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China's grazed temperate grasslands are a net source of atmospheric methane

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A B S T R A C T

A budget for the methane (CH_4) cycle in the Xilin River basin of Inner Mongolia is presented. The annual CH_4 budget in this region depends primarily on the sum of atmospheric CH_4 uptake by upland soils, emission from small wetlands, and emission from grazing ruminants (sheep, goats, and cattle). Flux rates for these processes were averaged over multiple years with differing summer rainfall. Although uplands constitute the vast majority of land area, they consume much less CH_4 per unit area than is emitted by wetlands and ruminants. Atmospheric CH_4 uptake by upland soils was −3.3 and −4.8 kg CH_4 ha^{-1} y^{-1} in grazed and ungrazed areas, respectively. Average CH_4 emission was 791.0 kg CH_4 ha^{-1} y^{-1} from wetlands and 8.6 kg CH_4 ha^{-1} y^{-1} from ruminants. The basin area-weighted average of all three processes was 6.8 kg CH_4 ha^{-1} y^{-1}, indicating that ruminant production has converted this basin to a net source of atmospheric CH_4. The total CH_4 emission from the Xilin River basin was 7.29 Gg CH_4 y^{-1}. The current grazing intensity is about eightfold higher than that which would result in a net zero CH_4 flux. Since grazing intensity has increased throughout western China, it is likely that ruminant production has converted China's grazed temperate grasslands to a net source of atmospheric CH_4 overall.

1. Introduction

Methane (CH_4) is the second most important anthropogenic greenhouse gas after carbon dioxide. Per unit mass, however, CH_4 has a global warming potential about 25-fold greater than that of CO_2 over 100 years (IPCC, 2007).

Upland grassland soils are a significant global sink for atmospheric CH_4 through the activity of aerobic CH_4-oxidizing bacteria (Mosier et al., 1991). However, most grasslands are grazed by domestic ruminants, which generate CH_4 in their rumens through microbiological fermentation and methanogenesis and expel it via eructation through the mouth and nose (Lassey, 2007). CH_4 is also emitted from ruminant dung (Ma et al., 2006; Pinares-Patiño et al., 2007). Temperate grasslands are one of the largest terrestrial biomes worldwide, and are widely used for grazing and economic activities related to livestock products, such as meat, milk, wool, and pelts. Chinese grasslands cover 41.7% of China's land area, and are distributed mainly in Inner Mongolia, Xinjiang, Gansu, and the Qinghai-Tibet plateau (NSBC, 2002). Temperate steppes account for approximately 80% of Chinese grasslands (Chen and Wang, 2000), in which the Inner Mongolia grasslands are an important component. The Inner Mongolia steppes are often recognized as a sink for atmospheric CH_4 (Wang et al., 2003). However, this sink may be offset considerably by CH_4 emission from numerous small wetlands scattered across the grasslands (Wang et al., 2005b) and a significant enteric CH_4 emission from ruminants (Wang et al., 2007). Many CH_4 flux measurements have been made in the Xilin River basin of the Inner Mongolia steppes but have not been generalized into a CH_4 budget. Overall, it is unknown whether temperate Inner Mongolia grasslands are a net source or net sink for atmospheric CH_4.

In this study, we evaluated the annual CH_4 budget in the Xilin River basin by developing an area-weighted average for CH_4 uptake in upland soils and CH_4 emission from small wetlands and ruminants.

2. Materials and methods

2.1. Site description

The Xilin River basin (43°26′–44°39′ N, 115°32′–117°12′ E; 902–1506 m above sea level, 10,786 km^2) is located on the eastern Inner Mongolia Plateau (Wang et al., 2005b). The 210-km Xilin River runs through the central area of the basin. The basin is within the semi-

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arid temperate climatic zone with a mean annual temperature of approximately 0.6 °C. The coldest monthly mean temperature is −21.4 °C in January, and the warmest is 18.5 °C in July. The basin receives an average of 350 mm precipitation annually, approximately 10% of which falls as snow. Plants usually grow from late April to early October and the dominant grasses are *Leymus chinensis* and *Stipa grandis*. Soils are mainly chernozems with a sandy loam texture (approximately 20% clay, 20% silt, and 60% sand). On the basis of topography, vegetation, soils, and land uses, the Xilin River basin may be classified into grasslands, meadows, small wetlands, farmlands, and sandlands with the average area percentages of 76.1%, 15.1%, 0.3%, 1.4%, and 7.1%, respectively; this distribution of land types and uses has been almost unchanged over the past few decades (Li et al., 1988; Xiao et al., 1997). Grassland-dominated uplands are the most extensive landscape. Because of the cold continental climate and sufficient water availability, numerous small riparian wetlands have developed along the Xilin River.

2.2. CH_4 budget estimate

2.2.1. CH_4 measurement in wetlands

Two riparian marshes with different soil and vegetation characteristics were chosen for measurements of *in situ* CH_4 flux. One was a sandy marsh with low organic carbon and total nitrogen contents, with no visual horizon boundary but sparsely interspersed with black peat. The other was an organic marsh that exhibited two distinct soil horizons, an upper sandy horizon and an underlying organic horizon. Two habitats were sampled in each marsh: a higher elevation habitat with the water table below the soil surface (wet meadow) and a lower elevation habitat with standing water (waterlogged habitat). The sandy marsh was an overlapping area of wetland and sandland; the water table in its waterlogged habitat was connected directly to the Xilin River and remained relatively stable. The waterlogged habitat of the organic marsh was a minor sub-stream with approximately 30 cm water depth in summer 2004 but varied over time; this particular wetland was not sampled in 2003.

CH_4 flux was determined using a closed chamber technique. Measurements taken in three wetlands in 2003 were described previously (Wang et al., 2005b). For June 2004–May 2005, chamber bases ($n = 5$) were established randomly in the wet meadows and waterlogged habitats of the two marshes described above. The chamber consisted of a 25-cm-tall gray polyvinyl chloride (PVC) base (30 cm in diameter) with a channel on the top and a 30-cm-tall PVC cover that fit into the channel on the base. Water was placed into the channel to form a gastight seal; in the winter warm water (∼50 °C) was used to prevent freezing. The water was removed by syringe immediately after sampling. The chamber was covered with reflective aluminum foil to block light and minimize internal heating. The vegetation inside and outside chamber base was not noticeably different.

CH_4 fluxes were measured approximately every 5 days during June–October 2004 and approximately every 10 days during November 2004–May 2005. Our previous studies indicated that CH_4 emission during the time interval of 09:00–10:00 in the morning or 16:00–17:00 in the afternoon was representative of the average rate over a 24-h cycle (Wang et al., 2005b). Hence we used the initial linear change of headspace CH_4 concentration over 30 min within the time intervals of 09:00–10:00 and 16:00–17:00 on each sampling date to represent the daily CH_4 flux. Daily CH_4 emission rate was an average of one measurement in the morning and one measurement in the afternoon. Air temperature, soil or water temperature at 10 cm depth, and water table depth were recorded at the time of the flux measurements. Detailed descriptions of these wetlands, base installation, sampling procedures, gas chromatography analysis, and flux calculations were published previously (Wang and Han, 2005).

2.2.2. Census of CH_4 uptake by upland soils

Over the past decade, many independent *in situ* CH_4 flux measurements have been published for upland grasslands in the Xilin River basin (Table 1). Some studies published flux measurements as monthly averages while others published seasonal averages. We converted seasonal results to monthly averages and combined them to produce annual flux estimates. Seasonal flux rates results were decomposed to corresponding monthly averages as follows: growing season (April–September), non-growing season (October–March), spring (April–May), summer (June–August), autumn (September–October), and winter (November–March). Monthly rates were summed to get the annual CH_4 uptake.

Table 1
Methane fluxes in the upland grasslands of the Xilin River basin, the temperate Inner Mongolia.

Measured period	Steppe	CH_4 flux (mg CH_4 m^{-2} d^{-1})[a]	Reference
May–October 1995	Ungrazed *Stipa grandis*	−1.63	Du et al., 1997
May–October 1995	Ungrazed *Leymus chinensis*	−0.87	Du et al., 1997
June–October 1995	Grazed steppe	−0.76	Du et al., 1997
Spring 1998	Ungrazed *Stipa grandis*	−1.92	Wang et al., 1998
Summer 1998	Ungrazed *Stipa grandis*	−2.88	Wang et al., 1998
Fall 1998	Ungrazed *Stipa grandis*	−1.20	Wang et al., 1998
Winter 1998	Ungrazed *Stipa grandis*	−0.72	Wang et al., 1998
Spring 1998	Ungrazed *Leymus chinensis*	−1.92	Wang et al., 1998
Summer 1998	Ungrazed *Leymus chinensis*	−1.68	Wang et al., 1998
Fall 1998	Ungrazed *Leymus chinensis*	−0.96	Wang et al., 1998
Winter 1998	Ungrazed *Leymus chinensis*	−0.96	Wang et al., 1998
Spring 1998	Ungrazed steppe	−2.64	Wang et al., 1998
Summer 1998	Ungrazed steppe	−2.16	Wang et al., 1998
Fall 1998	Ungrazed steppe	−1.20	Wang et al., 1998
Winter 1998	Ungrazed steppe	−0.72	Wang et al., 1998
July 1998	Grazed typical steppe	−0.94	Dong et al., 2000
July 1998	Grazed steppe	−1.33	Wang et al., 2000
September 1998	Grazed steppe	−2.89	Wang et al., 2000
June–September 1998	Ungrazed meadow *Stipa Baicalensis*	−0.86	Wang et al., 2003
May 1998–April 1999	Ungrazed *Leymus chinensis*	−1.57	Wang et al., 2005a
May 1998–April 1999	Grazed *Leymus chinensis*	−1.22	Wang et al., 2005a
Growing season	Ungrazed *Leymus chinensis*	−1.87	Wang et al., 2005a
Growing season	Grazed *Leymus chinensis*	−1.40	Wang et al., 2005a
Non-growing season	Ungrazed *Leymus chinensis*	−0.87	Wang et al., 2005a
Non-growing season	Grazed *Leymus chinensis*	−0.69	Wang et al., 2005a
July–October 2003	Grazed *Leymus chinensis*	−1.9	Wang et al., 2005b
June–September 2004	Ungrazed *Leymus chinensis*	−1.60	Liu et al., 2007
June–September 2004	Winter-grazed *Leymus chinensis*	−0.99	Liu et al., 2007
May–September 2005	Ungrazed *Leymus chinensis*	−2.14	Liu et al., 2007
May–September 2005	Winter-grazed *Leymus chinensis*	−1.02	Liu et al., 2007
March–June 2006	Ungrazed *Leymus chinensis*	−1.60	Liu et al., 2007
March–June 2006	Winter-grazed *Leymus chinensis*	−0.64	Liu et al., 2007
March–May 2006	Ungrazed steppe	−1.36	Holst et al., 2008
March–May 2006	Grazed steppe	−0.45	Holst et al., 2008

[a] CH_4 flux is an average value during the period of measurement.

2.2.3. Estimation of CH_4 emission from ruminants

We estimated the CH_4 emission from domestic ruminants using 2006 IPCC guidelines (Dong et al., 2006) as implemented by Zhou et al. (2007). In general, total CH_4 emission from domestic ruminants can be obtained by multiplying ruminant type-specific emission factors by the number of the particular ruminant type. In this study, we used the average CH_4 emission factors of enteric fermentation and manure management of 5.44, 4.75, and 74.2 kg CH_4 head^{-1} y^{-1} for sheep, goats, and cattle, respectively (Zhou et al., 2007). These emission factors account for age profiles, such as mature female, newborn, and other, for all of China. Since we lacked age data for our study area, we assumed that the age profile was the same as the national average. We also assumed that ruminants were born and died uniformly throughout a year so that the average life span during the year of birth or death of those born or killed in a given year is half of that year. The ruminant data were from the census records of the Baiyinxile Livestock Farm, a representative area in the Xilin River basin. Ruminant heads in the non-growing season are equal to the end-of-year census, while heads in the growing season are the sum of the non-growing season heads plus those born and slaughtered in that year.

For comparison with flux rates in uplands and wetlands, CH_4 emission from ruminants was normalized to the upland grassland area-equivalent using the ruminant emission factors and the calculated grazing intensities at the Baiyinxile Livestock Farm. Grazing intensity for all types of ruminants is standardized to sheep unit (SU), where one head of cattle is 13.64 SU and one goat is 0.87 SU, based on their respective CH_4 emission factors.

2.2.4. CH_4 budget calculation

The annual CH_4 budget was calculated by combining the CH_4 fluxes in uplands, wetlands, and ruminants. Positive values indicate a net emission of CH_4 to atmosphere, while negative values indicate a net uptake from atmosphere. Total CH_4 flux (T_{CH_4}) is calculated as:

$$T_{CH_4} = \sum_{i=1}^{n} F_{CH_4} \times A$$

where i is the ith component/sub-component, F_{CH_4} is the average annual CH_4 flux, and A is land area.

2.3. Statistical analysis

The SAS (Statistical Analysis System) program (SAS Institute, 1999) was used to analyze the linear correlation between CH_4 emission and environmental factors in wetlands, including air temperature, soil or water temperature at 10 cm depth, and water table depth.

3. Results

3.1. In situ CH_4 emission from wetlands

CH_4 emission varied seasonally in the two wetlands (Fig. 1). During July–November 2004, CH_4 emission rates in the sandy wetland varied from 13.7 to 439.8 mg CH_4 m^{-2} d^{-1} in the wet meadow and from 10.8 to 397.3 mg CH_4 m^{-2} d^{-1} in the waterlogged habitat (Fig. 1b). There was a significant positive correlation between CH_4 emission and both air temperature ($R^2 = 0.6311$, $P < 0.01$, $n = 31$ for the wet meadow; $R^2 = 0.7116$, $P < 0.01$, $n = 31$ for the waterlogged habitat) and soil temperature at 10 cm ($R^2 = 0.7491$, $P < 0.01$, $n = 31$ for the wet meadow; $R^2 = 0.8833$, $P < 0.01$, $n = 31$ for the waterlogged habitat) (Fig. 1a,b).

In the organic wetland CH_4 emission varied from 23.4 to 1132.5 mg CH_4 m^{-2} d^{-1} in the wet meadow and from 179.0 to 3293.6 mg CH_4 m^{-2} d^{-1} in the waterlogged habitat (Fig. 1d). There was a significant positive correlation between CH_4 emission and air temperature ($R^2 = 0.5044$, $P < 0.01$, $n = 28$ for the wet meadow; $R^2 = 0.5959$, $P < 0.01$, $n = 28$ for the waterlogged habitat). Also, CH_4 emission was significantly correlated with soil or water temperature at 10 cm ($R^2 = 0.6394$, $P < 0.01$, $n = 28$ for the wet meadow; $R^2 = 0.7858$, $P < 0.01$, $n = 28$ for the waterlogged habitat). In the organic wetland, CH_4 emission was not significantly correlated with the water table depth ($P > 0.05$), which was fairly stable throughout the sampling period (Fig. 1c,d).

During April–May 2005, CH_4 emission in the sandy wetland varied from 56.8 to 324.6 mg CH_4 m^{-2} d^{-1} in the wet meadow and from 27.0 to 452.6 mg CH_4 m^{-2} d^{-1} in the waterlogged habitat. For the organic wetland, CH_4 emission ranged from 17.7 to 88.4 mg CH_4 m^{-2} d^{-1} in the wet meadow and from 88.4 to 375.5 mg CH_4 m^{-2} d^{-1} in the waterlogged habitat.

Based on CH_4 flux measurements taken in June 2004 and May 2005 (the current study) and in July–October 2003 (Wang et al., 2005b), average monthly CH_4 emissions were obtained. Total wetland CH_4 emission was generalized at 791.0 kg CH_4 ha^{-1} y^{-1} during the period of from July 2003 to May 2005 (Table 3).

3.2. In situ CH_4 uptake by upland soils

CH_4 flux has been investigated widely in the upland grasslands of the Xilin River basin (Table 1). On average, the CH_4 uptake in grazed grasslands was approximately 68% of that in ungrazed grasslands and CH_4 uptake during the non-growing season was approximately half of that during the growing season. Integrated CH_4 flux rates ranged from −0.59 to −1.28 mg m^{-2} d^{-1} in grazed grasslands and from −0.82 to −1.89 mg m^{-2} d^{-1} in ungrazed grasslands, with the lowest rates in November to March and the highest rates in April to September (Table 3). In grazed grasslands the highest rates occurred in late summer, whereas in ungrazed grasslands the highest rates occurred in the spring. CH_4 uptake was approximately −3.3 and −4.8 kg CH_4 ha^{-1} y^{-1} in grazed and ungrazed grasslands, respectively (Table 3). In addition, it is assumed that upland farmlands and sandlands had the same CH_4 uptake rate as the grazed grasslands, −3.3 kg CH_4 ha^{-1} y^{-1} (Table 3).

3.3. CH_4 emission from ruminants

Baiyinxile Livestock Farm is a typical pasture that covers 3555 km^2, one-third of the Xilin River basin (total area, 10,786 km^2). We took this farm to be typical of the basin for ruminant intensity. Sheep, goats, and cattle are the dominant ruminants in the area. Census data indicate that the farm totally produced 23,874 head of cattle, 1,658,506 head of sheep, and 275,828 head of goats over 2004–2006 (Table 2). We estimate that annual grazing intensities averaged 1.59 SU ha^{-1} y^{-1}, with 1.09 and 2.09 SU ha^{-1} in the non-growing and growing seasons respectively. Estimated average annual CH_4 emission from ruminants was 8.6 kg ha^{-1} y^{-1} (Table 3).

3.4. CH_4 budget in the Xilin River basin

The area-weighted annual CH_4 fluxes in the Xilin River basin were estimated to be −3.45, 2.56 and 8.48 Gg y^{-1} (1 Gg = 10^9 g) in upland grasslands, small wetlands, and ruminants, respectively (Table 3). In addition to grasslands, upland farmlands and sandlands account for approximately 8.5% of the basin. If they had the same CH_4 uptake rate as the grazed grasslands, the additional CH_4 uptake would reduce the total net basin areal emission to 6.76 kg CH_4 ha^{-1} y^{-1}. Scaling to the entire basin gives a total annual CH_4

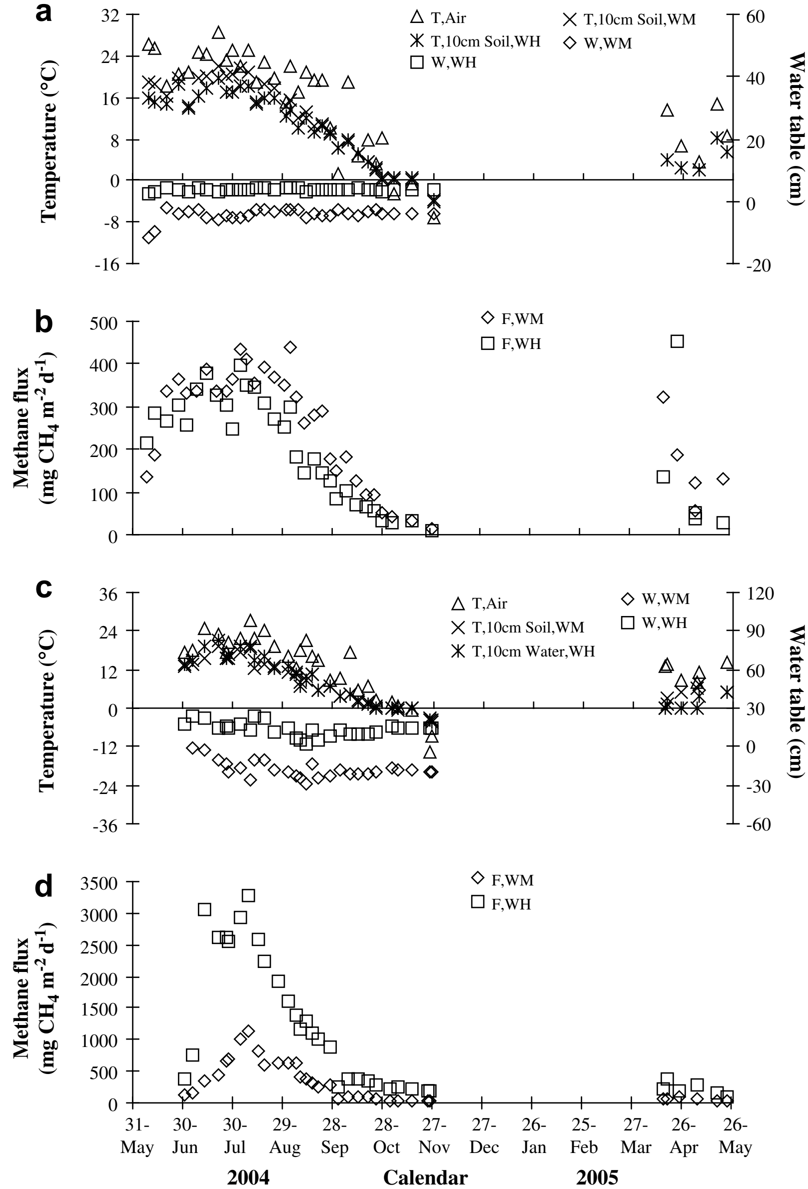

Fig. 1. Annual variations in temperature, water table, and daily average CH_4 flux ($n = 5$) in the small wetlands of the Xilin River basin during June 2004–May 2005 in the sandy (a, b) and organic (c, d) wetlands. Abbreviations: F (flux), T (temperature), W (water table), WM (wet meadow), WH (waterlogged habitat).

emission of 7.59 Gg y^{-1} without farmlands and sandlands, and 7.29 Gg y^{-1} with farmlands and sandlands.

4. Discussion

We have developed a CH_4 budget for the Xilin River basin in temperate Inner Mongolia based on census data and measurements for individual sources and sinks, including upland grasslands, small wetlands, and domestic ruminants. We assume that this typical grassland region is representative of cold temperate grasslands throughout Western China. Our results show that the temperate grasslands may be a net source of atmospheric CH_4 because the combined CH_4 emissions of small wetlands and grazing ruminants exceed the uptake of CH_4 by bacterial CH_4 oxidation in upland soils. This result is consistent with a simulated result by Bergamaschi et al. (2007), who identified a significant CH_4 source during the summer months in the general area of temperate Inner Mongolia via satellite retrieval and independent inversion modeling.

We judge that the greatest uncertainty in our budget calculation is the emission rate of CH_4 from small wetlands. CH_4 emission from wetlands can continue at low rates during the winter, even after the build-up of ice (Thomas et al., 1996). We did not conduct CH_4 measurements between December 2004 and March 2005 due to

Table 2
Current status of domestic ruminants at the Baiyinxile Livestock Farm.

Year	Ruminant (head)						Grazing intensity (SU ha^{-1})[a]		
	Growing season			Non-growing season			Growing season	Non-growing season	Annual
	Cattle	Sheep	Goat	Cattle	Sheep	Goat			
2004	7902	561569	99376	2047	286598	31350	2.13	0.96	1.54
2005	8620	555444	88975	6232	284946	56551	2.11	1.18	1.64
2006	7352	541493	87477	4942	292711	43160	2.02	1.12	1.57

[a] Grazing intensity for all types of ruminants normalized to sheep units (SU). The Baiyinxile Livestock Farm has an area of 3555 km^2.

Table 3
Annual budget of CH_4 in the Xilin River basin.

Component	Sub-component	Average CH_4 flux (mg CH_4 m^{-2} d^{-1})												Annual CH_4 flux (kg CH_4 ha^{-1} y^{-1})	Area (km^2)	Basin-wide flux (Gg CH_4 y^{-1})
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
Extensive upland	Grazed steppe	−0.69	−0.69	−0.59	−0.83	−0.88	−0.96	−1.04	−1.21	−1.28	−1.12	−0.69	−0.69	−3.3	8208.1	−2.67
	Ungrazed steppe	−0.82	−0.82	−1.04	−1.89	−1.77	−1.73	−1.74	−1.74	−1.37	−1.12	−0.82	−0.82	−4.8	1628.7	−0.78
	Farmland and sandland													−3.3[a]	916.8	−0.30
Small wetland		74.37	74.37	74.37	222.26	88.23	261.85	488.47	670.05	361.37	122.08	74.37	74.37	791.0	32.4	2.56
			Growing season					Non-growing season								
Grazed ruminants			3.10					1.61						8.6[b]	9836.8	8.48
Net flux																7.29

[a] Annual CH_4 flux is assumed to equal the flux rate in grazed steppe.
[b] CH_4 emission from grazed ruminants was calculated using the upland grassland area-equivalent.

cold weather (average monthly air temperature of from −22.1 to −7.7 °C) and site inaccessibility. We assumed that microbial CH_4 production and oxidation was stable throughout the winter. We used the average CH_4 emission rate observed in November with a temperature of −7.4 °C to infer the CH_4 emission during December-March. This approach may overestimate annual CH_4 emission slightly.

Some small wetlands in the Xilin River basin are ephemeral and their area varies from year to year. Drought is a recurring climate feature in arid and semi-arid lands (LeHouérou, 1996) and greatly reduces wetland CH_4 emission in a dry year. For example, in August and September 2004, CH_4 emission from the waterlogged habitat of the organic wetland was 2600.7 and 1208.1 mg CH_4 m^{-2} d^{-1}, respectively (Fig. 1d). This habitat dried up in summer 2005, when CH_4 emission was only 5.6 and 5.4 mg CH_4 m^{-2} d^{-1} in August and September, respectively (data not shown and not included in the CH_4 budget calculation). This difference between years demonstrates that temporarily drained wetlands are a small source of CH_4 and that the interannual variability of the CH_4 budget is likely to be greater than we have captured in this study. Additional monitoring is necessary to determine how variable the annual budget may be.

There are also uncertainties in our estimate of ruminant CH_4 emission. We used the average emission factors from Zhou et al. (2007), who estimated CH_4 emission from livestock in all of China. Because age class data were not available for ruminants in the Xilin River basin, we assumed that our age ratios were the same as those for all of China; until better census data become available for the area, we cannot determine whether this assumption tends to over- or underestimate ruminant CH_4 emission. The CH_4 emissions of ruminants may vary between non-growing and growing seasons based on the quality of feed and differences in temperature-related stress. In the non-growing season, domestic ruminants are often confined and fed grasses harvested from ungrazed steppe in the autumn. Feed quality therefore is not substantially different from the growing season. Lacking information about the effects of temperature stress on ruminant CH_4 emission from manure management in this region, we assumed that there was no significant difference in CH_4 emission factors between free-roaming and enclosed ruminants, as well as between summer and winter. The emission factors of Zhou et al. (2007) also include emissions from manure management. Since the Xilin River Basin is colder than average for all of China, these factors likely overestimate CH_4 emission from manure in our study site. However, since CH_4 emission from manure is a small fraction of total ruminant emission, the uncertainty associated with manure management is likely insignificant compared with other factors.

Since basin-wide CH_4 uptake by upland soils was larger than the estimated emission from small wetlands, the Xilin River basin would likely be a net CH_4 sink in the absence of ruminants. Based on our estimates, the Xilin River basin becomes a net source of atmospheric CH_4 above the compensation grazing intensity (the intensity at which the basin has a net zero flux) of 0.22 SU ha^{-1} y^{-1}. If we have overestimated wetland CH_4 emission as described above, then the compensation intensity would be slightly higher. However, since estimated ruminant CH_4 emission was 2–3 fold higher than the estimated upland uptake, and the recent annual grazing intensity (1.59 SU ha^{-1} y^{-1}) was almost eightfold higher than the estimated compensation intensity, the uncertainties in CH_4 flux calculation are not likely to be large enough to challenge our conclusion that the Xilin River basin is a strong net source of atmospheric CH_4 because of the farming of domestic ruminants.

Overgrazing is the primary cause of severe grassland degradation and associated dust storms in temperate Inner Mongolia. It is also the most important source of atmospheric CH_4 in this system because high-intensity ruminant grazing shifts the net ecosystem exchange of CH_4 from consumption to emission. Based on the 100-year global warming potential of CH_4 (IPCC, 2007), the annual forcing of CH_4 from the Xilin River basin is equivalent to 182 Mt CO_2.

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