JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, D13304, doi:10.1029/2004JD005548, 2005

Methane emission from small wetlands and implications for semiarid region budgets

Zhi-Ping Wang, Xing-Guo Han, Ling-Hao Li, and Quan-Sheng Chen
Laboratory of Quantitative Vegetation Ecology, Institute of Botany, Chinese Academy of Sciences, Beijing, China

Yi Duan
Lanzhou Institute of Geology, Chinese Academy of Sciences, Lanzhou, China

Wei-Xin Cheng
Department of Environmental Studies, University of California, Santa Cruz, California, USA

Received 26 October 2004; revised 3 February 2005; accepted 6 April 2005; published 12 July 2005.

[1] Despite considerable research, large uncertainties exist in the various area-scales budgets of CH_4 flux between soils and the atmosphere. We postulated that small wetlands greatly contribute to the CH_4 budget in semiarid regions, where wetland contributions are often assumed to be insignificant. To test this hypothesis, small riparian mires of the Xilin River basin in Inner Mongolia were selected as a case study for weekly measurements of in situ CH_4 flux. Average CH_4 fluxes were 234.3 and −1.9 mg CH_4 m^{-2} d^{-1} for the riparian mires and the upland grassland, respectively, during July–October 2003. Although the riparian mires cover only 0.4% of the Xilin River basin, their total CH_4 emission was about half of the amount of CH_4 consumed by the upland grassland with 89.7% land cover ratio. Our results indicate that estimated CH_4 budgets for semiarid regions should include an assessment of small wetlands.

Citation: Wang, Z.-P., X.-G. Han, L.-H. Li, Q.-S. Chen, Y. Duan, and W.-X. Cheng (2005), Methane emission from small wetlands and implications for semiarid region budgets, *J. Geophys. Res.*, *110*, D13304, doi:10.1029/2004JD005548.

1. Introduction

[2] Methane (CH_4) is an important greenhouse gas with both natural and anthropogenic sources. Although the major contributors to the global CH_4 budget have been generally identified, most of them remain uncertain quantitatively [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. Natural wetlands are a highly variable source for CH_4 emission, and a large uncertainty exists in the estimated CH_4 budget for these ecosystems.

[3] There are increasing numbers of studies for CH_4 flux on natural wetlands [cf. *Bartlett and Harriss*, 1993; *Rask et al.*, 2002; *Juutinen et al.*, 2003; *Nykänen et al.*, 2003]. To our knowledge, however, most of these measurements have been taken from landscapes where extensive or clustered wetlands comprise a substantial proportion of the total land area. In contrast, little information exists about soil/atmosphere exchange of CH_4 from small wetlands. On the Earth's surface, there are scattered numerous small natural wetlands (usually scaling from less than 100 m^2 to thousands of square meters) such as riparian mires in semiarid grasslands, oases in arid desert regions, bogs in savannas and shrublands, pools in plains, and ravines in forests. *DeFries et al.* [1998] reported that woodlands, savannas, shrublands, and grasslands cover about 40% of the Earth's surface. Because of their predominately well drained soils, these semiarid systems are usually considered to be strong sinks for atmospheric CH_4. However, the ecosystems also include ubiquitous small patches of natural wetlands, scattered in areas of low relief and poor drainage. If CH_4 flux from these small wetlands is substantial, then the uptake of atmospheric CH_4 by soils in semiarid regions may be overestimated in current budget estimates.

[4] The general objective of this study was to determine whether it is necessary to account for the contributions of small wetlands in the Xilin River basin for assessing the overall CH_4 budget of the region. Hence we carried out field measurements of CH_4 flux in riparian mires and adjacent uplands on the Xilin River basin. We then developed an area-adjusted assessment of the contribution of small wetlands to the total CH_4 budget of the upland grassland-dominated Xilin River basin.

2. Materials and Methods

2.1. Site Descriptions

[5] This work was carried out in the Xilin River basin (43°26′–44°39′N, 115°32′–117°12′E; 902–1506 m above sea level (asl), 10,786 km^2) in the eastern Inner Mongolia Plateau (Figure 1). This region belongs to the semiarid temperate climatic zone. The mean annual temperature is approximately 0.6°C. The coolest monthly temperature is −21.4°C, in January, and the warmest is 18.5°C, in July. The mean annual precipitation is about 350 mm, with the

0148-0227/05/2004JD005548$09.00

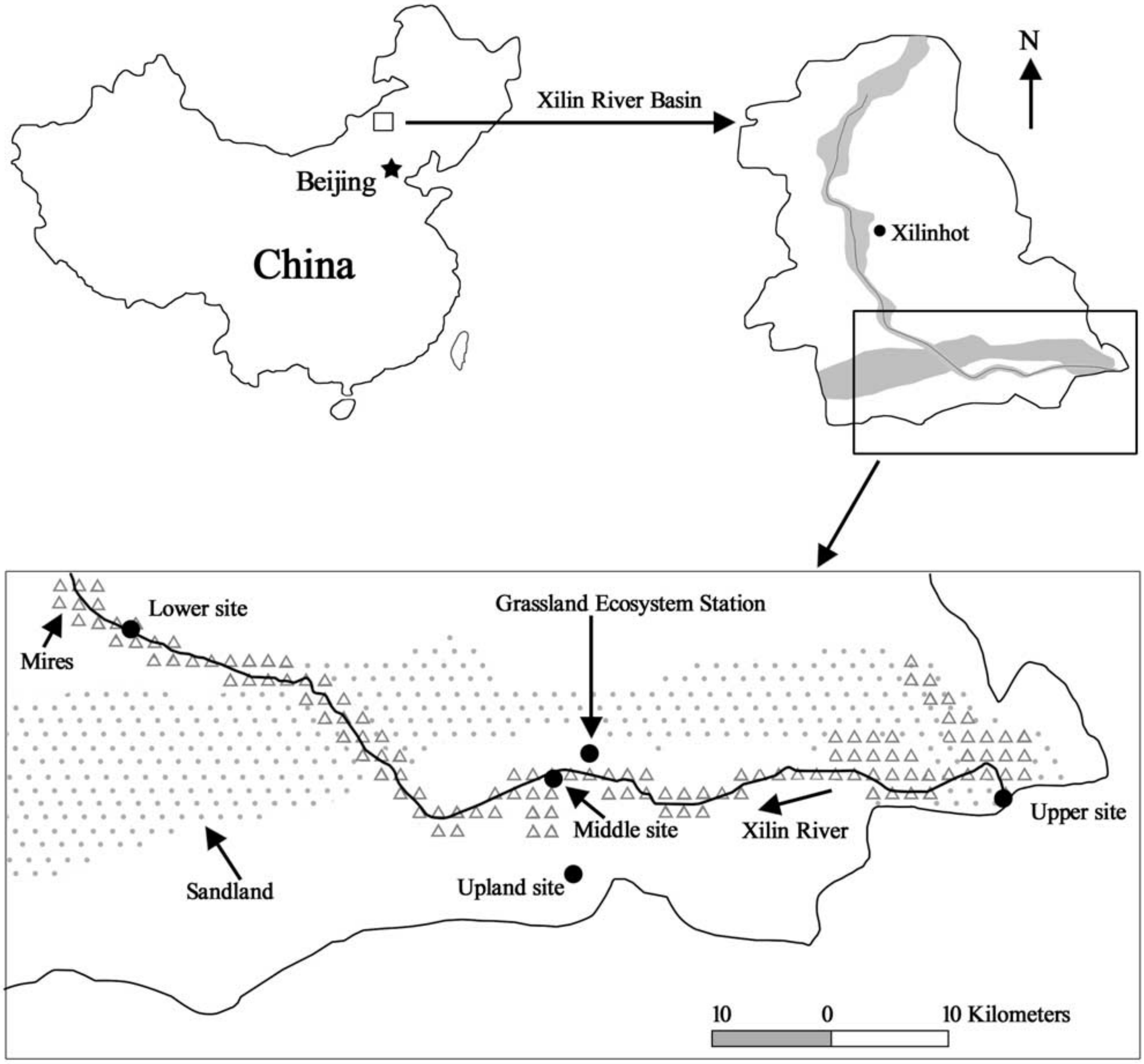

Figure 1. Geographic location of the study region and sampling sites.

rainy season between June and September. Approximately 10% of annual precipitation falls as snow in winter.

[6] The 175-km Xilin River is one of the major inland streams in the Inner Mongolia Plateau. On average, its flow rate is roughly 0.91 $m^3 s^{-1}$, its water depth is 0.29 m, and its annual runoff is 2.9×10^7 m^3. Because of the cool plateau climate and sufficient water availability, numerous small wetlands have developed along the river's banks. Three riparian mire sites along the Xilin River, dominantly composed of *Carex*, *Juncus wallichianus* Laharpe, *Blysmus sinocompressus* Tang et Wang, and *Agrostis divaricatissima* Mez. were selected for measurements of CH_4 flux. For the riparian mires, there is a high degree of spatial variability in the peat content of the sediments. In the upper site, the sediment is predominantly sand with a minor peat content. In the middle and lower sites, there are higher peat contents, with depths reaching up to 1 m. Previous studies on CH_4 flux in the Xilin River basin focused on upland grasslands due to their dominant landscape [*Du et al.*, 1997; *Wang et al.*, 1998; *Dong et al.*, 2000; *Wang et al.*, 2000]. Therefore only one upland grassland site, the popular grazing *Leymus chinensis–Stipa grandis* steppe, was sampled for a contemporaneous comparison (Figure 1).

2.2. In Situ Measurement of CH_4 Flux

[7] Methane flux was determined using a closed-chamber technique. Six bases were installed at each site along two gentle slope transects. Each base, a 25-cm-tall grey polyvinyl chloride (PVC) pipe (30 cm in inner diameter), was driven 15 cm into the soil 1 week prior to the formal experiment and was left in place throughout the study. For each riparian site the bases were installed on two contrasting habitats, hummock and hollow, with three bases for each habitat. On the basis of a visual survey, each habitat accounts for roughly half of the wetland area. The vegetation inside and outside the bases was not noticeably

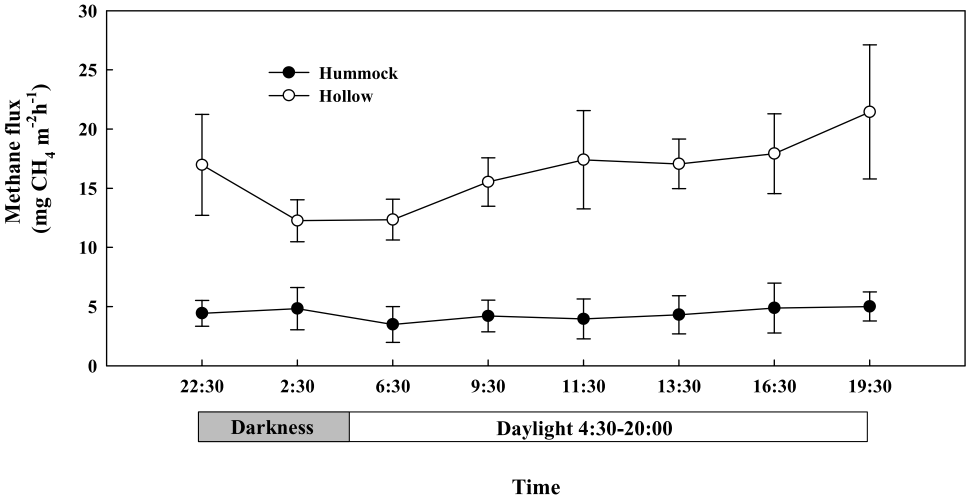

Figure 2. Diurnal variation in CH_4 emissions from the middle site during 21–22 July 2003.

different. Because of unique habitat properties, adjacent hummocks may be used as a natural boardwalk for taking samples. The PVC chamber (35 cm height) was sealed to the base using a 6-cm-wide rubber ring. Care was taken not to physically disturb the sediments below the chambers. A butyl rubber stopper (20 mm diameter) was inserted through the top center of the chamber for sampling by syringe. The chamber was covered with aluminum foil to minimize heating. We selected the middle mire site as a case diurnal measurement during 21–22 July (Figure 2). Diurnal CH_4 emissions averaged 4.38 and 16.36 mg CH_4 m^{-2} h^{-1} (i.e., 105.1 and 392.7 mg CH_4 m^{-2} d^{-1}) (n = 3) at the hummock and hollow habitats, respectively. For the hollow, the highest flux rate appeared at 1900–2000 LT, the lowest flux in early morning. However, there existed no significant diurnal flux variation at the hummock. On a diurnal flux basis, CH_4 emission at time interval of 0900–1000 or 1600–1700 LT may approximately reflect the average status over a 24-hour cycle. Hence we selected the initial linear portion of 0–30 min within the time interval of 0900–1000 LT or 1600–1700 LT on each sampling occasion to determine CH_4 flux.

[8] Headspace gas samples were taken with 100-mL polypropylene syringes fitted with three-way nylon stopcocks and then transferred immediately to 0.5-L gas bags. Before gas samples were transferred to bags, the soft bags were vacuumed. The CH_4 concentration was determined by gas chromatography (GC) within 1 week of sampling. The GC was a Hewlett Packard 5890 Series II equipped with an injection loop, a flame-ionization detector operated at 200°C and a 2-m stainless steel column packed with 13 XMS (60/80 mesh). The column oven temperature was 55°C, and the carrier gas was N_2 with a flow rate of 30 mL min^{-1}. Certified CH_4 standard in 9.39 μl L^{-1} (China National Research Center for Certified Reference Materials, Beijing) was used for calibration.

2.3. Determination of Soil Physico-Chemical Factors

[9] The 0–20 cm peat/soils for background analyses were sampled and minimally processed in early September 2003, and then temporarily stored in polypropylene bags in the dark at 4°C prior to assay. Soil characteristics were determined following standard procedures [after *Liu*, 1996; *Wang et al.*, 2004]. NH_4^+ and NO_3^- were extracted by adding 10 g fresh soil to 50 mL 2-M KCl and shaking for 1 hour. NH_4^+ and NO_3^- concentrations were measured colorimetrically by an automated flow injection analyzer (FIAstar 5000, FOSS). Soil pH was determined by shaking 5 g of air-dried soil (1 mm sieved) in 25-mL deionized water, using a glass combination electrode (PH B-4, Leici Ltd., Shanghai). Total C was determined using the combustion method. First, 5 mL 0.8-M $K_2Cr_2O_7$ solution and 5 mL H_2SO_4 were added into the weighed soil and then boiled at 170–180°C for 5 min, and then the remaining $K_2Cr_2O_7$ was titrated using 0.2-M $FeSO_4$. Total N was determined by the Semi-micro Kjeldahl method, using Kjeltec System, 1026 Distilling Unit (Tecator, S-263 21 Höganäs, Sweden). Site soil characteristics are listed in Table 1.

2.4. Calculations and Statistical Analyses

[10] The CH_4 flux was calculated using the CH_4 concentration change in the chamber headspace according to the equation of *Parashar et al.* [1993] and *Singh et al.* [1996]. The significance of differences was assessed by analysis of variance using the SAS program [*SAS Institute*, 1999].

3. Results and Discussion

3.1. Variation of Net CH_4 Emission From Riparian Mires

[11] Methane fluxes in the riparian mires averaged 234.3 mg CH_4 m^{-2} d^{-1} throughout the measurement period, but varied by 2–3 orders of magnitude. Similar results have been reported for other freshwater mires [*Singh et al.*, 2000; *Rask et al.*, 2002; *Ding et al.*, 2004]. Because the chambers were installed along a transect from the edge to the center of mire, there was a systematic spatial variation in CH_4 emission of the parallel chambers (Figures 3b, 3c, and 3d). By capturing this variation, we are confident that we obtained representative average values for CH_4 flux from each mire site. Generally, the middle site exhibited the highest flux rates, followed by the lower site and then the upper site (Table 1). Soil factors generally differed significantly ($P < 0.05$) among the riparian mire sites. Hence the disparity in CH_4 flux among sites probably resulted partly

Table 1. Characteristics of Soils and Flux Rates of CH_4 From Each Site

			Soil Analysis						Methane Flux Rate, mg CH_4 m^{-2} d^{-1}		
Ecosystem	Site	Habitat	pH	Soil Type	Total N, g kg^{-1}	Total Organic C, %	NH_4^+-N, μg (gram dry weight)$^{-1}$	NO_3^-N, μg (gram dry weight)$^{-1}$	Mean[a]	Standard Error	Range
Riparian mires	upper	hummock	8.5	sandy	0.5 (d)	0.4 (d)	2.1 (d)	0.2 (d)	132.2 (c, b)	52.1	26.4–277.2
		hollow	8.7	sandy	0.5 (d)	0.6 (d)	2.3 (d)	0.3 (d)	244.2 (b)	81.0	38.2–464.9
	middle	hummock	7.4	organic	13.9 (a)	19.9 (a)	22.9 (b)	2.5 (b)	108.8 (c)	60.8	12.2–192.7
		hollow	7.0	organic	13.2 (a)	20.8 (a)	33.9 (a)	4.2 (a)	487.6 (a)	147.2	60.2–1243.9
	lower	hummock	8.7	organic	6.1 (c)	7.5 (c)	9.2 (c)	1.2 (c)	28.3 (c)	15.5	4.6–101.3
		hollow	8.0	organic	9.0 (b)	12.1 (b)	33.6 (a)	3.0 (b)	404.5 (a)	188.1	67.0–777.8
Upland grassland		drained	7.4	chestnut soil	1.6	1.8	4.2	1.5	−1.9	0.4	−0.8 to −3.3

[a] Methane flux rate is mean of 15–16 occasions for mean and SE at the riparian mire sites. Mean values ($n = 3$) are shown for soil variables. Means with different letters (a, b, c, d) identify significant differences ($P < 0.05$) between the riparian mire habitats using Duncan's multiple range test.

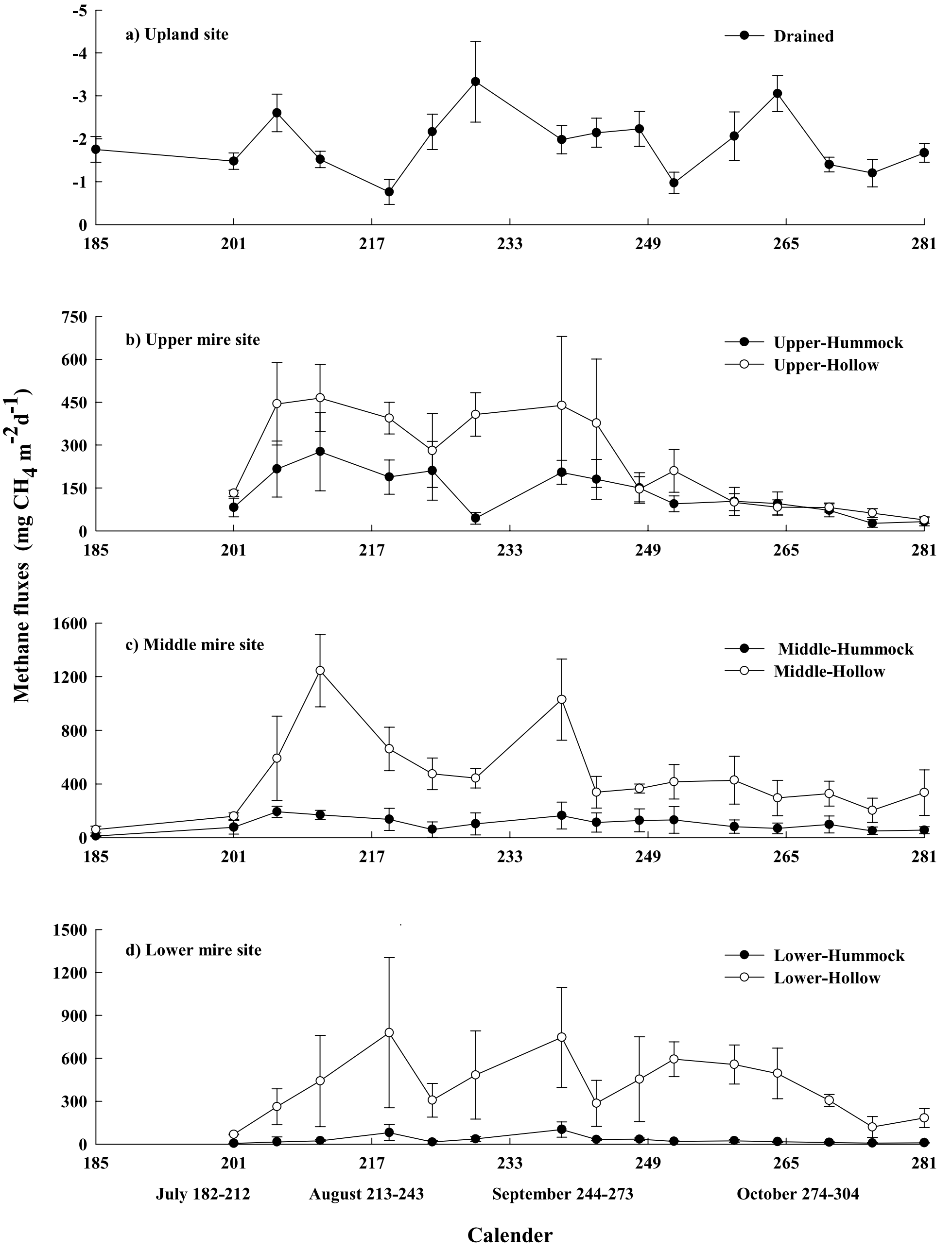

Figure 3. Temporal variation in methane flux at the sampling sites.

from differences in soil characteristics. For instance, the amount of total N and organic C in the soils corresponded roughly with the mean rates of CH_4 emission from mire hollows in the three riparian sites (Table 1).

[12] At the three riparian sites, the maximal flux rates occurred during middle to late summer, with a temporary decrease during mid-August; in the only lower site hollow, flux rates peaked again during September (Figures 3b, 3c, and 3d). Low rates occurred during early July and in October (Figures 3b, 3c, and 3d). Daily average air temperatures at the Grassland Ecosystem Station (Figure 1) correlated significantly with CH_4 fluxes at the upper site (R^2 = 0.4739 for hummock, 0.5888 for hollow; n = 15; $P < 0.01$) and the middle site (R^2 = 0.3623 for hummock, 0.2487 for hollow; n = 16; $P < 0.1$) during July–October 2003. The strong correlation at the upper site probably resulted from the high sensitivity of sandy soils to temperature. Because the lower site was located in the basin area, in addition to temperature, other factors such as microtopography and vegetation characteristics might have exerted great controls on CH_4 flux. On the basis of a preliminary visual survey, the primary productivity was higher in the lower site than in the other two riparian sites. Vegetation is important in CH_4 transport from sediments to the atmosphere and provides substrates for methanogenesis [*Saarnio et al.*, 1997; *Singh et al.*, 2000]. Hence, in addition to differences in soil and climate characteristics, vegetation differences may have been a key factor determining variation of CH_4 flux, including temporal dynamics, among the sites.

[13] For the middle and lower sites, CH_4 emission from hollows was significantly larger ($P < 0.05$) than that from hummocks (Table 1). Since the riparian mires were usually grazed and breached by the local cattle and sheep, together with lower air pressure in the Inner Mongolia Plateau when compared to sea level, the portion of CH_4 accumulated inside hollows was easily released to the atmosphere in the form of bubbles. The large difference between replicates in hollows was probably at least partly derived from bubbles. Oxidation of CH_4 by methanotrophic bacteria during diffusion to the atmosphere is postulated to be a major CH_4 removal mechanism in oxic soils [*Yavitt et al.*, 1988]. Since the hummocks emerge above the water table, they present an oxic upper horizon in which a portion of CH_4 should be oxidized during diffusion to the atmosphere.

[14] Although the upper mire site emitted less overall CH_4 than the other two mire sites, it actually emitted more CH_4 from its hummock habitat than did the other two sites, even though it had the lowest organic carbon content. As a result, there was no significant difference ($P > 0.05$) between the hummock and hollow habitats within this site (Table 1). The upper site was an overlapping area of wetland and sand land. Because the soil was sandy, there was a relatively small elevation difference between hummocks and hollows and water was easily permeable between them. Also, gases likely diffused more quickly in the sandy soils compared with the peaty soils. Hence there was probably less CH_4 oxidized in the sandy hummocks during diffusion to the atmosphere compared with hummocks at the other two sites. Although the upper site had very low soil organic matter content, its strong CH_4 emission probably derived mainly from turnover of recently photosynthesized carbon. Using an isotopic approach, *Chanton et al.* [1995] demonstrated that a large fraction of the organic material that supports methanogenesis is indeed derived from recently fixed carbon.

3.2. Implications for CH_4 Budget of the Xilin River Basin

[15] Methane uptake on the upland grassland averaged -1.9 mg CH_4 m^{-2} d^{-1}, ranging from -0.8 to -3.3 mg CH_4 m^{-2} d^{-1} during July–October 2003 (Figure 3a; Table 1). This result was consistent with previous measurements on upland grasslands of the Xilin River basin [*Du et al.*, 1997; *Wang et al.*, 1998; *Dong et al.*, 2000; *Wang et al.*, 2000] and thus provided a reliable comparison with CH_4 flux at the riparian sites.

[16] On an area basis, average CH_4 emission at the riparian mires was approximately 2 orders of magnitude higher than CH_4 uptake on the upland grassland (Table 1). On the basis of land cover percentages (Figure 4a) and average CH_4 fluxes (Figure 4b), total CH_4 fluxes were estimated to be 10.1 and -18.4 Mg CH_4 day^{-1} for the small wetlands and large upland grassland, respectively, of the Xilin River basin over July–October 2003 (Figure 4c). Although the riparian wetlands cover only 0.4% of the Xilin River basin, their total CH_4 emission was about half of CH_4 uptake by the upland grassland, which covered 89.7% of the basin area. This contribution of wetland habitats was probably a conservative estimate, because we did not consider contributions from water body and wet meadow habitats, which accounted for about 1% of the land cover. Together with CH_4 release from sheep and cattle, it is possible that the Xilin River basin as a whole is a net source of CH_4 to the atmosphere. This hypothesis requires further works to test.

3.3. Implications for CH_4 Budgets of Semiarid Regions of China and the World

[17] When compared with high-latitude boreal and low-latitude tropical regions, extended natural wetlands are scarce in China. An important category of natural wetlands is widely distributed in the form of small wetlands such as riparian mires in semiarid regions. In China, there are over 50,000 rivers with individual river basin areas larger than 100 km^2, and there are numerous small streams that are not well documented [*China National Forestry Bureau*, 2000]. At present, detailed area inventories are not available for natural wetlands of China. Therefore there are profound implications for how small wetlands affect the CH_4 budget of China.

[18] Our sampling sites are located in the center of the semiarid region of China, predominantly covered by upland grasslands, in which numerous small patches of natural wetlands are scattered in areas of low relief and poor drainage. The semiarid temperate regions of China cover $1.75–2.59 \times 10^6$ km^2, accounting for 18.2–27% of the territory of China [*Qu et al.*, 1990; *Zhao et al.*, 1990]. Assuming the flux rates we measured were typical, we estimated CH_4 emission from natural wetlands of semiarid temperate regions to be 0.27–0.79 Tg yr^{-1} (assuming 0.4–0.8% land cover ratio and 160–165 days of thaw season), with an average of 0.53 Tg yr^{-1}. Semiarid temperate grasslands represent a significant global sink for CH_4 [*Mosier et al.*, 1991]. Our results suggest that this large

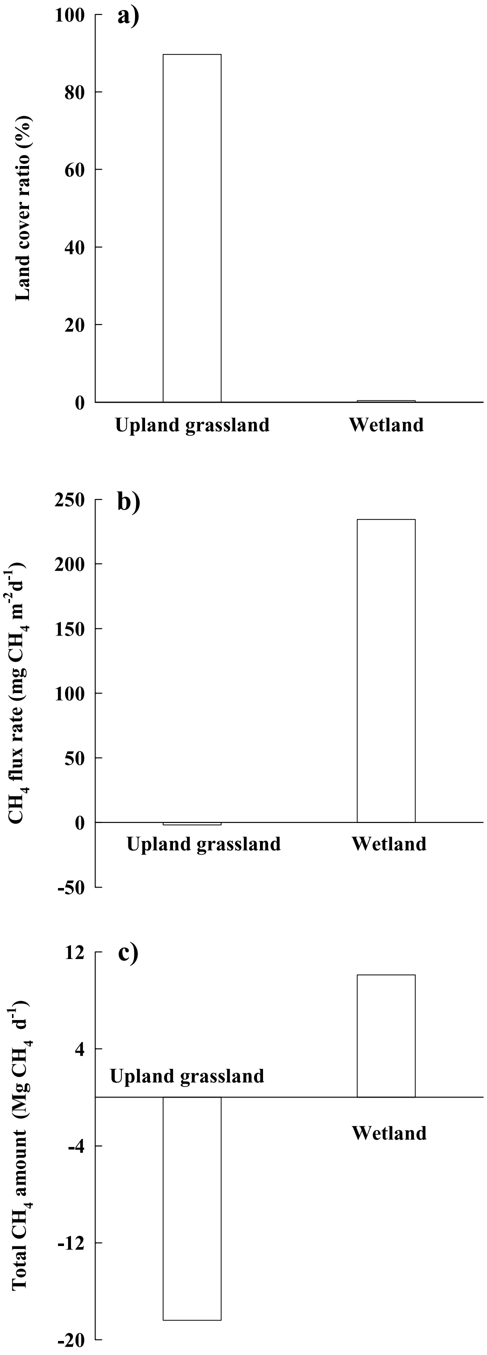

Figure 4. Methane fluxes in two contrasting ecosystems in the Xilin River basin.

CH_4 sink can be offset considerably by CH_4 emission from small wetlands scattered among the extensive uplands.

[19] The average CH_4 emission rate for riparian mires in this study (234.3 mg CH_4 m^{-2} d^{-1}) was at the upper end of the range reported from previous studies of natural wetlands in China [e.g., *Cui*, 1997; *Jin et al.*, 1999; *Wang et al.*, 2002; *Ding et al.*, 2004], but was much larger than the average flux rates of 70–135 mg CH_4 m^{-2} d^{-1} from temperate mires outside China [cf. *Bartlett and Harriss*, 1993]. If our result is considered in the calculation of CH_4 emission from natural wetlands of China, total flux is probably larger than the latest estimate of 1.76 Tg CH_4 yr^{-1} [*Ding et al.*, 2004]. With additional field measurements of CH_4 flux, together with more information on wetland areas, an improved assessment of CH_4 emission from natural wetlands of China may be possible. Evidently, obtaining data from poorly studied small wetlands will be an important step in refining the CH_4 budget for China.

[20] Our results suggest that small wetlands significantly contribute to total CH_4 budget in semiarid regions and that neglecting their contributions may yield severe overestimates of the strength of semiarid CH_4 sinks. Hence small wetlands have a potential role as a CH_4 emission source to help reconcile some of the uncertainties in the country-specific CH_4 budget. Because small wetlands have a higher temporal-spatial variability of CH_4 flux affected by environmental factors when compared with extensive natural wetlands [cf. *Bartlett and Harriss*, 1993], estimating the size of this potentially large but poorly quantified CH_4 source will probably be a challenging task. Nevertheless, the low land cover ratios of small wetlands in semiarid regions should not be construed as justification for neglecting their contributions to regional and country-specific CH_4 budgets.

[21] **Acknowledgments.** This work was supported by grants from The National Key Basic Research Support Foundation (NKBRSF) of China (G 2000018603) and the K. C. Wong Education Foundation, Hong Kong. Jay Gulledge, Shi-Qiang Wan, and anonymous reviewers and editors are much thanked for their constructive comments and revisions.

References

Bartlett, K. B., and R. C. Harriss (1993), Review and assessment of methane emissions from wetlands, *Chemosphere*, *26*, 261–320.

Chanton, J. P., J. E. Bauer, P. A. Glaser, D. I. Siegel, C. A. Kelley, S. C. Tyler, E. H. Romanowicz, and A. Lazrus (1995), Radiocarbon evidence for the substrates supporting methane formation within northern Minnesota peatlands, *Geochim. Cosmochim. Acta*, *59*, 3663–3668.

China National Forestry Bureau (Ed.) (2000), *China National Wetlands Conservation Action Plan*, pp. 1–6, China For. Press, Beijing.

Cui, B. S. (1997), Estimation of methane emission from marshland in the plain of northeastern China (in Chinese), *Sci. Geogr. Sinica*, *17*, 93–95.

DeFries, R. S., M. Hansen, J. R. G. Townshend, and R. Sohlberg (1998), Global land cover classifications at 8 km spatial resolution: The use of training data derived from Landsat imagery in decision tree classifiers, *Int. J. Remote Sens.*, *19*, 3141–3168.

Ding, W. X., Z. C. Cai, and D. X. Wang (2004), Preliminary budget of methane emissions from natural wetlands in China, *Atmos. Environ.*, *38*, 751–759.

Dong, Y. S., S. Zhang, Y. C. Qi, Z. Z. Chen, and Y. B. Geng (2000), Fluxes of CO_2, N_2O and CH_4 from a typical temperate grassland in Inner Mongolia and its daily variation, *Chin. Sci. Bull.*, *45*, 1590–1594.

Du, R., G. X. Chen, D. R. Lu, and G. C. Wang (1997), The primary research on in situ measurements of N_2O and CH_4 fluxes from the Inner Mongolia grassland ecosystem (in Chinese), *J. Clim. Environ. Res.*, *2*, 264–272.

Intergovernmental Panel on Climate Change (2001), *Climate Change 2001: The Scientific Basis*, edited by J. H. Houghton et al., 42 pp., Cambridge Univ. Press, New York.

Jin, H. J., J. Wu, G. D. Cheng, N. Tomoko, and G. Y. Sun (1999), Methane emissions from wetlands on the Qinghai-Tibet Plateau, *Chin. Sci. Bull.*, *44*, 2282–2286.

Juutinen, S., J. Alm, T. Larmola, J. T. Huttunen, M. Morero, P. J. Martikainen, and J. Silvola (2003), Major implication of the littoral zone for methane release from boreal lakes, *Global Biogeochem. Cycles*, *17*(4), 1117, doi:10.1029/2003GB002105.

Liu, G. S. (1996), *Soil Physical and Chemical Analysis and Description of Soil Profiles* (in Chinese), China Stand. Press, Beijing.

Mosier, A., D. Schimel, D. Valentine, K. Bronson, and W. Parton (1991), Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands, *Nature*, *350*, 330–332.

Nykänen, H., J. E. P. Heikkinen, L. Pirinen, K. Tiilikainen, and P. J. Martikainen (2003), Annual CO_2 exchange and CH_4 fluxes on a subarctic palsa mire during climatically different years, *Global Biogeochem. Cycles*, *17*(1), 1018, doi:10.1029/2002GB001861.

Parashar, D. C., P. K. Gupta, J. Rai, R. C. Sharma, and N. Singh (1993), Effect of soil temperature on methane emission from paddy fields, *Chemosphere*, *26*, 247–250.

Qu, Z., Y. F. Qian, and Y. G. Zhang (1990), The distribution of arid regions in China, in *Studies on Climate and Environment in Arid- and Semi-arid Regions of China and Their Exploitations* (in Chinese), edited by J. F. Li, pp. 16–23, China Meteorol. Press, Beijing.

Rask, H., J. Schoenau, and D. Anderson (2002), Factors influencing methane flux from a boreal forest wetland in Saskatchewan, Canada, *Soil Biol. Biochem.*, *34*, 435–443.

Saarnio, S., J. Alm, J. Silvola, A. Lohila, H. Nykanen, and P. J. Martikainen (1997), Seasonal variation in CH_4 emissions and production and oxidation potentials at microsites on an oligotrophic pine fen, *Oecologia*, *110*, 414–422.

SAS Institute (1999), *SAS/STAT™ User's Guide Release 8.0 Edition*, Cary, N. C.

Singh, J. S., S. Singh, A. S. Raghubanshi, S. Singh, and A. K. Kashyap (1996), Methane flux from rice/wheat agroecosystem as affected by crop phenology, fertilization and water level, *Plant Soil*, *183*, 323–327.

Singh, S. N., K. Kulshreshtha, and S. Agnihotri (2000), Seasonal dynamics of methane emission from wetlands, *Chemosphere Global Change Sci.*, *2*, 39–46.

Wang, D. X., X. G. Lu, W. X. Ding, Z. C. Cai, J. F. Gao, and F. M. Yang (2002), Methane emission from marshes in Zoige plateau (in Chinese), *Adv. Earth Sci.*, *17*, 877–880.

Wang, G. C., R. Du, Y. F. Wang, and G. R. Liu (1998), Characteristics of N_2O and CH_4 fluxes and their seasonal variations from Inner Mongolia grassland (in Chinese), *Acta Agrestia Sin.*, *6*, 306–311.

Wang, Y. F., B. M. Ji, Z. Z. Chen, and O. Dennis (2000), Preliminary results of a study on CH_4 flux in Xilin river basin steppe under different grazing intensities (in Chinese), *Acta Phytoecol. Sin.*, *24*, 693–696.

Wang, Z. P., Y. Duan, J. R. Yang, L. H. Li, and X. G. Han (2004), Plateau marsh methane oxidation as affected by inorganic N, *Pedosphere*, *14*, 195–204.

Yavitt, J. B., G. E. Lang, and D. M. Downey (1988), Potential methane production and methane oxidation rates in peatland ecosystems of the Appalachian Mountains, United States, *Global Biogeochem. Cycles*, *2*, 253–268.

Zhao, S. Q., L. P. Yang, and Q. Y. Yang (1990), *Arid Regions in China* (in Chinese), 1 p., China Sci. Press, Beijing.

Q.-S. Chen, X.-G. Han, L.-H. Li, and Z.-P. Wang, Laboratory of Quantitative Vegetation Ecology, Institute of Botany, Chinese Academy of Sciences, Nanxincun 20, Xiangshan, Beijing 100093, China. (wangzp5@yahoo.com)

W.-X. Cheng, Department of Environmental Studies, University of California, Santa Cruz, CA 95064, USA.

Y. Duan, Lanzhou Institute of Geology, Chinese Academy of Sciences, Lanzhou 730000, China.