature of the study area from 2010 to 2012

2.2 CH_4 fluxes

The patterns of CH_4 emission rates are shown in Fig. 2. The alpine wetlands and alpine grasslands of the Tianshan Mountains serve as the sources and sink of CH_4, respectively. CH_4 fluxes of the alpine wetland showed obvious and regular seasonal patterns in the study area. The CH_4 emissions during the growing season accounted for 92.2% of the fluxes of the whole year, while the emissions from May to August contributed 87.8% of the total annual fluxes. Dynamics of the CH_4 fluxes in the growing season and cumulative seasonal fluxes are shown in Table 1.

2.3 CO_2 fluxes

The patterns of CO_2 emission rates in growing and non-growing seasons of the alpine grassland and wetland are shown in Fig. 3. The CO_2 emission fluxes of the alpine wetland showed large seasonal variations in the study area, and there were significant differences in the CO_2 emission rates between the growing season and non-growing season. During the growing season, the CO_2 emissions accounted for 96.6% of the annual fluxes, and emissions from May to August accounted for 88.1% of the annual fluxes. The CO_2 emission fluxes in the alpine grassland also showed fluctuant curve and the peak fluxes observed during growing season. The maximum monthly average CO_2 fluxes were 86.7±6.6, 122.8±11.4 and 171.2±45.4 mg/(m^2·h) in the three years, respectively. The monthly average CO_2 emission fluxes and cumulative annual CO_2 emissions also showed large variations. However, CO_2 fluxes of the grassland and wetland showed different variations. The cumulative annual CO_2 fluxes for 2010 and 2011 were 217.8 and 303.8 g/m^2 (Table 2).

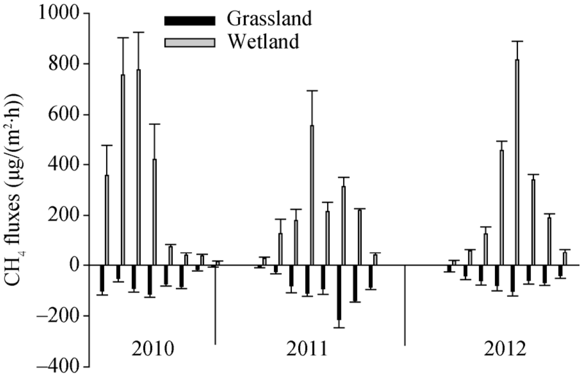

Fig. 2 Monthly average CH_4 fluxes in the alpine grassland and wetland of the study area from 2010 to 2012

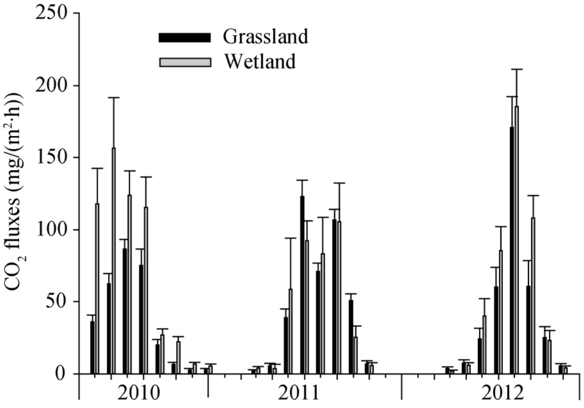

Fig. 3 Monthly average CO_2 fluxes in the alpine grassland and wetland of the study area from 2010 to 2012

2.4 N_2O fluxes

The grassland and wetland are both sources of N_2O (Fig. 4). The N_2O emission fluxes of the grassland and wetland presented large seasonal variations, suggesting

Table 1 Dynamics of CH_4 emission fluxes in the growing season (May to October) and the cumulative seasonal CH_4 fluxes

Land type	Year	CH_4 emission fluxes (μg/(m^2·h))			Cumulative CH_4 fluxes (mg/m^2)		
		Maximum	Minimum	Average	Growing season	Non-growing season	Annual
Wetland	2010	777.1±146.7	40.5±9.0	404.7±290.6	1,632.6	199.2	1,831.8
	2011	556.1±138.9	41.6±8.2	254.1±157.1	1,078.8	139.4	1,218.2
	2012	814.7±204.4	51.1±12.3	308.3±195.0	1,377.3	-	-
	Average			322.4	1,362.9	169.3	1,525.0
Grassland	2010	–113.4±13.4	–52.2±13.8	–85.7 ±19.5	–339.9	–61.9	–401.8
	2011	–212.6±33.4	–81.3±27.4	–120.2±45.5	–511.5	–51.2	–562.7
	2012	–71.2±18.9	–39.8±10.7	–58.6±10.8	–231.5	-	-
	Average			–88.2	–361.0	–56.6	–482.3

Table 2 Dynamics of CO_2 emission fluxes in the growing season (May to October) and the cumulative seasonal CO_2 fluxes

Land type	Year	CO_2 emission fluxes (mg/(m^2·h))			Cumulative CO_2 fluxes (g/m^2)		
		Maximum	Minimum	Average	Growing season	Non-growing season	Annual
Wetland	2010	156.5±35.4	22.3±3.6	93.8±50.7	365.3	33.0	398.3
	2011	105.6±22.6	5.7±2.0	61.8±36.1	260.4	30.1	290.5
	2012	185.5±49.2	4.3±1.1	74.4±41.0	307.1	-	-
	Average			76.7	310.9	31.6	344.4
Grassland	2010	86.7±6.6	6.7±1.3	47.8±29.1	194.6	25.2	217.8
	2011	122.8±11.4	6.8±2.4	66.2±39.6	280.6	23.2	303.8
	2012	171.2±45.4	5.5±1.5	57.8±34.5	240.8	-	-
	Average			57.3	238.7	24.2	260.8

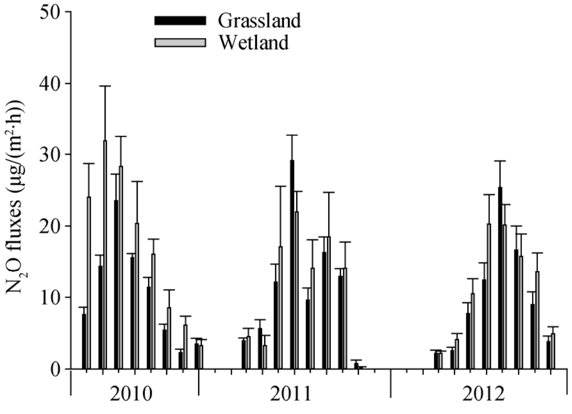

Fig. 4 Monthly average N_2O fluxes in the alpine grassland and wetland of the study area from 2010 to 2012

a strong source during the growing season and a weak source during the non-growing season. The N_2O emission fluxes of the grassland and wetland during the growing season accounted for 88.3% and 83.6% of the annual fluxes, respectively. The cumulative annual N_2O emissions were 67.0 and 64.8 mg/m^2 in 2010 and 2011, respectively (Table 3).

2.5 Relationships between CH_4, CO_2, N_2O fluxes and environmental variables

To identify the factors regulating the CH_4, N_2O and CO_2 fluxes, the relationships between CH_4, CO_2, N_2O fluxes and environmental variables were analyzed for the grassland and the wetland, respectively (Figs. 5 and 6). Linear equations describing T_{soil}, T_{air} and SWC fitted well to changes of CH_4 emissions in the alpine grassland. T_{soil}, T_{air}, CO_2 fluxes and N_2O fluxes showed positive exponential relationships. With regard to CO_2 emissions in the alpine grassland and wetland, both N_2O and CO_2 fluxes showed positive linear correlations with SWC.

3 Discussion

In this study, we observed that the alpine grassland absorbed CH_4, while the alpine wetland emitted CH_4. Tomomichi et al. (2011) reported that the average CH_4 emission per unit area from the wetland was at least

Table 3 Dynamics of N_2O emission fluxes in the growing season and the cumulative seasonal N_2O fluxes

Land type	Year	N_2O emissions fluxes (μg/(m^2·h))			Cumulative N_2O fluxes (mg/m^2)		
		Maximum	Minimum	Average	Growing season	Non-growing season	Annual
Wetland	2010	31.9±7.8	8.5±2.5	21.5±7.7	86.6	18.4	105.0
	2011	22.0±2.8	0.2±0.1	14.3±6.9	55.8	10.4	66.2
	2012	29.1±3.6	4.9±1.4	14.2±5.4	59.3	-	-
	Average			16.7	67.2	14.4	81.6
Grassland	2010	23.5±3.7	5.4±0.8	13.0±5.9	54.2	12.8	67.0
	2011	25.3±7.0	0.8±0.5	13.5±8.5	54.1	10.7	64.8
	2012	20.2±5.6	3.8±1.1	12.5±7.0	52.9	-	-
	Average			12.7	53.7	11.8	65.5

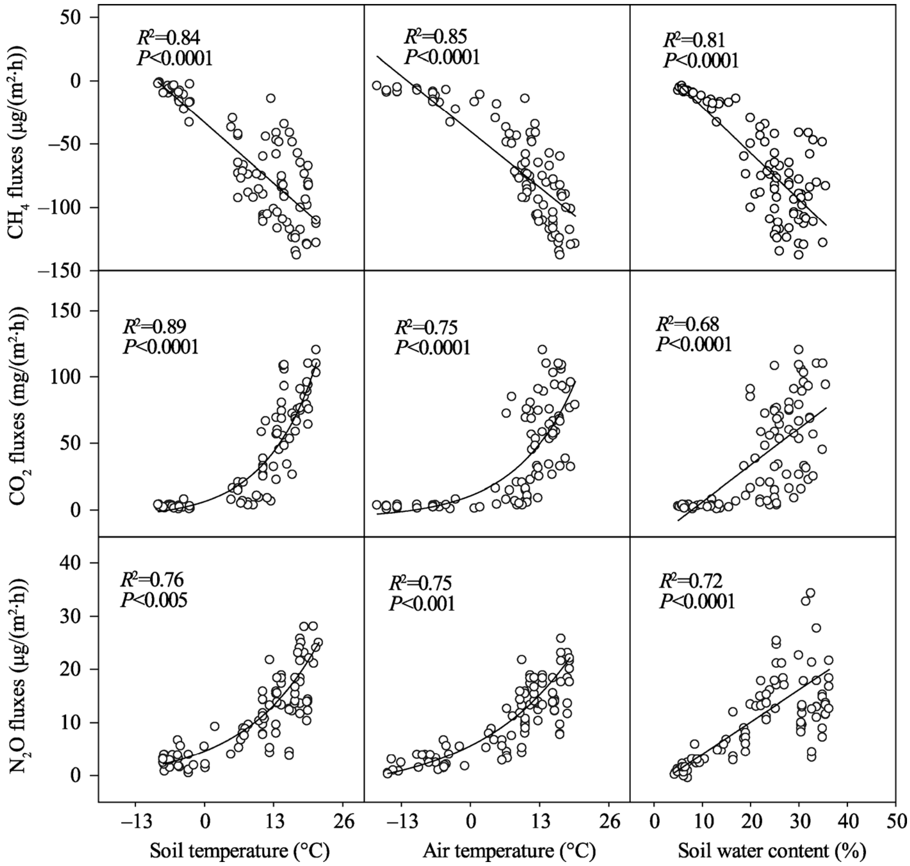

Fig. 5 Relationships between CH_4, N_2O and CO_2 fluxes and T_{soil} at 10-cm soil depth, T_{air} and SWC at 10-cm soil depth of the grassland

100 times larger than the average CH_4 uptake per unit area by the grasslands on the Qinghai-Tibet Plateau. In our work, the average CH_4 emission from the wetland was normally several (sometimes up to ten) times higher than that from the grassland. The pattern and magnitude of CH_4 fluxes in the alpine grassland and wetland were markedly different, which may be attributed to completely different soil moisture conditions and different responses of microbial activity in soil substrate to temperature changes (Van den Bos, 2003). For the grassland, CH_4 consumption was significantly correlated with air temperature, soil temperature and topsoil (0–10 cm) moisture. CH_4 uptake is determined by two important factors: (1) soil temperature (Daulat and Clymo, 1998), since CH_4 oxidation is a microbe-driven process; and (2) gas transport

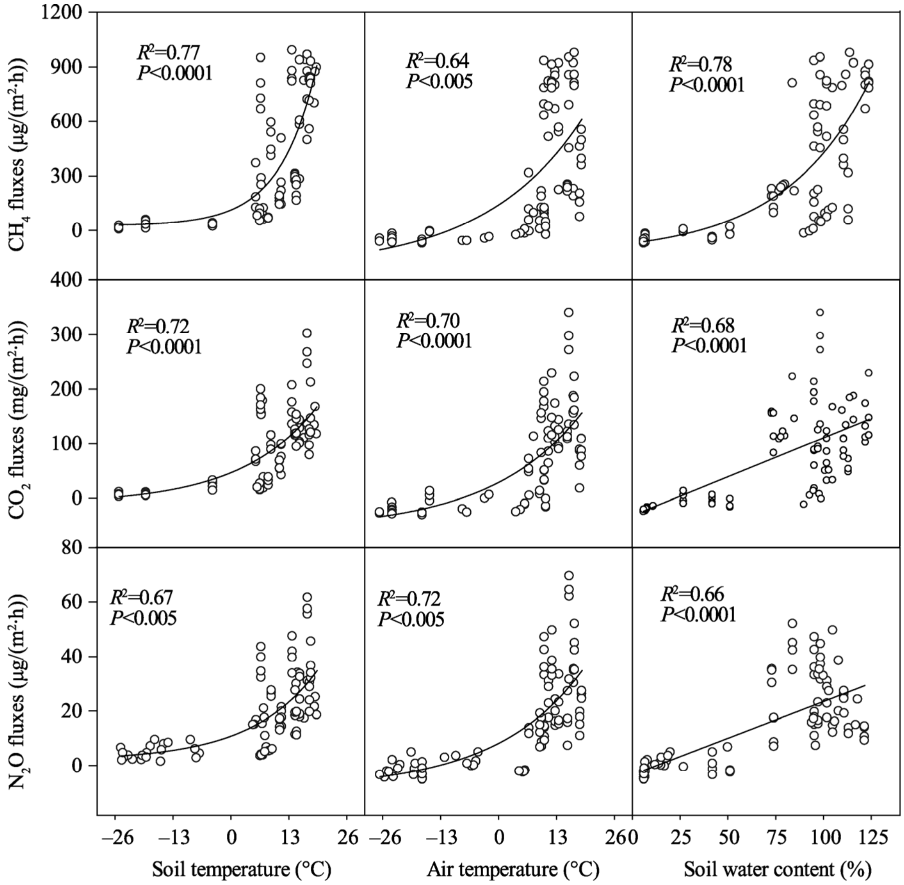

Fig. 6 Relationships between CH_4, N_2O and CO_2 fluxes and T_{soil} at 10-cm soil depth, T_{air} and SWC at 10-cm soil depth of the wetland

resistance, which is influenced by soil wetness and structure. Drier and warmer soil favored CH_4 oxidation, and the optimum soil moisture and temperature for CH_4 consumption were 21%–24% and 5°C–10°C, respectively (Castro et al., 1995; Dasselaar et al., 1998). For the wetland, soil moisture and temperature strongly control methane dynamics because CH_4 production occurs under anaerobic conditions and thus requires saturated soils (Jones et al., 2005), while CH_4 consumption is obligatory aerobic and requires unsaturated soils (Gulledge and Schimel, 1998).

In our study, distinct seasonal variations were observed in CH_4 and CO_2 fluxes, as well as in precipitation and air temperature. Such seasonal variations were also observed by other researchers (Hirota et al., 2010; Wang et al., 2010; Hao et al., 2011). We attributed these results to the obvious variations in weather conditions at our study sites (Fig. 1). Seasonal changes in CH_4 and CO_2 fluxes are usually related to air temperature, soil moisture and temperature, soil nutrients, biomass and vegetation types (Jia et al., 2005; Pen-Mouratov et al., 2006). In this study, regression analysis showed that CO_2 fluxes were significantly correlated with air temperature as well as with soil temperature and moisture at a 10-cm depth. Our findings are in line with the results of previous reports (Mikha et al., 2005; Gao et al., 2011). Plant productivity and the growth of micro-organisms, which depend heavily on air temperature and variations in climate (Hirota et al., 2004), are relatively low in alpine ecosystems because of the short growing season and severe weather conditions (Körner, 2003). Hence, seasonal changes of climate and environmental factors can contribute to seasonal changes of CO_2 fluxes. In our study, CO_2 emission rates were lower in grassland soil than in wetland soil, indicating that wetland soil can emit more CO_2 than grassland soil. The aboveground biomass in the alpine wetland was much higher than in the alpine grassland because of affluent soil moisture and soil nutrients (Braun et al., 2013). More plants produce more CO_2 through respiration. Humid conditions of wetlands are very conducive to the growth of micro-organisms, which will produce more CO_2 through anaerobic respiration. This might be due to the fact that aerobic respiration is more efficient for CO_2 emission than anaerobic respiration (Melling et al., 2005).

Average N_2O fluxes were smaller than those recorded from previous studies conducted in two alpine grasslands, which gave a 3-year average of 39.4–51.6 N_2O μg/(m^2·h) (Du et al., 2008). The N_2O flux for the alpine grassland was generally stable throughout 2010, 2011 and 2012, and averaged 13.0 μg/(m^2·h) during growing season. This pattern compared well with the results for the N_2O fluxes of the wetland, which fluctuated strongly from 21.5±7.7 to 14.2±5.4 μg/(m^2·h) over the three years. The production of soil N_2O is primarily the result of micro-organism mediated nitrification and denitrification processes (Bremner, 1997; Barnard et al., 2005; Liu et al., 2007) as well as coupled nitrification and denitrification (Kremen et al., 2005). It was well documented that because both aerobic and anaerobic microsites can be found within soil aggregates (Renault and Stengel, 1994), nitrification and denitrification processes can occur simultaneously in different microsites of the same soil. Therefore, the magnitude of fluxes between soil and atmosphere depends largely on soil temperature, soil water content and O_2 availability, and biochemistry processes in substrate (Farquharson and Baldock, 2008). Due to considerable differences in soil chemical property and soil microbial quantity between the alpine grassland and wetland, mechanism of N_2O production from the two soil types must be different. Therefore, the alpine grassland and wetland performed different seasonal and annual variations.

4 Conclusions

The mean flux rates of CH_4, N_2O and CO_2 for the alpine wetland (from May to October) were estimated to be 322.4 μg/(m^2·h), 16.7 μg/(m^2·h) and 76.7 mg/(m^2·h), respectively, in the growing season. The values for the alpine grassland were –88.2 μg/(m^2·h), 12.7 μg/(m^2·h) and 57.3 mg/(m^2·h), respectively. Both the alpine grassland and the alpine wetland showed large seasonal and annual variations in greenhouse gas fluxes, suggesting strong fluxes during the growing season and weak fluxes during non-growing periods. The proportions of CH_4, N_2O and CO_2 fluxes in the wetland during the growing season were 92.2%, 96.6% and 88.3% of their respective annual total, with 87.8%, 88.1% and 71.4% absorbed or emitted from May to August, respectively.

Linear equations describing T_{soil}, T_{air} and SWC showed a good fit to CH_4 emission changes for the alpine grassland. T_{soil}, T_{air}, CO_2 fluxes and N_2O fluxes showed positive exponential relationships. With regard to CO_2 emissions in the alpine grassland and wetland, both N_2O and CO_2 fluxes showed positive linear correlations with SWC. In the future, further studies should focus on the relative contribution of N_2O, CO_2 and CH_4 emissions from alpine grasslands and wetlands to global greenhouse gas budgets and the indirect effects of elevated N deposition and climate change on greenhouse gas emission in alpine ecosystems.

Acknowledgements

This work was funded by the National Basic Research Program of China (2009CB825103), the National Natural Science Foundation of China (41340041), the West Light Foundation of the Chinese Academy of Sciences (XBBS201206). The authors would like to express their deep gratitude to the anonymous reviewers for their valuable suggestions that greatly improved the manuscript.

References

Barnard R, Leadley P W, Hungate B A. 2005. Global change, nitrification, and denitrification: a review. Global Biogeochemical Cycles, doi: 10.1029/2004GB002282.

Bonneville M C, Strachan I B, Humphrey E R, et al. 2008. Net ecosystem CO_2 exchange in a temperate cattail marsh in relation to biophysical properties. Agricultural and Forest Meteorology, 148(1): 69–81.

Braun M, Bai Y G, McConkey B, et al. 2013. Greenhouse gas flux in a temperate grassland as affected by landform and disturbance. Landscape Ecology, 28: 709–723.

Bremner J M. 1997. Sources of nitrous oxide in soils. Nutrient Cycling in Agroecosystems, 49(1–3): 7–16.

Castro M S, Steudler P A, Melillo J M, et al. 1995. Factors controlling atmospheric methane consumption by temperate forest soils. Global Biogeochemical Cycles, 9(1): 1–10.

Dalal R C, Allen D E. 2008. Greenhouse gas fluxes from natural ecosystems. Australian Journal of Botany, 56(5): 369–407.

Dasselaar P A, Beusichem M V, Oenema O. 1998. Effects of soil moisture content and temperature on methane uptake by grassland on sandy soils. Plant and Soil, 204(2): 213–222.

Daulat W E, Clymo R S. 1998. Effects of temperature and watertable on the efflux of methane from peatland surface cores. Atmospheric Environment, 32(19): 3207–3218.

Du Y G, Cui Y G, Xu X L, et al. 2008. Nitrous oxide emissions from two alpine meadows in the Qinghai-Tibetan Plateau. Plant and Soil, 311(1–2): 245–254.

Farquharson R, Baldock J. 2008. Concepts in modelling N_2O emissions from land use. Plant and Soil, 309(1–2): 147–167.

Gao J Q, Ouyang H, Lei G C, et al. 2011. Effects of temperature, soil moisture, soil type and their interactions on soil carbon mineralization in Zoigê Alpine Wetland, Qinghai-Tibet Plateau. Chinese Geographical Science, 21(1): 27–35.

Gulledge J, Schimel J P. 1998. Moisture control over atmospheric CH_4 consumption and CO_2 production in diverse Alaskan soils. Soil Biology and Biochemistry, 30(8): 1127–1132.

Hao Y B, Cui X Y, Wang Y F, et al. 2011. Predominance of precipitation and temperature controls on ecosystem CO_2 exchange in Zoige alpine wetlands of Southwest China. Wetland, 31(2): 413–422.

Hirota M, Tang Y H, Hu Q W, et al. 2004. Methane emissions from different vegetation zones in a Qinghai-Tibetan Plateau wetland. Soil Biology and Biochemistry, 36(5): 737–748.

Hirota M, Tang Y H, Hu Q W, et al. 2006. Carbon dioxide dynamics and controls in a deep-water wetland on the Qinghai-Tibetan Plateau. Ecosystems, 9(4): 673–688.

Hirota M, Zhang P C, Gu S, et al. 2010. Small-scale variation in ecosystem CO_2 fluxes in an alpine meadow depends on plant biomass and species richness. Journal of Plant Research, 123(4): 531–541.

Jia B R, Zhou G S, Wang F R, et al. 2005. Affecting factors of soil microorganism and root respiration. Chinese Journal of Applied Ecology, 16(8): 1547–1552.

Jones S K, Rees R M, Skiba U M, et al. 2005. Greenhouse gas emissions from a managed grassland. Global and Planetary Change, 47(2–4): 201–211.

Körner C. 2003. Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems (2nd ed.). Berlin: Springer.

Kremen A, Bear J, Havit U, et al. 2005. Model demonstrating the potential for coupled nitrification denitrification in soil aggregates. Environmental Science & Technology, 39(11): 4180–4188.

Li K H, Gong Y M, Song W, et al, 2012. No significant nitrous oxide emissions during spring thaw under grazing and nitrogen addition in an alpine grassland. Global Change Biology, 18(8): 2546–2554.

Liu X J., Mosier A R, Halvorson A D, et al. 2007. Dinitrogen and N_2O emissions in arable soils: effect of tillage, N source and soil moisture. Soil Biology and Biochemistry, 39(9): 2362–2370.

Ma X Z, Zhang Q L. 2012. Temporal variation of soil greenhouse gases fluxes in a cold-temperate *Larix gmelinii* forest in Inner Mongolia, China. The Journal of Applied Ecology, 23(8): 2149–2156.

Melling L, Hatano R, Goh K J. 2005. Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. Tellus, 57(1): 1–11.

Merbold L, Steinlin C. 2013. Winter greenhouse gas fluxes (CO_2, CH_4 and N_2O) from a subalpine grassland. Biogeosciences, 10(5): 3185–3203.

Mikha M M, Riceb C W, Millikenc G A. 2005. Carbon and nitrogen mineralization as affected by drying and wetting cycles. Soil Biology and Biochemistry, 37(2): 339–347.

Morse J L, Ardon M, Bernhardt E S, et al. 2012. Greenhouse gas fluxes in southeastern US coastal plain wetland under contrasting land uses. Ecological Applications, 22(1): 264–280.

Mouratov P S, Rakhimbaev M, Steinberger Y. 2006. Spatio-temporal effect on soil respiration in fine-scale patches in a desert ecosystem. Pedosphere, 16(1): 1–9.

Oechel W C, Hastings S J, George V, et al. 1993. Recent change of Arctic tundra ecosystems from a net carbon dioxide sink to a source. Nature, 361(6412): 520–523.

Renault P, Stengel P. 1994. Modeling oxygen diffusion in aggregated soils: anaerobiosis inside the aggregates. Soil Science Society of America Journal, 58(4): 1017–1023.

Schrier-Uijl A P, Kroon P S, Hensen A, et al. 2010. Comparison of chamber and eddy covariance-based CO_2 and CH_4 emission estimates in a heterogeneous grass ecosystem on peat. Agricultural and Forest Meteorology, 150(6): 825–831.

Tomomichi K, Mitsuru H, Tang Y H,et al. 2011. Spatial variability of CH_4 and N_2O fluxes in alpine ecosystems on the Qinghai-Tibetan Plateau. Atmospheric Environment, 45(31): 5632–5639.

Trumbore S E, Bubier J L, Harden J W, et al. 1999. Carbon cycling in boreal wetland: a comparison of three approaches. Journal of Geophysical Research Atmospheres, 104(D22): 27673–27682.

Van den Bos R M. 2003. Human influence on carbon fluxes in coastal peatlands: process analysis, quantification and prediction. PhD Dissertation. Amsterdam: VU University.

Wan X H, Wang Y C, Zhou H, et al. 2013. Research of greenhouse gases (CH_4 and CO_2) emission flux in Baiyangdian wetland. Intelligent System Design and Engineering Applications (ISDEA), 1120–1124.

Wang J, Wang G, Hu H, et al. 2010. The influence of degradation of the swamp and alpine meadows on CH_4 and CO_2 fluxes on the Qinghai-Tibetan Plateau. Environmental Earth Sciences, 60(3): 537–548.

Zhang J B, Song C C, Yang W. 2005. Cold season CH_4, CO_2 and N_2O fluxes from freshwater marshes in northeast China. Chemosphere, 59(11): 1703–1705.