An Investigation on the Relationship Between Emission/Uptake of Greenhouse Gases and Environmental Factors in Semiarid Grassland

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ABSTRACT

Measurements of greenhouse gases CO_2, CH_4, and N_2O were made by static chamber-gas chromatograph in Inner Mongolia. Results indicate that with growing seasons, the daily variation patterns of emission/uptake of greenhouse gases differ greatly in the prairie ecosystem. The peak of seasonal emission/uptake of three greenhouse gases occurs at the melting period in spring when soil moisture is high and rainfall is rich. The daily emissions of CO_2 from steppe vegetation in growing seasons are low during the daytime and high at night. Higher temperatures are advantageous to emission of CO_2, as aboveground biomass determines the amount of CO_2 photosynthetic uptake. The key factors that influence the daily variation patterns of CH_4 uptake and N_2O emission in semiarid grassland are soil moisture and the oxygen supplying condition, while the changes in daily temperature mainly affect the range of daily variations. The seasonal changes of N_2O emission are positively related to seasonal change in soil moisture. Free grazing reduces the daily mean deviation of exchange rates of CO_2, N_2O, and CH_4, but it decreases the amount of annual emission/uptake of N_2O and CH_4 yet it increases the annual emission of CO_2.

Key words: variation, temperature, moisture, emission/uptake, CO_2, CH_4, N_2O

1. Introduction

The area of temperate steppe in China is about 2.3×10^6 km^2, covering about 24% of the nation's land, consisting mostly of semiarid and arid grasslands (Chen, 1988). Owing to influences of natural and anthropogenic factors, such as overgrazing and cultivating as well as global warming and soil drought in North China etc., the temperate semiarid grassland of Inner Mongolia has become more heavily degraded day by day, which has an impact on source and sink of greenhouse gases, and exerts direct influence on the balance of greenhouse gases in the atmosphere. Many investigators indicate that using organic fertilizers can enhance CH_4 emission in rice paddies, whereas the amount of CH_4 emission in flood paddies changes with soil temperature variations; the use of nitrogen fertilizers can cause an increase in N_2O emission from cropland ecosystems, the rates of N_2O emission in dry farmland increase with the rise of soil moisture and temperature (Du et al., 1997; Huang et al., 1998). As early as the "8th Five-Year Plan" period there were preliminary experimental measurements of greenhouse gases, N_2O and CH_4 emission in some regions of Inner Mongolian grassland (Jia, 1999, Li and Lin, 2000). During the "9th Five-Year Plan", Lü Daren, Wang Yanfen, and Wang Gengchen observed and studied tentatively the N_2O emission in Inner Mongolian grassland (Li and Lin, 2000, Martin and Ralf, 1995, Mosier et al., 1991). In the "10th Five-Year Plan", such work is still going on (Wang et al., 1996; Wang et al., 1997a; Wang et al., 1997b; Wang et al., 1997c). However, research on the source and sink of greenhouse gases in semiarid grassland of China is not enough. There is still no systematic research on greenhouse gases emission from China's semiarid grassland and their relation with environmental factors such as soil

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moisture and temperature etc.

2. Measured regions, experimental methods, and data corrections

2.1 *Background of measured sites*

The experimental site is located in the vicinity of the Inner Mongolian Grassland Ecosystem Research Station (IMGERS), in the Xilin River Basin (abbreviated below as "station"). The grassland has been well preserved at this site, and it is very representative of China's temperate grassland and the whole Eurasian continental grassland in the respects of climate, vegetation, animals, and soils, etc. In the area of the experiment, it is a temperate terrestrial monsoon climate. Four seasons are clearly demarcated with a cold and long winter, and the frost-free period is short. The annual average temperature is about 1°C, with greater annual mean deviations and daily mean deviations, and sunshine is sufficient. Precipitation is concentrated in June-August, and annual variation is very large. To investigate patterns of greenhouse gas emission and its relation with environmental factors, this article surveys the following three sampling plots: ungrazed *leymus chinense* grassland, freely-grazed *leymus chinense* grassland, and *stipa grandis* grassland. Among these, the *leymus chinense* grassland and *stipa grandis* grassland have been fenced livestock since 1983, and have reached the appearances of original grassland.

2.2 *Experimental methods and data collection*

Compared with cropland that belongs to temperate semiarid grassland, the fluxes of greenhouse gases exchange between grassland and atmosphere are too small. Therefore, it is hard to use micrometeorological methods to get an accurate result, but it is advantageous to observe with a chamber method, for the biomass under ground is much more than that aboveground, and carbon and nitrogen take a comparatively long time cycling in the grass ecosystem.

N_2O, CO_2, and CH_4 fluxes were measured with a static chamber-gas chromatograph. Chambers were made of acrylic material and stainless steel. Five types of chambers were used in different grasslands, listed as, biggest: Length×Width×Height = 90 cm× 90 cm×35 cm;
middle-1: 65 cm×65 cm×70 cm;
middle-2: 40 cm×40 cm×35 cm;
small-1: 20 cm×20 cm×25 cm;
small-2: diameter×height=20 cm×25 cm.

By improving the gas chromatography sampling system, the analyses and measurements on the three kinds of greenhouse gases can be completed with a single injection. The experimental methods are described in detail by Wang et al.(2001).

During 1998 2000, measurements were made continuously, once or twice a week, on ungrazed *leymus chinense* grassland, freely-grazed *leymus chinense* grassland, and *stipa grandis* grassland. Six sampling sites were set up in the same region with three sampling chambers to collect samples alternatively in two series, and the average results of measurements were taken in order to reduce the disturbances on sampling site and to decrease the experimental errors resulting from spatial variations of emission /uptake. At the same time, daily variations of 24-hour continuous (once every 2 hours) measurements were acquired in ungrazed *leymus chinense* grassland, freely-grazed *leymus chinense* grassland, and *stipa grandis* grassland mentioned above, once (out of growing season) or twice (in growing season) monthly. Because of the relatively fixed daily variation patterns, the adjusting coefficient of greenhouse gas emission/uptake at each measured time and daily average value can be calculated. So the average flux on a measured day can be calculated more accurately by the result of a single measurement at any time one day (for example once a week), and the range of daily variations can also be corrected by the values of fluxes obtained from a measurement made once a week. The data adopted in this research are based on the mean results of each hour, each day, every 10 days and every month measured at the same (or similar) time in two years from April 1998 to April 2000.

3. Results and Discussions

3.1 *Relationship between daily variations of greenhouse gases emission/uptake from grassland and environmental factors*

3.1.1 *Daily variations of* CO_2 *emission*

Vegetation absorbs CO_2 through photosynthesis, while soils and plants emit CO_2 by respiration. The daily variation patterns of CO_2 emission in ungrazed *leymus chinense* grassland and freely-grazed *leymus chinense* grassland of Inner Mongolia are basically the same (Fig. 1). During the daytime, they are even sometimes a sink of atmospheric CO_2, and sometimes a source, yet the daily emission is much more than the uptake, which net results in the releasing of CO_2 into the atmosphere. When the weather is fine, all the peak values of CO_2 emissions occur at night, but at daybreak the values of emission fluxes decline rapidly to 0, then increase again slowly. In the four growing stages (before germinating, flowering, seeding, maturing) of grassland plants, all the minimum values of emission appear at 6–7 o'clock in the morning, while the uptake due to photosynthesis approaches a dynamic equilibrium. However, during this time, the soil temperature is the lowest, whereas plant and soil respiration are weaker, hence the least emission of CO_2, which causes a minimum value of daily emission fluxes in the early morning. In contrast, the maximum value of CO_2 emission occurs at 20–21 o'clock in the evening after it is dark, and the photosynthetic uptake of CO_2 stops completely at this time. Furthermore, while the soil temperature remains at a higher level, the plant and soil respiration are strong, so the highest value of CO_2 emission occurs in the daily variations during this period.

To more clearly analyze the relationship between the grassland CO_2 daily variations and radiation and soil temperature, Fig. 1a is remade into a daytime interval and a nighttime interval in Fig. 2, and compared with net radiation and soil daily temperature variations. It can be seen from Fig. 2 that the time interval of low CO_2 emission during the day coincides better with the interval when net radiation is greater than 0, but the emission fluxes have no significant linear correlation with net radiation intensity. That is to say, when the net radiation reaches a definite value, the photosynthetic uptake of CO_2 by the grassland plants is saturated; it doesn't change whether solar radiation is continuing to rise. To more precisely analyze Fig. 1 and Fig. 2, CO_2 emission fluxes are practically divided into a daytime interval and a night interval, and they are positively associated with daily variations. In the daytime, along with the rise of soil temperature, the emission fluxes of CO_2 also increase slowly at lower rates; at night, the CO_2 emission amount declines gradually with the drop in temperature, but the dropping rate is bigger.

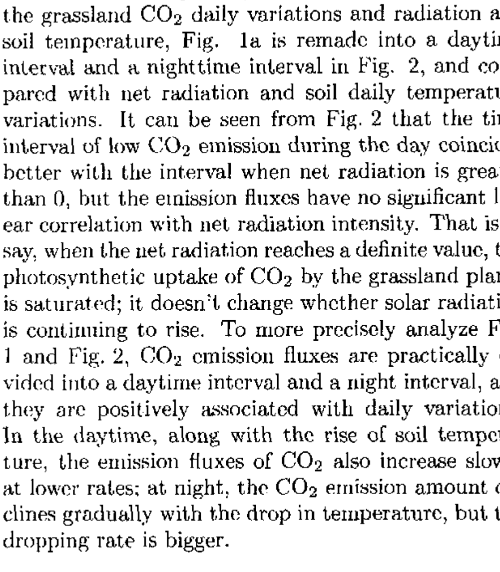

Fig. 1. Daily variations of CO_2 emission in *leymus chinense* grassland, (a) ungrazed, (b) freely-grazed. A: Before germinating, B: flowering, C: seeding, D: maturing.

3.1.2 *Daily variations of* N_2O *emission*

The N_2O emitted from semiarid grassland of Inner Mongolia is driven by heterotrophic nitrification. Because the nitrifying activity and intensity of heterotrophic nitrification are far lower than those of autotrophic nitrification, the mean daily deviation of N_2O emission of grassland terrestrial ecosystems is slightly small, and the variations are complicated. Nevertheless in flourishing growing stages of grassland, especially at the flowering stagė, the N_2O daily emission variations are still very obvious. It can be seen from Fig. 3 and Fig. 4 that in the case of relatively greater soil moisture (>15%) and better porosity, the peak of N_2O emission fluxes appears at midday, but at night when the soil temperature has dropped, a low value of emission occurs. This is probably because nitrification produces N_2O that is positively correlated with soil temperature, and which also makes daily variations of emission fluxes positively associated with soil daily temperature variations. As shown in Fig. 3b, c and Fig. 4b, the soil daily average moisture values are 15%, 20.3%, and 14.5% respectively; all their daily variations of emission fluxes and daily temperature variations have a better positive linear correlation. The results of measurements are roughly the same as the daily variations patterns measured by research on N_2O emission in dry farmland of East China (Zheng et al., 1997; Wang et al., 2000). Figure 4c is contrary to the regularity mentioned above: the soil average moisture is 19.9%, and there is an inverse correlation between N_2O daily variations and daily temperature variations. This is possibly because it is easy to produce anaerobic-micro zones in the seasons of spring melting which have more concentrated rainfall when the soil moisture is higher, especially in grazed grassland where the water-preserving capacity of surface soil is lower. At this time, N_2O emission from grassland mainly stems from denitrification. In the process of anaerobic denitrification, the ratio between emitted N_2O and nitrogen (N_2O/N_2) shows an inverse correlation with temperature. Namely, the higher the temperature, the more the N_2 produced in the process of denitrification, and the less the N_2O produced, therefore there is also an inverse correlation between daily N_2O emission variations and daily temperature variations. As shown in Figs. 4c and 3a, the peak values of N_2O emission occurring at night may be caused by denitrification. When the nitrification and denitrification processes coexist, the daily variations of N_2O emission are even more complicated. Both the subsidiary peak of N_2O emission appearing by 6 o'clock in Fig. 4c and the peak value in Fig. 4a, manifest a positive correlation between N_2O produced in nitrification and daily temperature, except that grazing has greatly changed the surface soil and surface biomass

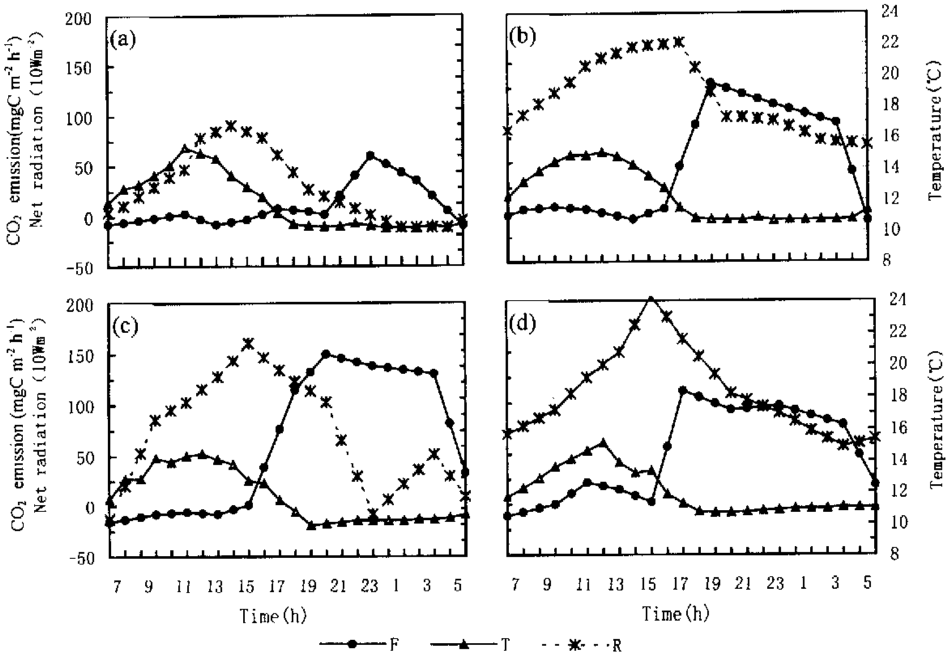

Fig. 2. Relationship of daily variation of CO_2 emission with net radiation and soil temperature in *leymus chinense* grassland of Inner Mongolia, F: emission fluxes, R: net radiation, T: average temperature in soil 0-10 cm. (a) Before germinating, (b) flowering, (c) seeding, (d) maturing.

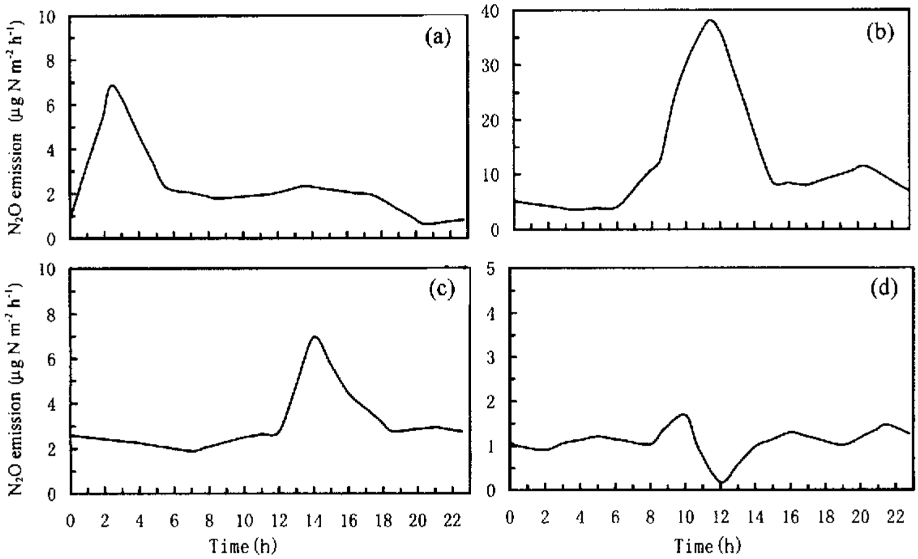

Fig. 3. Daily variations of N_2O fluxes at different growth stages in ungrazed *leymus chinense* grassland, (a) Before germinating, (b) flowering, (c) seeding, (d) maturing.

in the grassland, which makes a transition of peak value. In the post-maturing stage, grassland vegetation begins to wither and fall, or rot, while the temperature drops, the rainfall decreases, and N_2O emission flux variations are not as large as compared with other seasons, so daily variations are obviously insignificant.

In summary, the key factors that affect the daily variation pattern of N_2O emission in semiarid grassland are soil water content and physical properties of the surface soil, and the daily temperature variations exert influences mainly on the intensities of the various patterns mentioned above.

3.1.3 *Daily variations of* CH_4 *uptake in grassland*

The daily variation patterns of CH_4 uptake in grassland are dominantly influenced by soil water content, soil porosity (mainly affecting the oxygen-transferring capacity), and temperature and plant growth. It can be seen from Fig. 5 and Fig. 6 that when the soil is rich in porosity (ungrazed grassland) and water content ranges from 15% to 20%, grazing considerably reduces the daily mean deviation of CH_4 uptake in grassland. As shown in Fig. 5c and Fig. 6b, the daily average water contents of the soil are 15% and 19.9% respectively, indicating that at the seeding stage of the ungrazed grassland and at the flowering stage of grazed grassland, the daily variation patterns of CH_4 uptake in the ecosystem of grassland are positively related to daily temperature variations. But there are two exceptions, Fig. 6c, i.e., at the seeding stage of the grazed grassland, owing to greater soil moisture (daily average is 20.3%), the anaerobic-microzone trampled by cows and sheep not only greatly decreases in capacity for soil CH_4 uptake, but also can produce CH_4 (after rain, CH_4 emission is frequently observed). Under anaerobic conditions, the production and release of CH_4 are positively related to soil temperature (Chen et al., 1990; Du et al., 1997; Zheng et al., 1999).

3.2 *Relation between seasonal variations of emission/uptake of grassland greenhouse-gases and environmental factors*

3.2.1 *Seasonal variations of* CH_4

In Fig. 7a, the major effect of Inner Mongolian semiarid grassland on atmospheric CH_4 is uptake. The seasonal variation patterns of CH_4 uptake in the three kinds of grasslands are almost the same. The peak value of CH_4 uptake appears in the grazed grassland generally about 10 days either earlier or later than that in the ungrazed grassland. This is possibly due to the influence of variations of soil water retentive capacity on variations of soil moisture, so as to affect the process of variations of soil CH_4 uptake. In addition to spring melting, the increase in grassland soil water is mainly caused by precipitation; when moisture reaches the optimum for CH_4 uptake, the peak value of uptake occurs. In general, the water content ranging from 15%–20% is the optimum moisture for soil CH_4 uptake, for at this time the oxidizing bacteria of CH_4 in the soil are most active (Mosier, et al., 1991); but the soil water content ranging from 28% to 35% may weaken the oxidation of CH_4. Obviously, precipitation makes the soil of grazed grassland first reach the optimum range of moisture for CH_4 uptake, because the water retentive capacity there is low, and this may be the reason why the peak value of seasonal variations of CH_4 in the atmosphere occurs in grazed grassland earlier than in ungrazed grassland. The reason that the peak appears in the grazed grassland by the 240th–260th day, later than in ungrazed grassland, is presumably due to, during the time of soil with excessive moisture (the measurement in practice is over 20%) turning to soil with low moisture, the ungrazed grassland rich in porosity can attain the optimum moisture of soil CH_4 uptake very quickly, therefore the peak uptake in ungrazed grassland occurs earlier than in grazed grassland. Although the seasonal variation patterns are similar, the intensities of uptake differ to some extent. The CH_4 uptake flux values in *stipa grandis* grassland during the measured period range from 0.75 to 173 μgC m^{-2} h^{-1}; those in ungrazed *leymus chinense* grassland are 1.1–165 μgC m^{-2} h^{-1}; and those in freely-grazed *leymus chinense* grassland are 0.83–138 μgC m^{-2} h^{-1}. The order of intensities of average annual uptake is: *stipa grandis* > ungrazed *leymus chinense* >freely-grazed *leymus chinense* grassland. It is easy to see by comparing this with Fig. 7d (seasonal variations of soil water) that all the peak values of soil CH_4 uptake occur at various periods of soil water content. If soil water content is too low (>8%) or too high (>20%), it is not advantageous to the grassland soil for the uptake of atmospheric CH_4. These results agree with the conclusions obtained from daily variations.

3.2.2 *Seasonal variations of* N_2O

It can be seen from Fig. 7b that the semiarid grassland of Inner Mongolia exerts effects on atmospheric N_2O by the two functions, uptake and emission, but emission is much greater than uptake, and the net result is a source of atmospheric N_2O. The seasonal patterns of N_2O emission in the different kinds of grassland are basically the same. Two uptake peaks occur every year in March and July respectively (Fig. 7), and the strongest peak uptake appears generally in the months of June and July when annual precipitation is maximum. If there is more precipitation in the grassland in winter, leaving a covering of heavy snow, explosive emission of N_2O caused by spring melting in March probably makes its monthly average fluxes

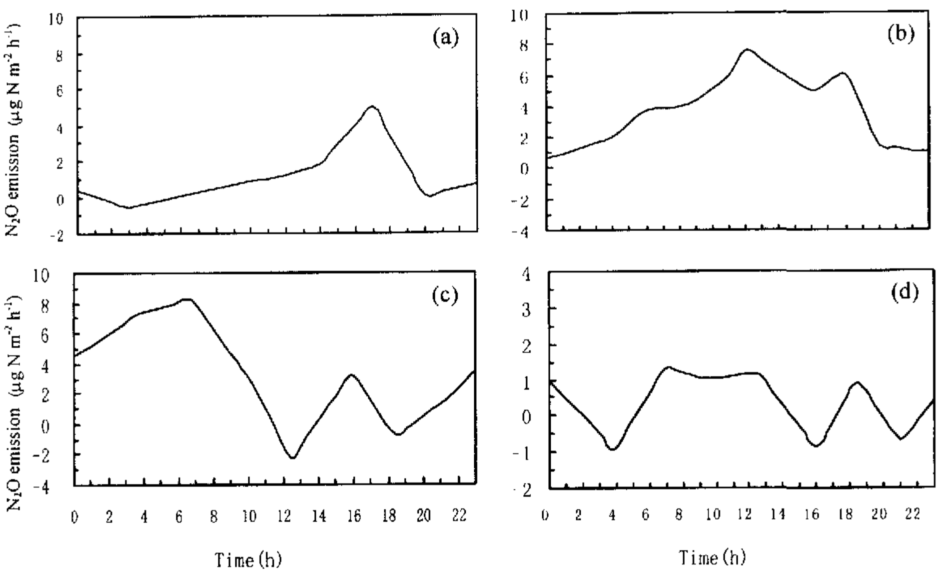

Fig. 4. Same as Fig. 3 except in freely-grazed *leymus chinense* grassland.

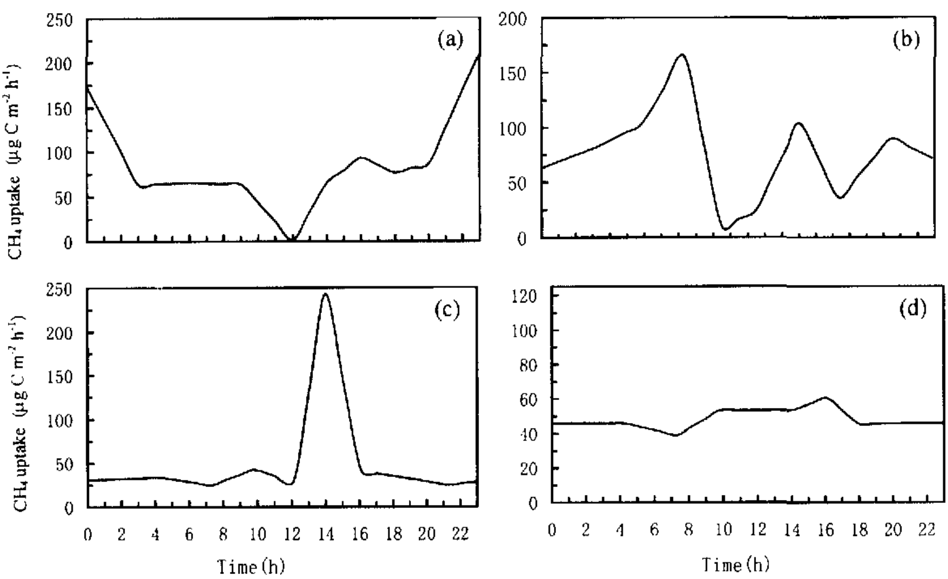

Fig. 5. Daily variations of CH_4 uptake fluxes at different growth stages in *ungrazed leymus chinense* grassland, (a) Before germinating, (b) flowering, (c) seeding, (d) maturing.

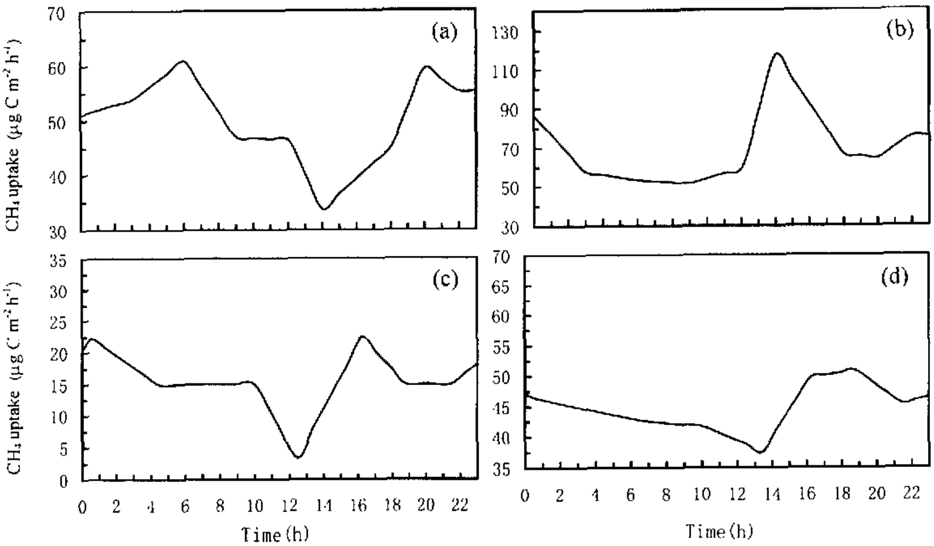

Fig. 6. Same as Fig. 5 except in freely-grazed *leymus chinense* grassland.

rank the highest of the annual emission. The N_2O annual average emissions of the three kinds of grassland are ranked as: ungrazed *leymus chinense*>freely-grazed *leymus chinense*>*stipa grandis*. Different grassland soil types, vegetation and below ground biomass conditions respond differently to soil water variations that cause the increase of N_2O emission (Huang et al., 1998).

3.2.3 *Seasonal variations of* CO_2

It can be seen from Fig. 7c that the ungrazed and freely-grazed *leymus chinense* grasslands are always a source of atmospheric CO_2, but the *stipa grandis* grassland sometimes releases CO_2, and sometimes absorbs CO_2. During the period of measurement (May 1998 to February 2000), the CO_2 emission from *stipa grandis* grassland ranged from 11 to 80 μgC m^{-2} h^{-1} with the average monthly strongest uptake peak values occurring in September at 3.0 μgC m^{-2} h^{-1} with the maximum of average monthly emission occurring in June at 6.2 μgC m^{-2} h^{-1}; the overall equilibrium is a weak source of atmospheric CO_2, with annual average CO_2 emission of 102 kgC ha^{-1} yr^{-1}. The CO_2 emission amount in ungrazed *leymus chinense* grassland is higher than in *stipa grandis* grassland, while the freely-grazed grassland is also higher in CO_2 emission when compared with ungrazed grassland, and the range of annual emission is larger than ungrazed grassland. The rise in temperature is beneficial to respirations of soil microorganisms, animals, and plants, which can promote CO_2 emission. By photosynthesis of plants, CO_2 is absorbed in the case of sufficient solar radiation, and the CO_2 uptake amount also increases with increase of soil surface biomass; on the other hand, the reduction in surface biomass may directly decrease the photosynthesis of plants, which results in the net increase of CO_2 emission. The peak value of CO_2 emissions in grazed grassland appears in July–August (about day of 180th–240th), and the radiation during this period is large, with daily net radiation intensity of 400–600 W m^{-2}. During this time, annual temperature is also the highest in the grassland, and the rise in temperature enhances the respiration of microorganisms in the soil, and the CO_2 emission increases. As a result by nibbling of livestock, the biomass in freely-grazed grassland is far less than that in ungrazed natural grassland, so that plants greatly reduce the CO_2 uptake by photosynthesis. The net result is the strongest CO_2 emission in the whole year occurring from July to August in freely-grazed *leymus chinense* grassland. Because ungrazed *leymus chinense* grassland is fenced and ungrazed, the aboveground biomass is evidently higher than in the freely-grazed grassland, and during the same time interval, the CO_2 emission from soil and plant respiration is slightly greater than that of CO_2 uptake by plant photosynthesis, so the results imply that under the lower rate of emission there are no significant fluctuations

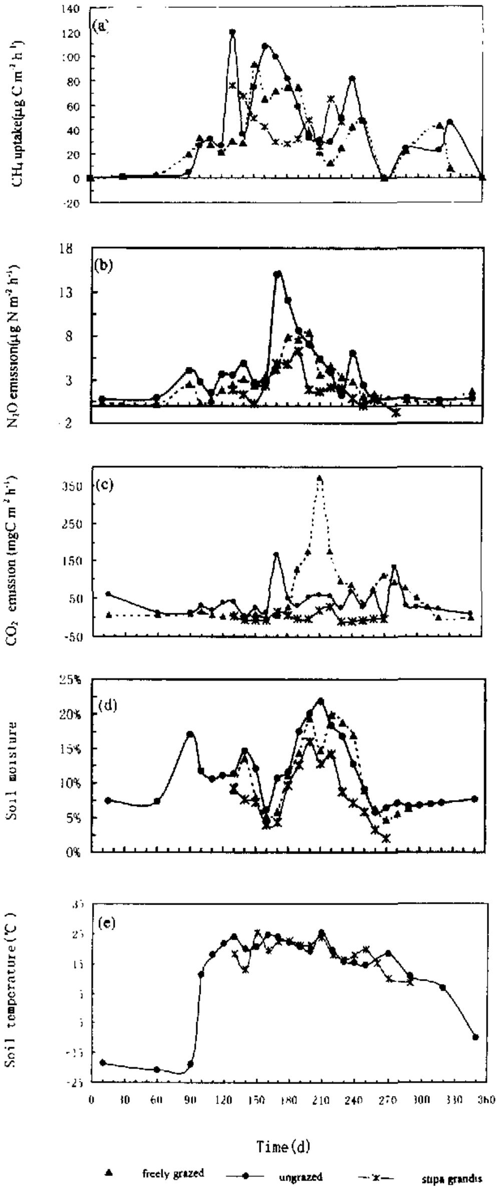

Fig. 7. Relations between seasonal variations of emission/uptake of greenhouse gases in grassland and main environmental factors, (a) CH_4, (b) N_2O, (c) CO_2, (d) soil moisture, (e) soil temperature.

in CO_2 emission fluxes.

4. Conclusions

The key factors affecting the variation patterns of daily CO_2 emission are solar radiation and soil temperature, and it is soil water content and oxygen-supply state that affect daily variation patterns of CH_4 and N_2O emission in semiarid grassland, whereas daily temperature variations exert the main influence on the intensity of daily variations. The seasonal variations of CH_4 uptake and N_2O emission show inverse and positive linear correlations with those of soil moisture respectively.

Soil types, vegetation, amounts of precipitation, radiation, and temperature that impact the exchange values of greenhouse gases in grassland are all factors of natural phenomena, but the effect of grazing upon the exchange values is anthropogenic activity. As far as greenhouse gases are concerned, grazing reduces N_2O emission in grasslands; hence decreases in emission amounts of greenhouse gases, however, are negligible compared with reduction in CH_4 uptake, especially with the increase in CO_2 emission value. For this reason, might we suggest the "enclosure of cattle with fences" to rehabilitate the "primitive grassland" and to diminish the emission of greenhouse gases?

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半干旱草原温室气体排放/吸收与环境因子的关系研究

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摘　要

静态箱–气相色谱法对内蒙古半干旱草原连续两年的实验观测研究结果表明，内蒙古草原是大气CO_2和N_2O的排放源，和CH_4的汇。在植物生长不同季节，草原生态系统排放/吸收温室气体CO_2、CH_4和N_2O的日变化形式各有不同，其中在植物生长旺季日变化形式最具特征。三种温室气体的季节排放/吸收高峰主要出现在土壤湿度较大的春融期和降雨较为集中时期。对所有草原植物生长季节，CO_2净排放日变化形式均为白天出现排放低值，夜间出现排放高值。较高的温度有利于CO_2排放，地上生物量决定着光合吸收CO_2量值的高低。影响半干旱草原吸收CH_4和排放N_2O日变化形式的关键是土壤含水量和供氧状况，日温变化则主要影响日变化强度。吸收CH_4和排放N_2O的季节变化与土壤湿度季节变化分别呈线性反、正相关，相关系数均在0.4–0.6之间。自由放牧使CO_2、N_2O和CH_4交换速率日较差降低，同时使N_2O和CH_4年度排放/吸收量减少和CO_2年度排放量增加。

关键词：变化，温度，湿度，排放，吸收，CO_2，CH_4，N_2O