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Fluxes of CO_2, CH_4 and N_2O from alpine grassland in the Tibetan Plateau

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Abstract: Using static chamber technique, fluxes of CO_2, CH_4 and N_2O were measured in the alpine grassland area from July 2000 to July 2001, determinations of mean fluxes showed that CO_2 and N_2O were generally released from the soil, while the alpine grassland accounted for a weak CH_4 sink. Fluxes of CO_2, CH_4 and N_2O ranged widely. The highest CO_2 emission occurred in August, whereas almost 90% of the whole year emission occurred in the growing season. But the variations of CH_4 and N_2O fluxes did not show any clear patterns over the one-year-experiment. During a daily variation, the maximum CO_2 emission occurred at 16:00, and then decreased to the minimum emission in the early morning. Daily pattern analyses indicated that the variation in CO_2 fluxes was positively related to air temperatures (R^2=0.73) and soil temperatures at a depth of 5 cm (R^2=0.86), whereas daily variations in CH_4 and N_2O fluxes were poorly explained by soil temperatures and climatic variables. CO_2 emissions in this area were much lower than other grasslands in plain areas.

Key words: CO_2, CH_4 and N_2O; flux; alpine grassland; Tibetan Plateau
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1 Introduction

The current concern about global climate change has made it of great interest to find out the root causes of air temperature increases. Observations and further analyses suggest that greenhouse gas increases are responsible for the climate change (Tett *et al.*, 1999; Crowley, 2000). Among all the greenhouse gases in atmosphere, the increasing concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) contribute more than 70% of the global warming (Lashof *et al.*, 1990; Rodhe, 1990).

Carbon dioxide is the primary gas involved in the exchange for carbon between the atmosphere and the Earth, and it is responsible for 50% of all greenhouse forcing (Rodhe, 1990). The concentration of atmospheric CO_2 has increased from 280 p.p.m.v. since pre-industrial times (pre-1800) to current 355 p.p.m.v., which is still increasing at a rate of 3 p.p.m.v. per year (Neftel *et al.*, 1985; Friedli *et al.*, 1986; Fan *et al.*, 1998). Besides anthropogenic changes, a large amount of carbon is returned to the biosphere from the atmosphere by plant photosynthesis and subsequently released from biota to the atmosphere by respiration or burning of plants, so the release of CO_2 from terrestrial biota has contributed significantly to the present atmospheric CO_2 concentration (Sommerfeld, 1993).

CH_4 and N_2O are also additional important greenhouse gases, which account for almost 20% of anticipated annual global warming (Rodhe, 1990). CH_4 is one of the several radioactively active trace gases undergoing an atmospheric concentration increasing of 0.8% or more (Phillips *et al.*, 2001). Each year soil microbes produce about 400 million metric tons of this gas, a huge mass that has profound effect on humankind (Ferry, 1997). Wetland is one of the most important terrestrial sources of CH_4 because of its anaerobic conditions, high organic matter contents, and large areas (Cao, 1996). It is currently estimated that wetlands, both natural and agricultural, account for 40-50% of the total CH_4 emitted to the atmosphere each year (Whiting, 1993). N_2O is implicated in destruction of ozone in the stratosphere, and its

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atmospheric concentration is presently increasing at a rate of 0.25% per year (Crutzen, 1977; Fluckiger, 1999). The main sources of N_2O in pre-industrial times have been reported in tropical and temperate soils, and the ocean in upwelling regions. The estimated contributions are 45%, 30% and 25%, respectively, but with high uncertainties (Fluckiger, 1999).

In order to make an accurate budget of greenhouse gases contributions from different regions, a lot of research has been done in various kinds of ecosystems about the greenhouse gas emissions to the atmosphere. These studies were mainly focused on terrestrial biomes such as forests (Bowden *et al.*, 1990; Castro *et al.*, 1993; Dixon *et al.*, 1994; Billings *et al.*, 2000), agriculture (Li *et al.*, 1996; Conen *et al.*, 2000; Kulshreshtha *et al.*, 2000), tundra (Whalen *et al.*, 1992; Christensen *et al.*, 1996; Steven *et al.*, 1996) and grasslands (Norman *et al.*, 1992; Kester *et al.*, 1997; Dong *et al.*, 2000) in plain areas.

As "the third pole" of the earth, the Tibetan Plateau is one and only active continental collision area. The mean altitude of the plateau is more than 4,000 m above sea level with a land area of about 2,500,000 km^2. Great uplift of the plateau since Late Cenozoic has been strongly affecting the physical environment of the plateau itself and its neighboring regions. Meanwhile, the plateau is also a sensitive trigger of climate change in Asian monsoon region, which is closely related to the global change (Zheng *et al.*, 2000). Due to the topographic features and the characteristics of the atmospheric circulation, typical alpine zones of forest, meadow, grassland and desert appear in succession from southeast to northwest in the plateau (Zheng *et al.*, 1979). Alpine grassland is one of the most important ecosystems on the Tibetan Plateau, which occupied almost 1/3 of the whole plateau area. However, it is unclear that how much or how fast those greenhouse gases are released from alpine grassland ecosystems.

2 Materials and methods

2.1 Site description

The study was carried out on the top of the hill beside Wudaoliang, Qinghai Province, China (35.13°N, 93.05°E). The altitude of the study site is 4,767 m above sea level. Climatically it is in the sub-frigid and semi-arid zone. The average monthly air temperature is below 0℃ throughtout the year except growing seasons, and the mean annual temperature is -5.6℃ (Sun, 1997). The annual mean precipitation in the study area ranges between 200 mm and 400 mm, with 84% of the annual precipitation occurring in growing seasons (from June to September). In this permafrost area, the soil type is mainly the alpine steppe soil. The ecosystem is classified as an alpine grassland ecosystem, and much of the study site is covered with *Stipa* lawn community dominated by *Stipa purpurea* (Zheng *et al.*, 1979).

2.2 Experimental design

Three sample plots were selected based on plant biomass of the study area. Fluxes of CO_2, CH_4 and CO_2 were measured from July 2000 to July 2001 using a dark Static Chamber Technique (Whalen *et al.*, 1992). CO_2, N_2O and CH_4 fluxes were measured once per month during non-growing seasons, and twice per month during growing seasons. In the measuring day, the flux measurements were made three times between 10:00 a.m. and 16:00 p.m. during growing seasons, and two times between 11:00 and 15:00 during non-growing seasons. In addition, we held an every-2-hour-flux-measurement from 12:00 (25th) to 12:00 (26th) in July 2001. Above-ground biomass (including live, standing dead and litter) in each plot was harvested before putting a stainless steel collar (0.5 m×0.5 m, 0.04 m high) into the soil. Next day, a non-transparent acrylic chamber (0.5 m×0.5 m, 0.3 m high, equipped with a thermometer and two fans inside the top) was placed over the collars, which had water filled grooves in the upper end to ensure gas tightness. Gas samples were taken with 100 ml polypropylene syringes equipped with three-way stopcocks into polyethylene-coated aluminum bags for further concentration analysis (Maljanen *et al.*, 2001). Gas samples were collected at intervals of 0, 10, 20, 40 minutes after the chambers were installed. In connection with gas sampling, air temperature, temperature inside the chamber, and soil temperature profiles (-0.05, -0.1, -0.15, -0.2, -0.5, -1.0, and -1.5 m) were measured (Tuittila *et al.*, 2000). Soil samples (3.2 cm in core diameter, from soil layers of 0-10 cm, 10-20 cm and 20-30 cm) and root samples were taken at the end of the experiment.

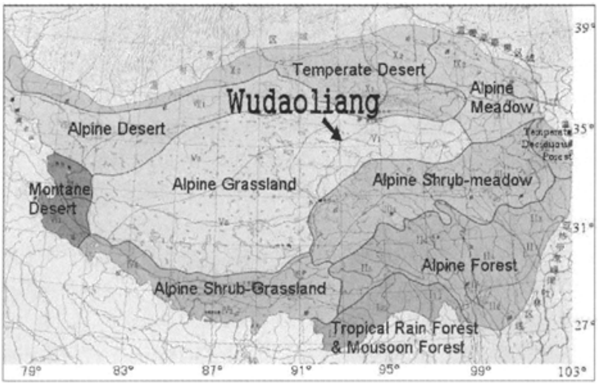

Figure 1 Map of the sample site

Table 1 Soil characteristics at the study site

Depth (cm)	Moisture (%)	pH	Organic C (%)	Total N (%)
0 - 10	3.61	9.02	0.15	0.04
10 - 20	5.05	9.03	0.15	0.04
20 - 30	7.28	8.90	0.32	0.07

The plant samples (both above and below ground) were all dried at 60℃ over 48 hours. After estimation of the amount of biomass, the samples were used to measure organic carbon by digestion with potassium dichromate and back-titrating with 0.025M ferrous ammonium sulphate (Kalembasa *et al.*, 1973) and total nitrogen by Kjeldahl (Bremner, 1965). The soil moisture was determined by oven dry method at 60℃ for 48 hours. Soil pH was measured using a glass electrode by a 1:2 soil-to-water ratio. Organic carbon and total nitrogen of soil were measured using the same method with the plant samples. CO_2 concentrations were measured by a CO_2 infrared analyzer (LI-COR6252). CH_4 and N_2O concentrations were analyzed by a Gas Chromatography (Hewlett-Packard 5890 II), which was equipped with a flame-ionization detector (FID) and an electron capture detector (ECD). For CH_4, the GC had a PORAPAK Q column (80-100 mesh, 3.15 mm o.d. and 3.68 m in length), and the oven temperature was held at 90℃. The carrier gas was nitrogen with a flow rate of 23 ml/min, and the FID temperature was maintained at 150℃. For NO_2, the GC had a backflush system with stainless steel precolumn (3.2 mm o.d. and 1.84 m in length) and analytical column (3.2 mm o.d. and 3.68 m in length) packed PORAPAK Q with 80-100 mesh for both, and the oven temperature was held at 90℃. The ECD temperature was maintained at 330℃. The carrier gas (5% CH_4 in Ar) flow was adjusted to 26 ml/min through the analytical column, and the backfulsh gas to 40 ml/min through the precolumn (Dong *et al.*, 2000).

2.3 Data analysis

The gas flux was calculated from the concentration change over the sampling period by using the following expression:

$$F = D \times V \times \frac{\Delta C}{\Delta t} \times \frac{1}{A} = D \times H \times \frac{\Delta C}{\Delta t} \tag{1}$$

where F means gas flux; D is gas density inside the chamber ($D = P/RT$, P is air pressure at the sampling site, R refers to the gas constant, and T is temperature inside the chamber); $\Delta C/\Delta t$ is the linear slope of concentration change during sampling period; V is volume of the chamber; A is area of the sampling soil surface, and H is the height of chamber. So the positive value of F means the gas emission into the atmosphere from soil and the negative value represents the gas flow from atmosphere to soil or soil absorption of this gas from the atmosphere (Huang *et al.*, 1995, Dong *et al.*, 2000).

3 Results and discussion

3.1 Soil and vegetation characteristics

The alpine steppe soil at the site was sandy loam with the permanent frozen layer at a depth of 1.5 m, and other characters of surface soil were showed in Table 1. The organic carbon and total nitrogen in the soil were 0.21% and 0.05%, respectively. The biomass in this area was a bit lower than that of other grasslands in the plain area (Table 2). The ratio of biomass between below-ground and above-ground was almost 16:1, a bit higher than other plain areas (Chen *et al.*, 2000). The root system here was larger than the plain area due to the frigid climate.

Table 2 Vegetation characteristics in the study area

	Biomass (g/m^2)	Total C (%)	Total N (%)
Fresh	50.52	39.39	1.51
Litter	4.85	35.69	0.82
Root	871.18	25.04	0.93

3.2 CO_2, CH_4 and N_2O fluxes

Temporal variations in CO_2, CH_4 and N_2O emission rates from the alpine grassland were presented in Table 3. Mean fluxes of CO_2, CH_4 and N_2O were 0.17, -9.01×10^{-4} and 0.05×10^{-4} $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively. The emission rates showed great variations during the whole year measurements.

As expected, the alpine steppe soil was a distinct source of CO_2, although the contribution to the atmospheric CO_2 was lower than other grasslands in plain areas (Dugas *et al.*, 1997; Dong *et al.*, 2000; Mielnick *et al.* 2001). The CO_2 emissions showed a very clear changing trend, that decreased in autumn and increased in spring (Table 3). CO_2 emissions during the growing seasons were much higher than that during the non-growing seasons, which accounted for almost 90% of the yearly emissions. The highest mean CO_2 emission occurred in August.

The CH_4 fluxes ranged widely from -14.73×10^{-4} to -0.32×10^{-4} $\mu mol \cdot m^{-2} \cdot s^{-1}$. The negative mean flux of CH_4 indicated that this alpine steppe soil absorbed CH_4 from the atmosphere. This result is consistent with the previous researches where the alpine tundra soil appeared to be a sink of atmospheric CH_4 (Mosier *et al.*, 1997; West *et al.*, 1998, 1999). Similarly, other studies in plain area showed that grasslands accounted for the absorption of CH_4 from the atmosphere (Dong *et al.*, 2000; Kammann *et al.*, 2001). The fluxes of N_2O in alpine grassland ranged from -0.09×10^{-4} to 0.18×10^{-4} $\mu mol \cdot m^{-2} \cdot s^{-1}$. The positive mean flux of N_2O implied that the alpine steppe soil released N_2O into the atmosphere although this emission value was much lower compared to the CO_2 emission. Other research also showed that the grasslands in plain area contribute to a N_2O source (Williams *et al.*, 1999). The variations in CH_4 and N_2O fluxes did not show any clear trends over the one-year-experiment.

3.3 Fluxes and environmental factors

In order to improve general understandings of the flux characters in the study area, we carried out an every-2-hour-measurement from 12:00 (25th) to 12:00 (26th) in July 2001. The CO_2 fluxes over a whole day measurement were showed in Figure 2. Soil CO_2 efflux showed an asymmetric daily pattern, which was almost the same as the pattern in northern California forest (Xu *et al.*, 2001). The maximum CO_2 emission occurred at 16:00 (Beijing Time), and decreased to the minimum in the early morning next day. Linear regression analyses showed that the variation in CO_2 fluxes was positively related to air temperature and soil temperature at a depth of 5 cm (Figure 3). Keith (1997) and Xu (2001) have suggested that soil temperatures had the greatest effect on CO_2 efflux and exhibited a highly significantly relationship (R^2 = 0.81) in the forest ecosystem. The same result was reported in a typical grassland ecosystem in Inner Mongolia (Dong *et al.*, 2000). Our studies implied that the daily fluctuations in temperatures near soil surface (both in soil and in air) strongly affected the variation in CO_2 fluxes, but deeper the soil temperatures did not show distinct correlativity with CO_2 fluxes ($R^2<0.4$). During this experiment, three plots (A, B and C) were selected by different amounts of above-ground biomass with 40.12, 63.44 and 75.16 g/m^2, respectively. Consequently the CO_2 fluxes in these three plots were 0.58, 0.61 and 0.69 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The above-ground biomass was positively correlated with soil CO_2 efflux, which was similar to another research in Texas grassland (Mielnick *et al.*, 2001).

In our study, we found that CH_4 emissions were negatively correlated (R = -0.92) with the atmospheric CH_4 concentrations (Figure 4). It appears that the higher CH_4 concentration in the

Table 3 Soil fluxes* ($\mu mol \cdot m^{-2} \cdot s^{-1}$) of CO_2, CH_4 and N_2O in Tibetan Plateau

Data	CO_2 Flux	CO_2 Standard Deviation	CH_4 ($\times 10^{-4}$) Flux	CH_4 ($\times 10^{-4}$) Standard Deviation	N_2O ($\times 10^{-4}$) Flux	N_2O ($\times 10^{-4}$) Standard Deviation
2000						
25 Jul	0.58	0.15	-2.28	1.16	0.13	0.19
10 Aug	0.69	0.31	- 6.08	4.39	0.15	0.26
25 Aug	0.56	0.13	-5.51	4.18	0.06	0.09
7 Sep	0.43	0.08	-14.73	4.71	0.03	0.08
25 Sep	0.29	0.25	-3.51	3.70	0.16	0.08
13 Oct	0.16	0.32	-7.84	2.10	0.18	0.49
13 Nov	0.09	0.18	-10.92	15.38	0. 00	0.50
14 Dec	-0.03	0.08	-8.16	7.60	0.05	0.11
2001						
13 Jan	0.01	0.12	-8.85	7.79	0.12	0.20
15 Feb	0.01	0.11	-2.68	4.73	-0.05	0.54
12 Mar	0.04	0.31	-12.84	10.80	-0.02	0.84
14 Apr	0.05	0.06	-9.45	4.95	0.18	0.26
13 May	0.05	0.04	-13.79	7.27	-0.10	0.40
9 Jun	0.08	0.14	-7.62	5.60	-0.09	0.19
23 Jun	0.40	0.28	-0.32	15.48	0.08	0.15
9 Jul	0.43	0.17	-5.11	8.44	0.10	0.08
25 Jul	0.69	0.26	-12.40	6.99	0.01	0.07

* n was usually 6 or 9

atmosphere caused more efficient soil absorption of CH_4 from the atmosphere. Previous field studies made across subarctic, temperate and tropical climate gradients in grasslands were used to demonstrate their influence of nutrient cycle perturbations on the soil consumption of atmospheric CH_4 and in increased N_2O emissions (Mosier *et al.*, 1997). It is also reported that night-time CO_2 and CH_4 fluxes were highly correlated in an ombortrophic peatland during a growing season (Greenup *et al.* , 2000). However, multiple linear regression analyses showed that variations in CH_4 and N_2O fluxes were poorly explained by soil temperature and climatic variables in our study. There were not any distinct correlations between CO_2, CH_4 and N_2O fluxes in this alpine grassland ecosystem. The high variability in fluxes may be a reflection of climate, vegetation, and soil, and their complex interactions (Regina *et al.*, 1999; Williams *et al.*, 1999; Kammann *et al.*, 2001).

As the most important greenhouse gas, CO_2 emitted less from this alpine grassland on Tibetan Plateau than those from other grasslands in plain areas. According to the above discussion and Raich (1992), there was a close correlation between the amount of biomass of different vegetation biomes and their mean annual soil respiration rates. Indicated from Frank's study (1998), soil potential microbial respiration was positively related to total C and N content, respectively. Many other studies also indicated that soil respiration rates correlated significantly with mean annual air temperatures, mean annual precipitation, and the interaction of these two variables (Klein, 1977; Raich *et al.*, 1992). Compared with other grasslands (Wang *et al.*, 1995; Dong *et al.*, 2000; Mielnick *et al.*, 2001; Ross *et al.*, 2001), the biomass (both above and below ground), soil organic carbon and total nitrogen, soil moisture, annual temperature, and annual precipitation at our study site were absolutely lower than other areas. The soil pH value in our study site was a little higher than those in other grasslands, whereas soil pH value was negatively correlated with CO_2 efflux according to Xu (2001). The compositive influence of those environmental factors determined certainly the lower soil respiration rates in alpine grassland, which resulted in a much lower CO_2 emission than other grasslands.

In our experiment, the above-ground biomass was gathered before the gas sampling, so the CO_2 emission was the result of all the respiration and uptake processes in the soil. The

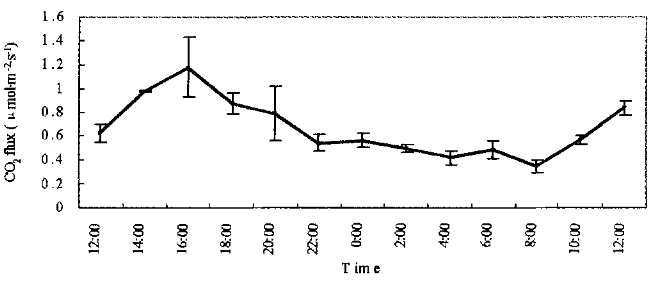

Figure 2 Daily variation of CO_2 fluxes

above-ground plant respirations were not involved in the CO_2 flux in this site. Except Zhang's research (2001), gathering the above-ground biomass could not be found in the literature (Saigusa *et al.*, 1998; Dong *et al.*, 2000; Mielnick *et al.*, 2001). The CO_2 fluxes included the dark respirations of the above-ground vegetations. It is reasonable that the CO_2 fluxes in other grassland sites were higher than that in our study site. The CO_2 concentration inside the chamber increased continuously during the sampling period because of the CO_2 emission from soil surface. During daytime, chambers were put on the ground just like mini greenhouses. Due to the high elevation, solar radiation at this site was much higher than that in other places (Ji, 2000). Temperatures inside the chambers would increase quickly, which introduced a difference of air pressures between inside and outside chambers. The higher pressures would directly restrict the CO_2 emission from the soil surface, whereas the higher temperatures directly resulted in a lower atmospheric concentration in the chamber during the latter sampling period. Finally yet importantly, the sampling time period (40 min) in our experiment was longer than in other experiments, which would enforce the influences of higher temperatures and pressures inside chambers. Indicated from the data, the increasing rates of concentrations did decrease in the latter period of sampling time. Generally, the CO_2 flux should be a bit lower than it originally was.

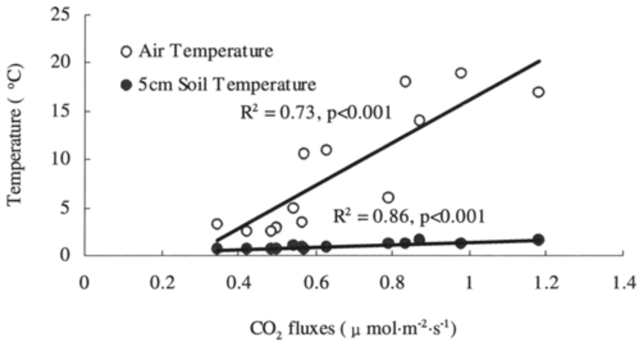

Figure 3 Relationships between CO_2 fluxes and temperatures

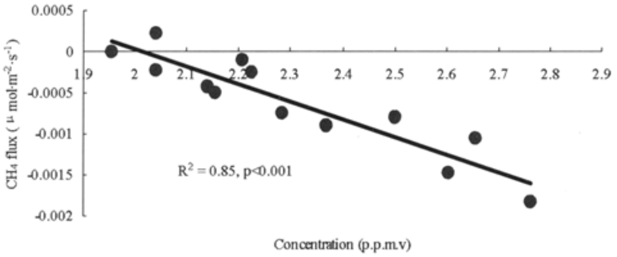

Figure 4 Relationships between atmospheric CH_4 concentrations and CH_4 fluxes

4 Conclusions

(1) Mean fluxes of CO_2, CH_4 and N_2O from the alpine grassland in the Tibetan Plateau were 0.17, -9.01×10^{-4} and 0.05×10^{-4} $\mu mol\cdot m^{-2}\cdot s^{-1}$, respectively. CO_2 and CH_4 fluxes had different trends, whereas N_2O emission rates showed a wide and random variation during the whole year measurements.

(2) CO_2 fluxes were positively related to the temperatures near soil surface (both in soil and in air) and biomass. Compared with other studies, the combined influence of climatic, botanical and experimental factors resulted in a lower CO_2 emission in our study.

(3) In contrast to CO_2, variations of CH_4 and N_2O fluxes had weak relationships to soil temperature and climatic variables in our study. Multiple linear regression analyses indicated that there were not any significant correlations between CO_2, CH_4 and N_2O fluxes in this alpine grassland ecosystem.

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