Surface methane emissions from different land use types during various water levels in three major drawdown areas of the Three Gorges Reservoir

Le Yang,[1,2] Fei Lu,[1] Xiaoke Wang,[1] Xiaonan Duan,[3] Wenzhi Song,[1] Binfeng Sun,[1,2] Shuai Chen,[1,2] Qianqian Zhang,[1,2] Peiqiang Hou,[1,2] Feixiang Zheng,[1] Ye Zhang,[1] Xiaoping Zhou,[1,2] Yongjuan Zhou,[1] and Zhiyun Ouyang[1]

Received 25 December 2011; revised 26 March 2012; accepted 28 March 2012; published 24 May 2012.

[1] Methane (CH_4) emissions from the drawdown area of the Three Gorges Reservoir (TGR) have not been thoroughly investigated even though the drawdown area encompasses one third of the reservoir surface. In this study, CH_4 emissions from different land uses were measured in the TGR drawdown area. The average diffusive CH_4 emissions were 2.61, 0.19, 0.18, and 0.12 mg CH_4 m^{-2} h^{-1} in rice paddies, fallow lands, deforested lands, and croplands, respectively, and were positively related to the duration of the inundated season among the latter three land uses. On average the drawdown areas studied here (except rice paddies) were sources in the inundated season (0.22 ± 0.26 mg CH_4 m^{-2} h^{-1}) and a sink in the drained season (-0.008 ± 0.035 mg CH_4 m^{-2} h^{-1}). The water level was the dominant factor that controlled whether the drawdown area was either inundated or drained, which in turn determined whether the drawdown area was a source or sink of CH_4 emissions. The average diffusive CH_4 emissions from the fallow lands, croplands, and deforested lands increased as the distance from the dam increased from Zigui (0.10 ± 0.15 mg CH_4 m^{-2} h^{-1}) to Wushan (0.15 ± 0.29 mg CH_4 m^{-2} h^{-1}) to Yunyang (0.24 ± 0.27 mg CH_4 m^{-2} h^{-1}), which could reflect different sediment characteristics and water velocities. The total CH_4 emission from the drawdown area was estimated to range from 1033.5 to 1333.9 Mg CH_4 yr^{-1}, which would account for 42–54% of the total CH_4 emissions from the water surface of TGR.

Citation: Yang, L., et al. (2012), Surface methane emissions from different land use types during various water levels in three major drawdown areas of the Three Gorges Reservoir, *J. Geophys. Res.*, *117*, D10109, doi:10.1029/2011JD017362.

1. Introduction

[2] Methane (CH_4) is the second most abundant greenhouse gas in the atmosphere, with a relative contribution of about 20% of the greenhouse effect, second only to carbon dioxide (CO_2) [*Wuebbles and Hayhoe*, 2002]. At the molecular level, however, CH_4 can absorb infrared radiation 22 times more efficiently than CO_2 over 100 years, thus making it one of the most potent greenhouse gases [*Zhuang et al.*, 2009]. The atmospheric CH_4 concentration has more than doubled in the past two centuries [*Frankenberg et al.*, 2005], which is mainly attributed to the effects of fossil fuel combustion, waste management, enteric fermentation, the incineration of biomass, and agricultural and natural wetlands [*St. Louis et al.*, 2000; *Marani and Alvalá*, 2007]. While not officially acknowledged, artificial reservoirs have been recognized as an important anthropogenic source of CH_4 [*Duchemin et al.*, 1995; *Soumis et al.*, 2004; *Abril et al.*, 2005], with global estimates of 4 Tg yr^{-1} for CH_4 or 6% of the total emissions from natural lakes [*Barros et al.*, 2011].

[3] Several studies have measured CH_4 emissions from the water surfaces of reservoirs located in boreal, temperate, and tropical regions [*Huttunen et al.*, 2002; *Abril et al.*, 2005; *Demarty et al.*, 2009]; however, few reports are available on CH_4 emissions from drawdown areas [*Chen et al.*, 2009, 2011; *Lu et al.*, 2011]. The drawdown area is the vegetated (or cleared) littoral zone at the edge of the reservoir that experiences cycles between inundation and drainage based on water level of the reservoir, due to seasonal cycles or hydroelectric operations. The drawdown areas in reservoirs are considered "hotspot" zones for CH_4 emission [*Juutinen et al.*, 2001; *Chen et al.*, 2009]. Narrow littoral zones may even support most of the lake-wide CH_4 release during open water season [*Bergström et al.*, 2007], as

[1]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China.
[2]Graduate University of Chinese Academy of Sciences, Beijing, China.
[3]General Office of Chinese Academy of Sciences, Beijing, China.

Corresponding author: F. Lu, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China. (lu_fei@yahoo.cn)

0148-0227/12/2011JD017362

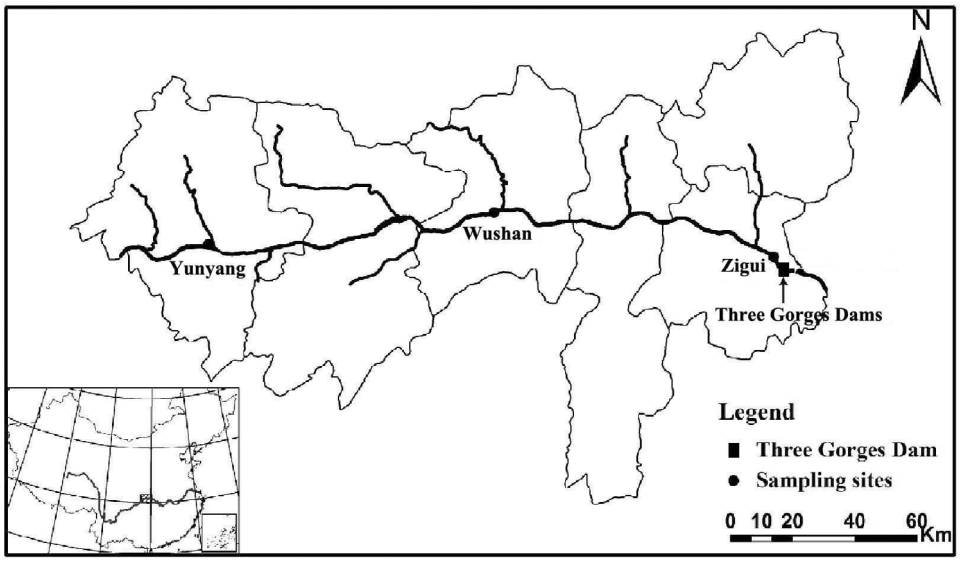

Figure 1. Location of the sampled sites and plots.

was seen in other studies [*Juutinen et al.*, 2003a, 2003b]. Thus drawdown areas are potentially important CH_4 emission sources and contribute to any spatial variability observed in emissions.

[4] A previous study on the Three Gorges Reservoir (TGR) has already shown that newly created marshes in the drawdown area are important CH_4 emitters [*Chen et al.*, 2009]. However, only 11% of the TGR drawdown area is actually occupied by marsh/wetlands with the remaining area dominated by dry lands, such as the deforested lands, croplands, and fallow lands [*Ye et al.*, 2006]. Compared with wetlands, dry lands are very minor CH_4 sources [*Jiang et al.*, 2009] and may even act as CH_4 sinks [*Iqbal et al.*, 2009]. Low CH_4 emissions from flooded dry lands were reported recently on the scale of 0.29 ± 0.37 mg CH_4 m^{-2} h^{-1} basing on six measurements in different seasons [*Chen et al.*, 2011]. *Lu et al.* [2011] argued that the drained dryland drawdown areas of TGR might emit lower CH_4 emission compared with that reported by *Chen et al.* [2011], due to the exposure of dry lands. The anaerobic conditions are crucial to CH_4 production and transfer because CH_4 is mineralized to CO_2 by methanotrophic bacteria under aerobic conditions [*Topp and Pattey*, 1997]. As seasonal fluctuations in the water level cause an alternating cycle between inundated and exposed dry lands that would effect CH_4 emissions, sufficient seasonal investigations of emissions from various drawdown land types are required to resolve the temporal and spatial variability. The above mentioned studies of TGR CH_4 emissions were quite limited spatially and temporally, and the environmental factors leading to these emission variations were not robustly analyzed [*Chen et al.*, 2009, 2011; *Lu et al.*, 2011]. Thus systematic long-term monitoring on a large spatial scale has been suggested to accurately assess the total CH_4 emission from TGR drawdown areas.

[5] In this study, CH_4 emissions were measured at four types of land (fallow land, cropland, deforested land, and rice paddies) in the drawdown area of TGR from November 2009 through January 2011. Our specific objectives were to (1) estimate the contribution of the drawdown area to total CH_4 emissions from TGR, (2) assess the effect of land use on CH_4 emissions in the drawdown areas, (3) analyze the spatiotemporal variations in CH_4 emissions from different land types, and (4) determine any factors that may influence CH_4 emission in the TGR drawdown area.

2. Methods and Materials

2.1. Site Description

[6] TGR is located within the watercourse of the Yangtze River, which has been flooded since 2003. The TGR is about 660 km in length, and has a surface area of 1084 km^2, including the drawdown area of 450 km^2. Water levels in TGR fluctuate seasonally by 30 m. The water level is held at 145 m during the flood season (June–August) to control flooding, which drains the drawdown area. The water level is gradually increased to 175 m after the flood season in order to increase the efficiency of electricity generation [*Zhou et al.*, 2010]. The capacity to generate electricity at TGR was 18.2 million kW in 2010 (84.7 billion kWh of electricity were actually produced in 2010), making the TGR the largest hydroelectric producer in the world.

[7] The TGR is located in a subtropical monsoon climate zone with an annual mean temperature of 16.3–18.2°C and annual precipitation of 987–1326 mm [*Guo et al.*, 2007]. Nearly 80% of the precipitation falls in the hot-wet season (April–September); only 20% falls in the cool-dry season (October–March) [*Guo et al.*, 2007]. This study was carried out at three sites in the drawdown area near Zigui (30°51′N, 110°58′E), Wushan (31°03′N, 109°51′E), and Yunyang (30°56′N, 108°39′E), which are 2 km, 120 km and 240 km upstream from the Three Gorges Dam (Figure 1).

[8] Three kinds of plots (fallow land, cropland, and deforested land) at each site were selected in September 2009 when the plots were drained and the water level was

Table 1. Elevation, Duration of Inundation, pH, and Soil Carbon and Nitrogen Levels at the Sampled Sites[a]

Site	Plot	Elevation (m)	Inundated Duration (d)	Soil pH	Organic C (g kg^{-1})	Total N (g kg^{-1})
Zigui	Fallow land	149	314	6.42 ± 0.16$^{(a)}$	10.72 ± 2.67$^{(a)}$	0.78 ± 0.17$^{(a)}$
	Cropland	160	175	6.64 ± 1.01$^{(a)}$	11.18 ± 3.56$^{(a)}$	0.90 ± 0.19$^{(a)}$
	Deforested land	148	326	6.21 ± 0.32$^{(a)}$	11.44 ± 1.65$^{(a)}$	0.85 ± 0.14$^{(a)}$
	Average	152	272	6.42 ± 0.22	11.11 ± 0.36	0.81 ± 0.12
Wushan	Fallow land	151	296	8.00 ± 0.20$^{(a)}$	8.11 ± 1.13$^{(a)}$	1.05 ± 0.10$^{(a)}$
	Cropland	157	229	8.28 ± 0.08$^{(a)}$	12.39 ± 2.43$^{(b)}$	1.26 ± 0.24$^{(b)}$
	Deforested land	161	167	8.12 ± 0.10$^{(a)}$	11.64 ± 2.69$^{(b)}$	1.19 ± 0.20$^{(a, b)}$
	Average	156	231	8.13 ± 0.14	10.71 ± 2.29	1.17 ± 0.11
Yunyang	Fallow land	149	314	8.29 ± 0.10$^{(a)}$	4.68 ± 2.38$^{(b)}$	0.57 ± 0.17$^{(b)}$
	Cropland	160	175	8.63 ± 0.50$^{(a)}$	2.66 ± 0.57$^{(a)}$	0.34 ± 0.04$^{(a)}$
	Deforested land	150	305	8.25 ± 0.05$^{(a)}$	3.55 ± 0.43$^{(b)}$	0.48 ± 0.18$^{(b)}$
	Average	153	265	8.39 ± 0.21	3.63 ± 1.01	0.46 ± 0.12
	Rice paddies	172	214	8.45 ± 0.26$^{(a)}$	16.49 ± 2.47$^{(c)}$	2.69 ± 0.83$^{(c)}$

[a]The letters (a), (b), and (c) indicate significant difference ($p < 0.05$) at each site. Values are the mean ± SE (standard error). The average values of Yunyang do not include the values measured in the rice paddies.

below 146 m. A rice paddy (*Oryza sativa*), located at an elevation of 172 m in Yunyang, was added in June 2010 as a kind of agricultural wetland; thus making 10 experimental plots over 3 sites (Table 1). As lands below 160 m were frequently inundated by normal water level fluctuations or summer floods, only lands above 160 m were reclaimed for crop cultivation. Croplands were thus only located in the upper zone of the drawdown area at each of the three sites, while fallow and deforested lands were located in the lower zone, except for the deforested land in Wushan. Maize (*Zea mays L.*) was grown in the croplands of Zigui and Wushan, and sesame (*Sesamum indicum L.*) was grown in the cropland of Yunyang and the deforested land in Wushan. In the deforested lands, trees were cut down before the reservoir was impounded and many stumps were left on site.

2.2. CH_4 Emission Measurements

[9] CH_4 emissions were measured using the static chamber method [*Duchemin et al.*, 1995]. Two kinds of static chambers were deployed: 1) a floating static chamber for measuring CH_4 emissions from the water surface, and 2) a closed static chamber was used for measuring CH_4 emissions from dry land or rice paddies during the drained season. The same chambers were used for measuring CH_4 emissions from dry lands both in the inundated and drained seasons. The floating static chamber (65 cm in length × 45 cm in width × 40 cm in height) consisted of a plastic box without a cover that was wrapped in light-reflecting and heatproof films to prevent temperature variation inside the chambers; in addition, plastic foam collars were fixed onto opposite sides of the chamber. The headspace height inside the chamber was about 30 cm. When the fallow lands, croplands, and deforested lands were drained, the above-described chambers were placed on permanently positioned aluminum bases (65 cm in length × 45 cm in width × 10 cm in height) with water grooves on top and inserted into the soil in order to ensure a tight fit at the air-soil interface. To avoid disturbing plant respiration and photosynthesis, any new growth grasses around the base were cleared before the gas samples were collected. A closed, static, steel frame chamber (50 cm in length × 50 cm in width × 75 cm in height for measuring emissions from rice paddies) was covered in polyethylene plastic film (85% transparent) and used to collect gas samples from rice paddy [*Duan et al.*, 2005; *Zheng et al.*, 2011a]. A silicone tube (0.6 cm and 0.4 cm outer and inner diameters, respectively) was inserted into the upper side of the chamber to collect gas samples and another silicone tube was inserted into the chamber to keep air pressure balanced between the inside and outside of the chamber. All measurements were performed in triplicate.

[10] In either flooded or drained seasons, the gases in the headspace of the chamber were collected into air-sampling bags (0.5 L; Hedetech, Dalian, China) five times every 10 min over a 40 min period using a hand-driven pump (ICQS-1; Beijing Municipal Institute of Labour Protection, Beijing, China). The gas samples were transported within 2–3 days after sampling to the State Key Laboratory of Urban and Regional Ecology (Beijing, China) for analysis using a gas chromatograph (Agilent 6820; Agilent Technologies, Santa Clara, USA) equipped with a flame ionization detector (FID) and separated with a Teflon column (2 m × 3 mm) packed with TDX-01(60/80 mesh). The oven, injector, and detector temperatures were 80°C, 150°C, and 300°C, respectively. The flow rate of the carrier gas (N_2) was 30 mL min^{-1}, and the flow rate of H_2 and compressed air were set to 20 and 30 mL min^{-1}, respectively. Standard CH_4 gas (10.2 ppm in air; provided by China CH_4 National Research Center for Certified Reference Materials, Beijing) was used to quantify the CH_4 concentration in one of every 10 samples, which kept the coefficient of variation of the CH_4 concentration in the replicated samples below 1%.

[11] We separated the diffusive and bubble emissions based on the change of CH_4 concentration in the chambers. The CH_4 emission was considered diffusive if the linear correlation between the CH_4 concentration in the chamber and the elapsed time had r^2 greater than 0.90 [*Marani and Alvalá*, 2007]. If the CH_4 concentration was punctuated by one or more abrupt increases and the initial concentration in the chambers (at time t = 0) was close to the ambient air concentration, the abrupt increases were most easily explained by interception of rising gas bubbles by the chamber [*Keller and Stallard*, 1994]. The diffusive CH_4 emission (F_d; mg CH_4 m^{-2} h^{-1}) was determined using

$$F_d = \rho \times \mathrm{d}c/\mathrm{d}t \times 273.15/(273.15 + T) \times H \qquad (1)$$

where ρ is the density of CH_4 under standard conditions (0.714 kg m^{-3}), dc/dt is the slope of the linear regression of

the CH_4 concentration in the chamber versus time, H is the height of the chamber above the water or soil surface (0.3 m for dry lands and 0.75 m for rice paddies), and T is the air temperature (°C).

[12] The bubble CH_4 emission (F_b; mg CH_4 m^{-2} h^{-1}) was determined using

$$F_b = \rho \times \Delta C/\Delta T \times 273.15/(273.15 + T) \times H \quad (2)$$

where ΔC is the gas concentration difference between the beginning and the end of the enclosure time in the chamber (ppm) and ΔT is the total time of emplacement (h).

[13] Cropland, deforested land, and fallow land were selected along one side of the Yangtze River at each site (Figure 1 and Table 1). The rice paddy plot was located at 4 km upstream of Yunyang (Figure 1). In each sampling plot, all measurements were conducted at the same places during all seasons, regardless of inundation or drainage. CH_4 emissions were measured once or twice per month in the morning, weather depending, for 15 months (November 2009 to January 2011) in the fallow lands, croplands, deforested lands, and rice paddies at each growing stage and twice per month after the harvest. 17–21 times measurement was carried out at each land use of dry lands and 11 times at the rice paddy plot. CH_4 emissions were measured from 8:00–18:00 at 2 h intervals about once every two months in the fallow land, cropland and deforested land in Zigui in order to assess the variability in CH_4 emission during the daytime.

2.3. Environmental Variables

[14] During the inundated season, the following parameters were measured in situ: (1) velocity, using LS1206B, Midwest Group, Beijing, China; (2) pH, using HI 8424, Microcomputer HANNA, Rome, Italy; and (3) turbidity, using HI93703, Microcomputer HANNA. Air temperature, water temperature, and water depth were also measured in the field using alcohol thermometers and sounding ropes, respectively. In addition, water samples were collected once every month using plastic bottles (0.5 L) at a depth of 0.5 m and kept in a refrigerator at 4°C until laboratory analyses could be performed. Water quality parameters, including nitrate nitrogen (NO_3^--N), ammonium nitrogen (NH_4^+-N), total nitrogen (TN), and total phosphorus (TP), were measured according to the methods of the State Environmental Protection Administration of China [*Qi et al.*, 2002]. NO_3^--N was determined by the spectrophotometric method with phenol disulfonic acid, and NH_4^+-N was determined by Nessler's reagent spectrophotometric method [*Qi et al.*, 2002]. TN and TP were analyzed by peroxodisulfate oxidation of the original water samples. Total organic carbon (TOC) and total inorganic carbon (TIC) were detected using a total organic carbon analyzer (Liquic TOC; Elementar Co., Hanau, Germany). In the drained season, soil temperature was measured in the field using a waterproof thermometer (AD-5604; A&D Co., Tokyo, Japan) at a depth of 5 cm. Soil samples were collected once every month from a depth of 0–20 cm for laboratory analysis. Soil pH and organic carbon and total nitrogen levels were measured using a pH meter (Delta 320 pH meter; Mettler-Toledo Instruments Ltd., Shanghai, China) and elemental analyzer (Vario EL III; Elementar Co.), respectively.

2.4. Estimation of Total CH_4 Emissions From the Drawdown Area

[15] To estimate the total CH_4 emissions from the TGR drawdown area, two kinds of land (rice paddy and dryland, which included fallow land, cropland, and deforested land) and two periods (inundated and drained seasons) were studied. For each type of land use, the annual CH_4 emission was calculated as the summation of the products of the CH_4 emission rate, areas, and lengths of the inundated and drained season (equation (3)). Most of rice paddies were located in upland above the elevation of 170 m and inundated for 214 days with less variation (about 137 days as rice paddies in anaerobic condition, and 77 days as submerged drawdown areas). So the CH_4 emission from all rice paddies was estimated with a constant inundation period. The total CH_4 emission (TE) in the drawdown area was estimated by summing dryland and rice paddy emissions (equation (3)):

$$TE = \sum_{i=145}^{i=175} [P_i \times FE_{in} + (365 - P_i) \times FE_{dr}] \times A_i + [P' \times FE'_{in} + (365 - P') \times FE'_{dr}] \times A_0 \quad (3)$$

where i is the elevation; P_i is the inundated duration (days) for dryland at each elevation; FE_{in} and FE_{dr} are the CH_4 emission rates of dryland during the inundated and drained seasons, respectively; A_i is the area of dryland at each elevation (range: 145–175 m) that was calculated from digital elevation model (DEM) data of the TGR drawdown area using ArcGIS 9.3 (ESRI Co., Redlands, USA); P' is the inundated duration of the rice paddy; FE'_{in} and FE'_{dr} are the CH_4 emission rates of the rice paddy during the inundated and drained seasons, respectively; and A_0 is the total area of rice paddy, which accounted for 11% of the drawdown area [*Ye et al.*, 2006].

2.5. Statistical Analysis

[16] One-way analysis of variance (ANOVA), in combination with the Tukey test, was used to analyze differences in soil pH, organic carbon, and total nitrogen levels between different land uses at the same site. The normal distribution of the CH_4 emissions during the inundated and the drained seasons were tested using Kolmogorov-Smirnov Test. The skewed CH_4 emissions distributions required the data set to be normalized by natural logarithmic transformation, and then differences between sites and land uses were tested using ANOVA. Two-way ANOVA was used to test interactions between sites and land uses in terms of CH_4 emission during the inundated season. CH_4 emissions were linearly regressed in terms of soil temperature at a depth of 5 cm, air-water temperature difference, air temperature, NH_4^+-N content and water depth. A multiple regression model was used to determine the key environmental variables that influenced CH_4 emission during the inundated season. Data were analyzed with the SPSS 16.0 statistical package.

3. Results

3.1. Water Level and Inundation Period

[17] The water level steadily decreased from a high of 171 m above sea level that was measured on 11 November

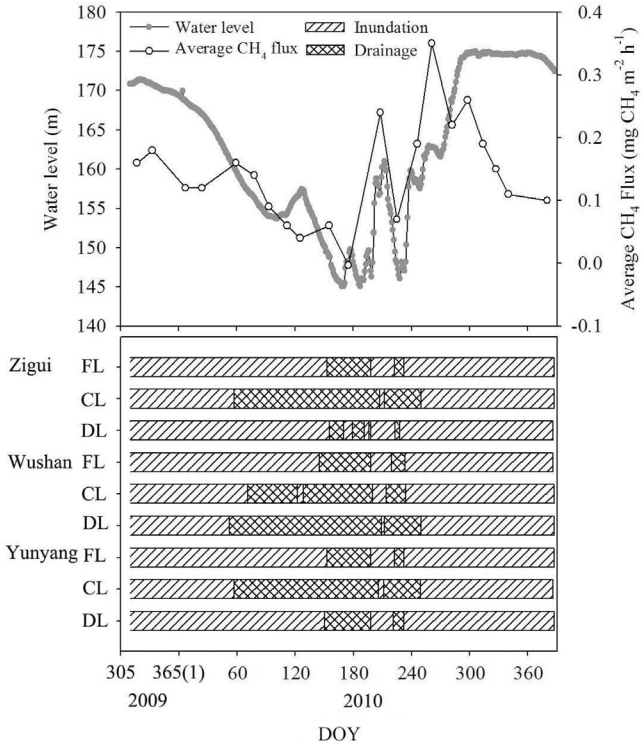

Figure 2. Seasonal variations in water levels, average CH_4 emission during the measured periods, and the duration of inundated or drained seasons in nine plots of dry lands. (top) The gray line with solid circles indicates the water level (left axis), and the solid line with open circles indicates the average CH_4 emission from all measurements in the dry lands together (right axis). (bottom) The abbreviations (FL, CL, DL) in the left axis are the same as in Figure 1.

2009 (DOY315, 2009) when the study began (Figure 2). On 21 April 2010 (DOY111, 2010), the water level rose because of spring floods. From 9 May (DOY129, 2010), the water level was decreased to 145 m in order to control flooding (Figure 2). Two floods in the summer of 2010 caused short pulses in the water level on 19 July (DOY200, 2010) and 24 August (DOY236, 2010). On 29 August (DOY241, 2010), the water level began to rise until the target level of 175 m was achieved on 26 October (DOY299, 2010) (Figure 2).

[18] The inundated period for each plot varied according to its elevation and water level. All of the plots in the drawdown area were drained from 5 June (DOY156, 2010) through 22 August (DOY234, 2010), except for the short inundated period that were caused by floods (Figure 2). The croplands were inundated for less than 229 days above an elevation of 157 m in order to guarantee that the crops would ripen (Table 1).

3.2. Soil pH, Carbon, and Nitrogen During the Drainage Season

[19] The average soil pH in Zigui was 6.42, which was significantly lower than the pH of Wushan and Yunyang (8.13 and 8.39, respectively) (Table 1).The mean soil organic carbon content in Zigui was 11.11 g kg^{-1}, which was similar to Wushan (10.71 g kg^{-1}) but more than twice as high as Yunyang (3.63 g kg^{-1}) (Table 1). The mean total nitrogen content in Zigui was 0.81 g kg^{-1}, which was significantly lower than that of Wushan (1.17 g kg^{-1}) but significantly higher than that of Yunyang (0.46 g kg^{-1}) (Table 1).

[20] There were no significant differences in terms of soil pH among the different land uses at the same sites. For organic carbon and total nitrogen, there were no significant differences among the three types of lands used in Zigui, but organic carbon and total nitrogen levels were significantly lower in the fallow land of Wushan and the cropland of Yunyang compared with the other types of lands in Wushan and Yunyang, respectively (Table 1). Organic carbon and total nitrogen levels in the rice paddies were significantly higher than the levels measured in the other types of land studies in Yunyang (Table 1).

3.3. Water Velocity and Water Quality During the Inundated Season

[21] There were significant difference in terms of water velocity at all three sites, with the highest measured in Wushan (21.3 cm s^{-1}) and the lowest in Zigui (5.2 cm s^{-1}) (Table 2). Although the average turbidity was lower in Zigui (11.88 NTU) and Wushan (19.11 NTU) compared with Yunyang (33.71 NTU), the difference was not significant (Table 2). TP, TN, NH_4^+-N, NO_3^--N, TIC, and TOC levels were not significantly different in the water samples collected at all three sites (Table 2).

3.4. Diffusive CH_4 Emissions From Different Land Uses and Sites

[22] The drawdown area was a source of CH_4 during the inundated season, with emissions ranging from 0.10 to 0.37 mg CH_4 m^{-2} h^{-1}. The drawdown area acted as a sink or weak source of CH_4 during the drained season, with emissions ranging from −0.034 to 0.036 mg CH_4 m^{-2} h^{-1}. The rice paddy, however, released 3.94 mg CH_4 m^{-2} h^{-1} during the drained season (Table 3). No significant differences were present in terms of CH_4 emission during the drained or the inundated seasons among the various land

Table 2. Water Velocity and Water Quality During the Inundated Season at the Zigui, Wushan, and Yunyang Sites of the Drawdown Area of the Three Gorges Reservoir[a]

Sites	V_{water} (cm s^{-1})	Turbidity (NTU)	Total Phosphorus (mg L^{-1})	Total Nitrogen (mg L^{-1})	NH_4^+-N (mg L^{-1})	NO_3^--N (mg L^{-1})	Total Inorganic Carbon (mg L^{-1})	Total Organic Carbon (mg L^{-1})
Zigui	5.2 ± 3.9	11.88 ± 15.36	0.11 ± 0.12	1.54 ± 0.43	0.12 ± 0.11	1.37 ± 0.31	22.75 ± 4.21	1.67 ± 0.93
Wushan	21.3 ± 14.6	19.11 ± 49.34	0.09 ± 0.04	1.28 ± 0.29	0.08 ± 0.05	1.11 ± 0.31	25.56 ± 3.29	2.00 ± 1.09
Yunyang	12.6 ± 8.5	33.71 ± 92.97	0.11 ± 0.04	1.58 ± 0.49	0.16 ± 0.13	1.26 ± 0.26	24.45 ± 3.05	1.68 ± 0.95

[a]Values are the mean ± SE (standard error).

Table 3. Average Diffusive CH_4 Emissions of Different Land Types During the Drained and Inundated Seasons and the Entire Field Study (mg CH_4 m^{-2} h^{-1})[a]

		Drainage			Inundation			Entire Study		
Land Use	Site	n	Mean	SE	n	Mean	SE	n	Mean	SE
Fallow land	Zigui	2	$-0.027^{(a)}$	0.089	16	$0.15^{(a)}$	0.12	18	$0.13^{(a)}$	0.13
	Wushan	3	$-0.034^{(a)}$	0.019	14	$0.31^{(b)}$	0.47	17	$0.25^{(a)}$	0.44
	Yunyang	3	$0.014^{(a)}$	0.044	14	$0.22^{(b)}$	0.14	17	$0.19^{(a)}$	0.15
	Average	8	−0.015	0.053	44	0.22	0.29	52	0.19	0.28
Cropland	Zigui	9	$-0.011^{(a)}$	0.024	9	$0.10^{(a)}$	0.09	18	$0.05^{(b)}$	0.08
	Wushan	7	$-0.017^{(a)}$	0.024	10	$0.21^{(b)}$	0.15	17	$0.12^{(a, b)}$	0.16
	Yunyang	9	$0.007^{(a)}$	0.041	8	$0.37^{(b)}$	0.39	17	$0.20^{(b)}$	0.34
	Average	25	$-0.007^{(a)}$	0.031	27	0.22	0.26	52	0.12	0.22
Deforested land	Zigui	2	$-0.002^{(a)}$	0.043	16	$0.14^{(a)}$	0.19	18	$0.13^{(a)}$	0.19
	Wushan	10	$-0.013^{(a)}$	0.024	7	$0.19^{(b)}$	0.14	17	$0.08^{(b)}$	0.14
	Yunyang	1	$0.036^{(a)}$	0.007	15	$0.30^{(b)}$	0.23	16	$0.28^{(c)}$	0.24
	Average	13	−0.007	0.030	38	0.21	0.21	51	0.18	0.24
Average[b]	Zigui	13	$-0.012^{(a)}$	0.040	41	$0.14^{(a)}$	0.15	54	$0.10^{(a)}$	0.15
	Wushan	20	$-0.018^{(a)}$	0.024	31	$0.25^{(b)}$	0.33	51	$0.15^{(b)}$	0.29
	Yunyang	13	$0.011^{(a)}$	0.040	37	$0.28^{(b)}$	0.25	50	$0.24^{(c)}$	0.27
Total average[c]		46	−0.008	0.035	109	0.22	0.26	155	0.16	0.24
Rice paddy	Yunyang	7	3.94	4.22	4	0.3	0.26	11	2.61	3.76

[a]The letters (a), (b), and (c) indicate significant difference ($p < 0.05$) for each land use or average values at each site. Abbreviations: n, number of samples; SE, standard error.
[b]Average CH_4 emission of the fallow land, cropland, and deforested land at each site.
[c]Total average CH_4 emission of the fallow lands, croplands, and deforested lands at Zigui, Wushan, and Yunyang.

uses at the same sites, except the rice paddy (Table 3). Although there were no significant differences in CH_4 emission between sites during the drained season, CH_4 emissions in Wushan and Yunyang were significantly higher than those in Zigui for the same fallow lands, croplands, and deforested lands during the inundated season (Table 3).

[23] The annual average CH_4 emission from the croplands (0.12 mg CH_4 m^{-2} h^{-1}) was significantly lower than that of the fallows lands (0.19 mg CH_4 m^{-2} h^{-1}) and the deforested lands (0.18 mg CH_4 m^{-2} h^{-1}) (Table 3). The average CH_4 emission across the entire sampled season was 2.61 mg CH_4 m^{-2} h^{-1} in the rice paddy (Table 3), which was the highest among the four types of land that were examined. The average CH_4 emission was the highest at Yunyang (0.24 mg CH_4 m^{-2} h^{-1}), followed by Wushan (0.15 mg CH_4 m^{-2} h^{-1}) and Zigui (0.10 mg CH_4 m^{-2} h^{-1}) (Table 3). There was a significant interaction between sites and land uses in terms of CH_4 emissions during the inundated season.

3.5. Bubble CH_4 Emission From the Drawdown Area

[24] During the inundated season, bubbles were observed 10 times in all the measurements, with a frequency of bubbles occurrence of 2.9% in the TGR drawdown area (Figure 3). The average bubble emission was 2.36 ± 2.15 mg CH_4 m^{-2} h^{-1} when bubbles occurred, but the average bubble emission was 0.068 mg CH_4 m^{-2} h^{-1} during the inundated season in consideration of the frequency of bubbles.

3.6. Variations in CH_4 Emission During the Daytime

[25] CH_4 emissions began to increase from 6:00 or 8:00 and reached maximum values at 12:00 or 14:00, then gradually decreased thereafter (Figure 4). The variations in CH_4 emission during the daytime in croplands were less than those measured in fallow and deforested lands (Figure 4). Such 2 h measurement was not conducted at the rice paddy plot during the daytime.

3.7. Environmental Variables Influencing CH_4 Emission

[26] There were significant relationships between CH_4 emission and water depth, air temperature, air-water temperature difference, and NH_4^+-N content during the inundated season and, additionally, soil temperature at a depth of 5 cm during the drained season (Figure 5). The results of the multiple regression analysis show that CH_4 emission (F) is significantly related to the air-water temperature difference

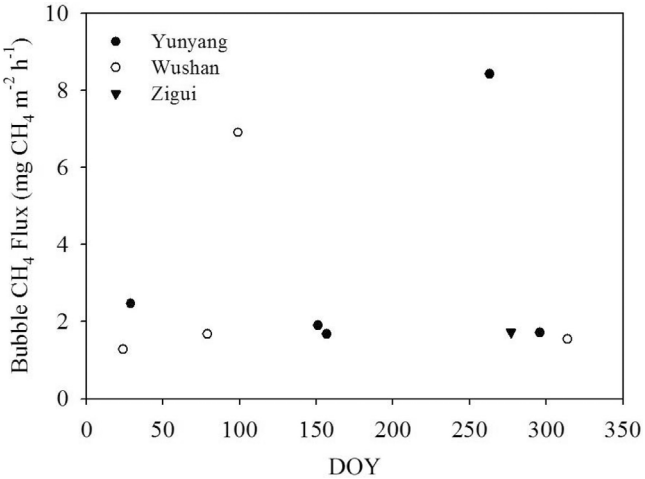

Figure 3. Bubble CH_4 flux and its distribution in Yunyang, Wushan, and Zigui in 2010.

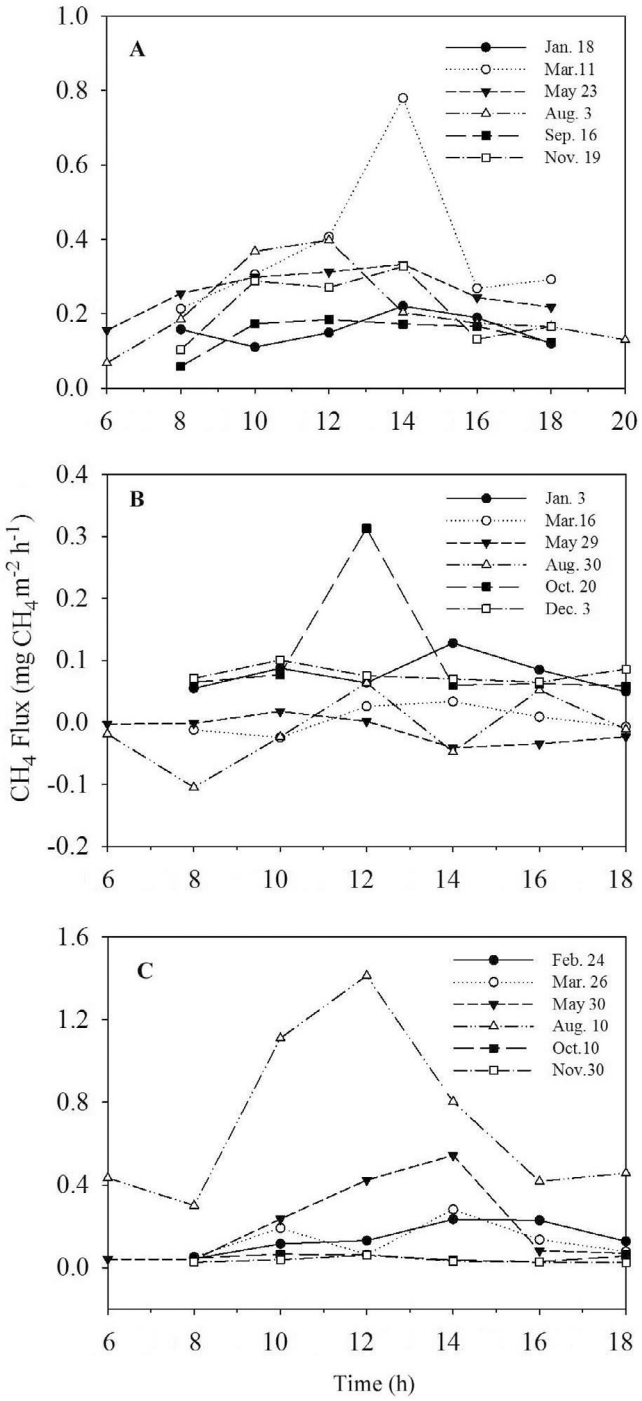

Figure 4. The variations in CH_4 emission during the daytime at (a) fallow land, (b) cropland, and (c) deforested land in Zigui.

(T), water depth (D), and air temperature (T_{air}), as shown by equation (4):

$$F = 0.122 + 0.013T - 0.003D + 0.008T_{air} \quad (4)$$

3.8. Total CH_4 Emission From the Drawdown Area of TGR

[27] In dryland, diffusive CH_4 emission was estimated to be 233.9–490.3 Mg CH_4 yr^{-1} during the inundated season and −22.4–21.6 Mg CH_4 yr^{-1} during the drained season. Therefore, the annual diffusive CH_4 emission was 211.5–511.9 Mg CH_4 yr^{-1} in dry lands in the TGR drawdown area (Table 4). CH_4 emission from rice paddies was estimated to be about 676.6 Mg CH_4 yr^{-1} (Table 4). In addition, 145.4 Mg CH_4 yr^{-1} was estimated from the drawdown area by bubbles (Table 4). Therefore, the total estimated CH_4 emission from the TGR drawdown area was 1033.5–1333.9 Mg CH_4 yr^{-1}, which accounts for 42–54% of the CH_4 emission from the water surface (2.46 Gg CH_4 yr^{-1}) [*Chen et al.*, 2011].

4. Discussion

4.1. Contribution of the Drawdown Area to CH_4 Emission in TGR

[28] Although hydropower, as a renewable source of energy, is considered an important way to mitigate global warming by replacing fossil fuel combustion for the generation of electricity, CH_4 emissions from man-made hydropower reservoirs cause doubts regarding its mitigation potential when compared with traditional forms of fossil fuel energy [*Cullenward and Victor*, 2006]. Based on our monthly to semimonthly measurement on CH_4 emissions from four types of land at three sites in the drawdown area along the mainstream of TGR, the annual average CH_4 emission was 0.23 mg CH_4 m^{-2} h^{-1} (0.16 mg CH_4 m^{-2} h^{-1} of diffusive flux plus 0.068 mg CH_4 m^{-2} h^{-1} of bubble flux) in the drawdown area of TGR in 2010 (Table 3), which is less than that reported by *Chen et al.* [2009] (6.7 mg CH_4 m^{-2} h^{-1}), *Chen et al.* [2011] (0.29 mg CH_4 m^{-2} h^{-1}), and *Lu et al.* [2011] (0.34 mg CH_4 m^{-2} h^{-1}). Since the emission accounts for up to a half of the total emissions from the water surface, the drawdown areas of this reservoir should not be neglected when assessing emissions from hydropower reservoirs by potentially others.

4.2. Effect of Land Use on CH_4 Emission

[29] The annual average CH_4 emissions from croplands were smaller than those of the fallow and deforested lands most likely because the croplands were at higher elevation and inundated for a shorter period of time, which had a relatively short duration of anoxia. The annual average CH_4 emissions from croplands, deforested lands, and fallow lands were positively related with their average durations of inundation (data not shown). Land use did not impact CH_4 emissions at the same site during any season, except for rice paddies. Rice paddies, as a parcel of land that is waterlogged during the drained season, are a significant source of CH_4 (Table 3). CH_4 emissions from rice paddies have been measured for a long time in China because of their significant contribution to national CH_4 emissions [*Zhuang et al.*, 2009]. The average CH_4 emission of Chinese rice paddies has been reported to be about 8.4 mg CH_4 m^{-2} h^{-1} [*Lu et al.*, 2010]. In this study, the average CH_4 emission during the growing stage was 5.85 mg CH_4 m^{-2} h^{-1}.

4.3. Spatiotemporal Variations in CH_4 Emission

[30] Seasonal variations in the water level affect the anaerobic conditions that ultimately determine CH_4 emission. From June to August, the decline in the water level

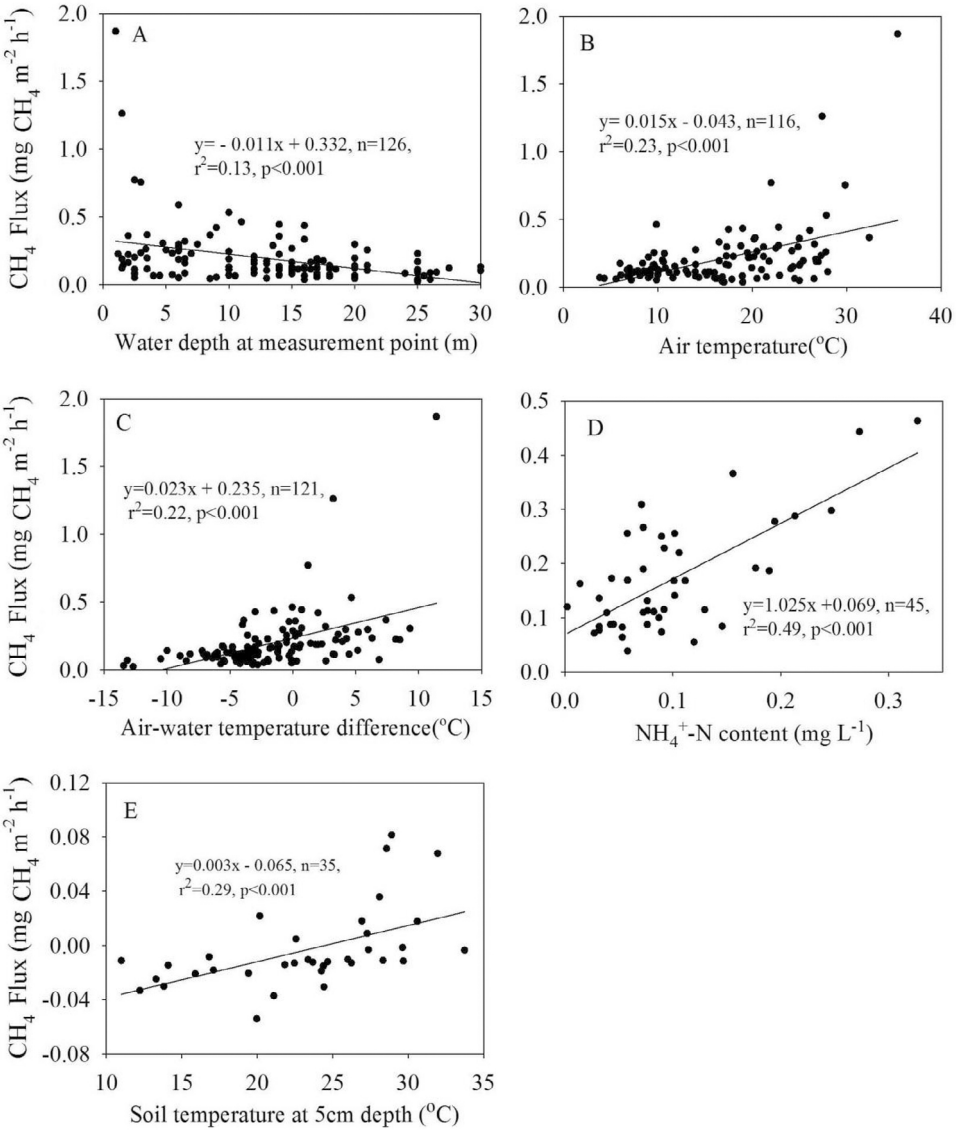

Figure 5. Relationships between CH_4 emissions in the seasonal variation and (a) water depth at the measurement point, (b) air temperature, (c) air-water temperature difference, (d) NH_4^+-N content in the inundated season, and (e) soil temperature at a depth of 5 cm during the inundated season.

effectively drained all of the measured plots (Figure 2), except the rice paddy. In the drained season, CH_4 emissions were weak, or the land acted as a weak sink because of the presence of methanotrophic bacteria under aerobic conditions. In this study during the drained period, the fallow lands, croplands, and deforested lands in Zigui and Wushan acted as CH_4 sinks (-0.012 and -0.018 mg CH_4 m^{-2} h^{-1}, respectively), while small CH_4 emissions were observed in Yunyang

Table 4. Estimation of CH_4 Emission Levels From the Drawdown Area of the Three Gorges Reservoir

			Inundated Season			Drained Season			
	Types	Area (km^2)	CH_4 Emission (mg CH_4 m^{-2} h^{-1})	Duration (d)	Total CH_4 Emission (Mg)	CH_4 Emission (mg CH_4 m^{-2} h^{-1})	Duration (d)	Total CH_4 Emission (Mg)	Total CH_4 Estimation (Mg)
Diffusion	Dry land	400	0.14–0.28	198[b]	233.9–490.3	−0.01–0.01	167	−22.4–21.6	211.5–511.9
	Rice land	50[a]	0.30	77	27.4	3.94[c]	137	647.2	676.6
						0.011[d]	151	2.05	
Ebullition		450	0.068	198[b]	145.4	0	167	0	145.4

[a]From *Ye et al.* [2006].
[b]Average inundated duration of the drawdown area at an elevation of 145–175 m.
[c]Average CH_4 emission during the rice growing stage.
[d]Average CH_4 emission after the rice paddy was harvested.

(0.011 mg CH_4 m^{-2} h^{-1}). *Iqbal et al.* [2009] reported that vegetable fields, citrus orchards, and pine forests in Zigui act as CH_4 sinks (−0.011 mg CH_4 m^{-2} h^{-1}). Compared with other reports on forest soil (−0.038 mg CH_4 m^{-2} h^{-1}) in Dinghushan Nature Reserve [*Tang et al.*, 2006] and pine plantation and orchard soils (−0.029 mg CH_4 m^{-2} h^{-1}) in Heshan, Guangdong Province [*Liu et al.*, 2008], the low CH_4 uptake values in this study may be attributed to a higher soil pH (6.21–8.63 versus 3.9 in Dinghushan and 3.95–5.91 in Heshan), since acidic soil usually leads to a higher rate of CH_4 uptake [*Sitaula et al.*, 1995].

[31] When plots were inundated from September through the following February, CH_4 was released from the water surface above the fallow lands, croplands, deforested lands, and rice paddies (Figure 2). CH_4 emission from the TGR drawdown area was 0.22 mg CH_4 m^{-2} h^{-1} during the inundated season, higher than that reported for the Ertan reservoir in southwest China (0.117 mg CH_4 m^{-2} h^{-1}) [*Zheng et al.*, 2011b] and close to that reported for the Xiangxi tributary of TGR (0.2449 mg CH_4 m^{-2} h^{-1}) [*Zhao et al.*, 2011]. In addition, our results are comparable to those reported for the boreal region of Canada, including the Laforge-1 (0.21 mg CH_4 m^{-2} h^{-1}) and La Grande-2 (0.58 mg CH_4 m^{-2} h^{-1}) [*Duchemin et al.*, 1995] and 55 reservoirs nationwide distribution in Canada (0.37 ± 0.5 mg CH_4 m^{-2} h^{-1}) [*Tremblay et al.*, 2005]. However, our results are remarkably lower than those reported for tropical reservoirs in Brazil (3.27 ± 2.75 mg CH_4 m^{-2} h^{-1}) [*dos Santos et al.*, 2006] and Petit Saut Reservoir in French Guiana (1.93 ± 1.20 mg CH_4 m^{-2} h^{-1}) [*Abril et al.*, 2005]. *Barros et al.* [2011] found that CH_4 emissions exponentially decline with increasing latitude, as the warm and anoxic conditions conducive to methanogenesis are less present in higher latitudes. This partly explains why TGR (29°16′–31°25′N) does not emit as much CH_4 as tropical reservoirs. In addition, tropical reservoirs that were created by flooding uncleared tropical forests, such as Balbina in Brazil or Petit Saut Reservoir in French Guiana, are rich in organic carbon and able to contribute significantly more CH_4 emissions. Intensive clearing before the impoundment of TGR did not provide much organic substrate for CH_4 production.

[32] Water velocity and turbulence were important factors that contributed to the annual average CH_4 emissions being highest upstream in Yunyang and decreasing gradually to Wushan and Zigui (Table 3). This spatial difference in CH_4 emissions was apparent during the inundated season, but not during the drained season (Table 3), and was thus related to factors specific to water flow. Water velocity is an important source of turbulence at the air-water interface and influences the gas transfer velocity (k_{600}), thereby enhancing CH_4 emission from water surface [*Borges et al.*, 2004; *Ferrón et al.*, 2007]. Zigui, located 2 km upstream from the Three Gorges Dam, had significantly lower water velocity (5.2 cm s^{-1}) than Wushan (21.3 cm s^{-1}) and Yunyang (12.6 cm s^{-1}) during the inundated season ($p < 0.05$) (Table 2). In addition, turbidity was higher upstream in Yunyang (33.71 NTU) than downstream in Wushan (19.11 NTU) and Zigui (11.88 NTU) during the inundated season (Table 2), potentially indicating that the greater sediment load upstream provided additional substrate for methanogenesis and thus emissions.

4.4. Environmental Factors Influencing CH_4 Emission

[33] Air temperature [*Bergström et al.*, 2007], water temperature [*Thérien and Morrison*, 2005], and soil temperature [*Juutinen et al.*, 2001] are important factors that influence the microbial activities that produce CH_4 under anaerobic conditions. Increased difference of the air and water temperatures ($T_{water} > T_{air}$) might cause destabilization near the water surface, thereby enhancing the gas transfer velocity by as much as 4–30% due to evaporation [*Guérin et al.*, 2007]. In this study, CH_4 emission was influenced by the air-water temperature difference during the inundated season (Figure 5c), as has been seen elsewhere [*Zheng et al.*, 2011b]. A regression analysis performed on the 2 h increment measurements at each site (data not shown) also revealed that air-water temperature difference accounted for 42.3% and 39.4% of CH_4 emission variability at the fallow and deforested lands, respectively. During the drained season of this study, the soil temperature at a depth of 5 cm was positively correlated with CH_4 emission (Figure 5e), which was in agreement with many other field studies [*Iqbal et al.*, 2009; *Liu et al.*, 2008]. Whether a soil was a net source or sink for CH_4 depended on the relative rates between methanogenic and methanotrophic activities [*Topp and Pattey*, 1997], but methanogenic bacteria were much more responsive to temperature than methanotrophic bacteria, and optimum temperatures for both processes were about 25°C [*Dunfield et al.*, 1993]. When temperature rose or fell, the CH_4 production rate increased or decreased faster than that of CH_4 consumption. Therefore, more CH_4 was emitted at high temperatures and less CH_4 was released at low temperatures.

[34] Due to seasonal fluctuations in the water level, the plots in the drawdown area switched from being a CH_4 source (0.10–0.37 mg CH_4 m^{-2} h^{-1}) during the inundated season to being a weak source or sink (−0.034–0.036 mg CH_4 m^{-2} h^{-1}) during the drained season (Table 3). A similar transformation has been reported in alternating wet and dry zones in riverine zones and wetlands [e.g., *Smith et al.*, 2000] and in a tundra ecosystem with areas of varying water saturation levels [e.g., *Merbold et al.*, 2009]. CH_4 is produced in soils as the end product of anaerobic organic matter decomposition [*Topp and Pattey*, 1997], and as exposed soils contain more oxygen than those overlain by water, higher emissions should happen when the drawdown areas are inundated. The negative relationship between CH_4 emission and water depth found in this study and elsewhere [*Soumis et al.*, 2004; *Duchemin et al.*, 1995; *Zheng et al.*, 2011b] is most likely due to the reduction in time for CH_4 oxidation to occur with decreasing depths. Thus, more CH_4 is able to reach the atmosphere [*Juutinen et al.*, 2001]. Water depth was an important factor influencing hourly emission variations on different sampling days, as exemplified by the largest variation occurring on 11 March in the fallow lands when water depth was the shallowest (5 m). Methane emissions were also high on 10 August and 30 May in deforested lands partly because of shallow water depths.

5. Conclusion

[35] Land uses, especially rice cultivation and its management, are critical contributors to CH_4 emission in the drawdown area of TGR. Among the other three land uses studied—fallow land, cropland, and deforested land—there was no significant difference in terms of CH_4 emission

during the drained and inundated seasons. Differences in annual average CH_4 emissions are attributed to the periods of time that the measurement plots were inundated. Water level fluctuations were the main environmental factors that influenced CH_4 emission. The average CH_4 emissions decreased from upstream to downstream plots nearer to the drawdown area, which could be due to differences in water velocities and amounts of deposited sediment. The drawdown area occupies one third or more of the TGR surface area, and the total CH_4 emission from the drawdown area is 42–54% of the total emissions from the reservoir surface. Ultimately, CH_4 emissions from the drawdown areas of reservoirs require further study and consideration when assessing total seasonal emissions from such water bodies.

[36] **Acknowledgments.** This work was supported by the National Natural Science Foundation of China (50809067), Ministry of Science and Technology of the People's Republic of China (2010CB955904–03), and the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA05060102 and XDA05050602). We also acknowledge Yafei Yuan for her suggestions on this article and three anonymous reviewers for their improvements to the paper.

References

Abril, G., F. Guérin, S. Richard, R. Delmas, C. Galy Lacaux, P. Gosse, A. Tremblay, L. Varfalvy, M. A. dos Santos, and B. Matvienko (2005), Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana), *Global Biogeochem. Cycles*, *19*, GB4007, doi:10.1029/2005GB002457.

Barros, N., J. Cole, L. Tranvik, Y. Prairie, D. Bastviken, V. Huszar, P. Giorgio, and F. Roland (2011), Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude, *Nat. Geosci.*, *4*, 593–596, doi:10.1038/ngeo1211.

Bergström, I., S. Mäkelä, P. Kankaaka, and P. Kortelainen (2007), Methane efflux from littoral vegetation stands of southern boreal lakes: An upscaled regional estimate, *Atmos. Environ.*, *41*, 339–351, doi:10.1016/j.atmosenv.2006.08.014.

Borges, A., J. Vanderborght, L. Schiettecatte, F. Gazeau, S. Ferrón, B. Delille, and M. Frankingnoulle (2004), Variability of gas transfer velocity of CO_2 in a macrotidal estuary (the Sceldt), *Estuaries*, *27*, 593–603, doi:10.1007/BF02907647.

Chen, H., Y. Wu, X. Yuan, Y. Gao, N. Wu, and D. Zhu (2009), Methane emissions from newly created marshes in the drawdown area of the Three Gorges Reservoir, *J. Geophys. Res.*, *114*, D18301, doi:10.1029/2009JD012410.

Chen, H., X. Yuan, Z. Chen, Y. Wu, X. Liu, D. Zhu, N. Wu, Q. Zhu, C. Peng, and W. Li (2011), Methane emissions from the surface of the Three Gorges Reservoir, *J. Geophys. Res.*, *116*, D21306, doi:10.1029/2011JD016244.

Cullenward, D., and D. G. Victor (2006), The dam debate and its discontents: An editorial comment, *Clim. Change*, *75*, 81–86, doi:10.1007/s10584-006-9085-7.

Demarty, M., J. Bastien, A. Tremblay, R. Hesslein, and R. Gill (2009), Greenhouse gas emissions from boreal reservoirs in Manitoba and Québec, Canada, measured with automated systems, *Environ. Sci. Technol.*, *43*, 8908–8915, doi:10.1021/es8035658.

dos Santos, M., L. Rosa, B. Sikar, E. Sikar, and E. dos Santos (2006), Gross greenhouse gas fluxes from hydro-power reservoir compared to thermo-power plants, *Energy Policy*, *34*, 481–488, doi:10.1016/j.enpol.2004.06.015.

Duan, X., X. Wang, Y. Mu, and Z. Ouyang (2005), Seasonal and diurnal variations in methane emissions from Wuliangsu Lake in arid regions of China, *Atmos. Environ.*, *39*, 4479–4487, doi:10.1016/j.atmosenv.2005.03.045.

Duchemin, E., M. Lucotte, R. Canuel, and A. Chamberland (1995), Production of the greenhouse gases CH_4 and CO_2 by hydroelectric reservoirs of the boreal region, *Global Biogeochem. Cycles*, *9*, 529–540, doi:10.1029/95GB02202.

Dunfield, P., R. Knowles, R. Dumont, and T. Moore (1993), Methane production and consumption in temperate and subarctic peat soils: Response to temperature and pH, *Soil Biol. Biochem.*, *25*, 321–326, doi:10.1016/0038-0717(93)90130-4.

Ferrón, S., T. Ortega, A. Gómez-Parra, and J. M. Forja (2007), Seasonal study of dissolved CH_4, CO_2 and N_2O in a shallow tidal system of the bay of Cádiz (SW Spain), *J. Mar. Syst.*, *66*, 244–257, doi:10.1016/j.jmarsys.2006.03.021.

Frankenberg, C., J. F. Meirink, M. van Weele, U. Platt, and T. Wagner (2005), Assessing methane emissions from global space-borne observations, *Science*, *308*, 1010–1014, doi:10.1126/science.1106644.

Guérin, F., G. Abril, D. Serça, C. Delon, S. Richard, R. Delmas, A. Tremblay, and L. Varfalvy (2007), Gas transfer velocities of CO_2 and CH_4 in a tropical reservoir and its river downstream, *J. Mar. Syst.*, *66*, 161–172, doi:10.1016/j.jmarsys.2006.03.019.

Guo, X., X. Huang, and K. Xu (2007), The natural and geological environment in the Three Gorges Reservoir, in *Prevention and Treatment of Landslide and Collapse Geological Hazards in Three Gorges Reservoir Project Area* [in Chinese], edited by G. Wu and Z. Huang, pp. 2–16, China Waterpower, Beijing.

Huttunen, J., T. Väisänen, S. Hellsten, H. Nykänen, H. Jungner, A. Niskanen, M. Virtanen, O. Nenonen, and P. Martikainen (2002), Fluxes of CH_4, CO_2, and N_2O in hydroelectric reservoirs Lokka and Porttipahta in the northern boreal zone in Finland, *Global Biogeochem. Cycles*, *16*(1), 1003, doi:10.1029/2000GB001316.

Iqbal, J., S. Lin, R. G. Hu, and M. L. Feng (2009), Temporal variability of soil-atmospheric CO_2 and CH_4 fluxes from different land uses in mid-subtropical China, *Atmos. Environ.*, *43*, 5865–5875, doi:10.1016/j.atmosenv.2009.08.025.

Jiang, C., Y. Wang, Q. Hao, and C. Song (2009), Effect of land-use change on CH_4 and N_2O emissions from freshwater marsh in northeast China, *Atmos. Environ.*, *43*, 3305–3309, doi:10.1016/j.atmosenv.2009.04.020.

Juutinen, S., J. Alm, P. Martikainen, and J. Silvola (2001), Effects of spring flood and water level drawn-down on methane dynamics in the littoral zone of boreal lakes, *Freshwater Biol.*, *46*, 855–869, doi:10.1046/j.1365-2427.2001.00721.x.

Juutinen, S., J. Alm, T. Larmola, J. T. Huttunen, M. Morero, S. Saarnio, P. J. Martikainen, and J. Silvola (2003a), Methane (CH_4) release from littoral wetlands of boreal lakes during an extended flooding period, *Global Change Biol.*, *9*, 413–424, doi:10.1046/j.1365-2486.2003.00595.x.

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

Keller, M., and R. Stallard (1994), Methane emission by bubbling from Gatun Lake, Panama, *J. Geophys. Res.*, *99*, 8307–8319, doi:10.1029/92JD02170.

Liu, H., P. Zhao, P. Lu, Y. Wang, Y. Lin, and X. Rao (2008), Greenhouse gas fluxes from soils of different land-use types in a hilly area of south China, *Agric. Ecosyst. Environ.*, *124*, 125–135, doi:10.1016/j.agee.2007.09.002.

Lu, F., X. Wang, B. Han, Z. Ouyang, and H. Zheng (2010), Straw return to rice paddy: Soil carbon sequestration and increased methane emission [in Chinese with English abstract], *Yingyong Shengtai Xuebao*, *21*, 99–108.

Lu, F., et al. (2011), Preliminary report on methane (CH_4) emissions from the Three Gorges Reservoir (TGR) in the summer drainage period, *J. Environ. Sci.*, *23*(12), 2029–2033, doi:10.1016/S1001-0742(10)60668-7.

Marani, L., and P. C. Alvalá (2007), Methane emissions from lakes and floodplains in Pantanal, Brazil, *Atmos. Environ.*, *41*, 1627–1633, doi:10.1016/j.atmosenv.2006.10.046.

Merbold, L., W. L. Kutsch, C. Corradi, O. Kolle, C. Rebmann, P. C. Stoy, S. A. Zimov, and E. D. Schulze (2009), Artificial drainage and associated carbon fluxes (CO_2/CH_4) in a tundra ecosystem, *Global Change Biol.*, *15*, 2599–2614, doi:10.1111/j.1365-2486.2009.01962.x.

Qi, W., et al. (2002), Comprehensive indexes of nutritive salt and organic contaminant, in *Monitoring and Analysis Methods for Water and Wastewater* [in Chinese], 4th ed., edited by S. Wu, pp. 236–284, Chinese Environ. Sci., Beijing.

Sitaula, B. K., I. R. Bakken, and G. Abrahamsen (1995), CH_4 uptake by temperature forest soil: Effect of N input and soil acidification, *Soil Biol. Biochem.*, *27*(7), 871–880, doi:10.1016/0038-0717(95)00017-9.

Smith, L. K., W. M. Lewis, J. P. Chanton, G. Cronin, and S. K. Hamilton (2000), Methane emissions from the Orinoco River floodplain, Venezuela, *Biogeochemistry*, *51*, 113–140, doi:10.1023/A:1006443429909.

Soumis, N., E. Duchemin, R. Canuel, and M. Lucotte (2004), Greenhouse gas emissions from reservoirs of the western United States, *Global Biogeochem. Cycles*, *18*, GB3022, doi:10.1029/2003GB002197.

St. Louis, V. C., C. Kelly, E. Duchemin, J. W. M. Rudd, and D. M. Rosenberg (2000), Reservoir surface as sources of greenhouse gases to the atmosphere: A global estimate, *BioScience*, *50*, 766–775, doi:10.1641/0006-3568(2000)050[0766:RSASOG]2.0.CO;2.

Tang, X., S. Liu, G. Zhou, D. Zhang, and C. Zhou (2006), Soil-atmospheric exchange of CO_2, CH_4, and N_2O in three subtropical forest ecosystems in southern China, *Global Change Biol.*, *12*, 546–560, doi:10.1111/j.1365-2486.2006.01109.x.

Thérien, N., and K. Morrison (2005), Production of GHG from the decomposition of *in vitro* inundated phytomass and soil, in *Greenhouse Gas Emissions—Fluxes and Processes: Hydroelectric Reservoirs and Natural Environments*, edited by A. Tremblay et al., pp. 315–338, Springer, New York, doi:10.1007/3-540-26643-7_13.

Topp, E., and E. Pattey (1997), Soils as sources and sinks for atmospheric methane, *Can. J. Soil Sci.*, *77*, 167–177, doi:10.4141/S96-107.

Tremblay, A., J. Therrien, B. Hamlin, E. Wichmann, and L. LeDrew (2005), GHG emissions from boreal reservoirs and natural aquatic ecosystems, in *Greenhouse Gas Emissions—Fluxes and Processes: Hydroelectric Reservoirs and Natural Environments*, edited by A. Tremblay et al., pp. 209–232, Springer, New York, doi:10.1007/3-540-26643-7_8.

Wuebbles, D., and K. Hayhoe (2002), Atmospheric methane and global change, *Earth Sci. Rev.*, *57*, 177–210, doi:10.1016/S0012-8252(01)00062-9.

Ye, Y., C. Yin, and Y. Ye (2006), On the landscape planning mode of the ebbing area of the Three Gorges—The landscape design of the ebbing area on the north land of Wanzhou, Chongqing [in Chinese with English abstract], *Art Design*, *9*, 118–119.

Zhao, Y., Y. Zeng, R. Wu, Q. Wang, C. Yuan, and Z. Xu (2011), Observation on greenhouse emissions from Xiangxi River in Three Gorges region [in Chinese with English abstract], *Adv. Water Sci.*, *22*(4), 546–553.

Zheng, F., et al. (2011a), Effects of elevated zone concentration on methane emission from a rice paddy in Yangtze River Delta, China, *Global Change Biol.*, *17*, 898–910, doi:10.1111/j.1365-2486.2010.02258.x.

Zheng, H., X. Zhao, T. Zhao, F. Chen, W. Xu, X. Duan, X. Wang, and Z. Ouyang (2011b), Spatial-temporal variations of methane emissions from the Ertan hydroelectric reservoir in southwest China, *Hydrol. Processes*, *25*, 1391–1396, doi:10.1002/hyp.7903.

Zhou, Y., X. Wang, Q. Wu, F. Lu, and J. Qiu (2010), The characteristics of the drawdown areas of Three Gorges Reservoirs, in *Ecological Vulnerability and Protection in the Drawdown Area of the Three Gorges Reservoir*, edited by L. Liu, pp. 30–37, Chinese Environ. Sci., Beijing.

Zhuang, Q., J. Melack, K. Walter, C. Butenhoff, and M. Khalil (2009), Global methane emissions from wetlands, rice paddies and lakes, *Eos Trans. AGU*, *90*(5), 37, doi:10.1029/2009EO050001.