Int. J. Environ. Sci. Technol. (2014) 11:77–86
DOI 10.1007/s13762-013-0385-y

ORIGINAL PAPER

Spatial variations in methane emissions from natural wetlands in China

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Received: 6 October 2011 / Revised: 29 April 2012 / Accepted: 5 November 2012 / Published online: 3 December 2013

Abstract Natural wetlands are thought to be one of the largest natural sources of atmospheric methane concentrations. Although numerous studies referred to the rate of methane fluxes in different geophysical regions, only a few had estimates of the overall geographical methane emissions in China. This study estimated the spatial variations of annual methane emissions with the pixel size of 1 km × 1 km from natural wetlands, excluding water surface, in China. The natural wetland areas were extracted from the database of the 2000 land covers, and geophysical divisions were used to represent different climate conditions. Methane emission in every geophysical region was calculated based on methane release factors obtained from an extensive overview of published literature and the data of elevation and vegetation proportion. The estimated annual methane emissions ranged from 0 to 5,702.8 kg per pixel within the area of 1 km^2, and the spatial variation in methane emissions was strongly correlated with proportion of wetlands in the area. The total methane emission from natural wetland in China ranged from 3.48 to 7.16 Tg (terrogram, unit of weight) per year, with the mean value of 4.94 Tg per year, based on the area 133,000 km^2 of natural wetlands. Specifically, the wetland in Northeast China had the highest contribution in China (39 %). Inner Mongolia and Qinghai-Tibet highland represented for about 25 and 21 %, respectively. The other 15 % of the measured methane was released in Northwest, North, Central, and South China.

Keywords Methane release · Geophysical region · Plant types · Wetland distribution

Introduction

Next to water vapor and carbon dioxide, methane (CH_4) is considered as the most abundant greenhouse gas in the troposphere, affecting both the natural environment and human health (Bicheldey and Latushkina 2010; Zhang et al. 2011, 2012). Natural wetlands are thought to be one of the largest natural sources, contributing 20 % of the global annual flux of CH_4 to the atmosphere (Bachelet and Neue 1993). CH_4 production and emission in wetlands involve complex physiological processes of plants and microorganism, which are regulated by climatic and environmental factors (Ding et al. 2004; Chang and Yang 2003). Therefore, considerable uncertainties exist in estimates of CH_4 emissions levels and fluxes from natural wetland at regional scale.

In recent years, CH_4 emissions from natural wetlands around China have been given a lot of attention, most of which were conducted in boreal zones and different temperature zones in China. Most of theses studies used closed chamber to monitor gas exchanges between the biosphere and atmosphere. The detailed information is listed in Table 1. In Qianghai-Tibetan Plateau, Jin et al. (1999) observed strong spatial and temporal variations in Huashixia. Hirota et al. (2004) mentioned in his study that CH_4 fluxes from different vegetation zones in Luanhaizi wetland increased with increasing aboveground biomass and

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Table 1 Methane fluxes from natural wetland in China

Wetland	Measured period	Investigators	Vegetation/wetland type	Mean CH_4 fluxes (mg CH_4 m^{-2} h^{-1})
Xiao-xing' anling	2007/5–10	Sun et al. (2011)	*Carex schmidtii* and *Calamagrostis angustifolia*	19.03
	2008/5–10		*Betula ovalifolia*	0.27
			Alnus sibirica	9.97
			Betula platyphylla	0.45
			Larix gmelinii–Carex schmidtii	−0.03
			Larix gmelinii–Moss	−0.06
			Larix gmelinii–Sphagnum spp.	1.09
Sanjiang Plain	2001/5–10	Ding et al. (2004)	*Carex lasiocarpa*	19.6
	2002/5–10			
	2001/8	Ding et al. (2005)	*Carex meyeriama*	23.8
	2002/8		*Deyeuxia angustifolia*	21.85
	2002/5–10	Song et al. (2008)	*Carex lasiocarpa*	11.15
	2003/5–10		*Deyeuxia angustifolia*	6.24
	2004/5–10		*Shrub*	0.24
	2003/6–9	Song et al. (2006)	*Carex lasiocarpa*	11.40
			Deyeuxia angustifolia	1.59
			C. pseudocuraica	10.80
	11–12	Zhang et al. (2005)	*Carex lasiocarpa*	0.5
	1–4		*Deyeuxia angustifolia*	0.18
Liaohe Delta	4–11	Huang et al. (2011)	*Phragmites australis*	0.52
Zoige Plateau	2001/5–9	Ding et al. (2004)	*Carex muliensis*	2.06
	2002/5–9		*Carex meyeriana*	3.88
	2005/6–9	Chen et al. (2008)	*Carex muliensis*	22.85
			Eleocharis valleculosa	14.1
			Dry hummock	6.79
	2006/12–2007/1–2	Zhu et al. (2011)	*Carex muliensis*	2.74
	2007/12–2008/1–2		*Eleocharis valleculosa*	0.87
			Dry hummock	0.08
Huahu	2006/6–8	Chen et al. (2009b)	*G. maxima*	45.0
	2007/6–8		*K. tibetica*	0.60
			H. vulgaris	11.1
			C. muliensis	4.60
			Bare shore	4.90
			P. amphibium	4.90
Huashi-xia	1997/5–9	Jin et al. (1999)	–	1.69
Luanhaizi	2002/7–9	Hirota et al. (2004)	*Carex allivesers*	9.00
			Scirpus distigmaticus	5.80
			Hippuris vulgaris	12.1
			Potamogeton pectinatus	2.40
Taihu	2003/8–2004/8	Wang et al. (2006a)	Infralittoral zone	10.0
			Eulittoral zone	2.60
			Bare shore	0.4
			Pelagic zone	0.50
			Supralittoral zone	0.10
Yangtze Estuary	2004/8–2005/7	Wang et al. (2009a, b)	Middle flat	2.06
			Low flat	0.04

Table 1 continued

Wetland	Measured period	Investigators	Vegetation/wetland type	Mean CH_4 fluxes (mg CH_4 m^{-2} h^{-1})
Min River Estuary	2007/1–12	Tong et al. (2010)	*Phragmites australis*	4.34
			Cyoerus malaccensis	4.65
			Scirpus triqueter	0.71
			Bare shore	5.54
			Spartina alterniflora	11.02
			Phragmites australis	4.98
Tai-wan	1995/9–1999/4	Chang and Yang (2003)	–	1.82
			–	0.14
Hai-nan	1997/5,11	Lu et al. (1999)	Mangrove	0.03
Wu-liangsu	2003/4–10	Duan et al. (2005)	*Phragmites communis*	8.75
Xilin River basin	2003–2005/4–10	Wang et al. (2009b)	–	13.18
	11–12, 1–3			3.1

the spatial and temporal variation in CH_4 flux that was determined by vegetation zones. Ding and his collaborators (Ding et al. 2004; Ding and Cai 2007) measured the seasonal variations in CH_4 fluxes from *carex* wetland, and they concluded that water and temperature were the key factors to influence the emission rate of CH_4. Chen and his collaborators (Chen et al. 2008, 2009a, b; Zhu et al. 2011) discussed the spatial and temporal variations in CH_4 emissions that resulted from these variations in temperature, plant growth, and water factors.

In Northeast China, researchers at the Northeast Institute of Geography, Agricultural and Ecology (Zhang et al. 2005; Song et al. 2006, 2008; Sun et al. 2011), in collaboration with the State Key Laboratory of Soil and Sustainable Agriculture (Ding et al. 2004, 2005; Ding and Cai 2007), measured CH_4 fluxes from herbaceous swamp and forested wetland, and discussed the spatial and temporal variations in CH_4 fluxes and their influencing factors. They found that standing water depth determined the type of marsh plants, which governed CH_4 transport and the amount the of plant litters (Sun et al. 2011; Ding and Cai 2007).

In North China, there was only one report on CH_4 emission from *Phragmites australis* in Liaohe Delta (Huang et al. 2011). Field experiments showed that this wetland acted as a CH_4 sink in spring, a strong source in summer, and a weak source in autumn, and this temporal variation was positively related to temperature and negatively related to Eh (soil redox potential) value and water depth. In inner Mongolia, two measurements were carried out in the middle and lower reaches of large rivers and lakes in semiarid region (Duan et al. 2005; Wang et al. 2005, 2009b) and showed that vegetation cover, water depth, bottom silt temperature, and light intensity were important factors influencing seasonal and diurnal variation in CH_4 flux.

In the two geophysical regions of South and Central China, CH_4 fluxes from natural wetlands were measured over one year. Yangtze and Min River Estuary, Taihu, Taiwan, and Hainan attracted much attention (Lu et al. 1999; Chang and Yang 2003; Wang et al. 2009a; Tong et al. 2010). These studies showed that CH_4 emissions from herbaceous swamps were much higher than those from mangroves, and the emission rates from beaches were greatly influenced by tidal stages.

Although numerous studies referred to the rate of CH_4 fluxes in different types of geophysical regions, only a few made estimates about overall geographical CH_4 emissions from natural wetlands in China. Ding et al. (2004), and Ding and Cai (2007) discussed the spatial and temporal variations in CH_4 releases from natural wetlands in Northeast China and Qianghai-Tibetan Plateau, estimated total emissions based on their in situ measurements, and showed the available CH_4 fluxes measured in North China, South China, and Qianghai-Tibetan Plateau (Huang et al. 2011; Lu et al. 1999; Jin et al. 1999). The preliminarily estimated emissions levels of CH_4 from natural wetlands in China were 1.48 Tg (terrogram, unit of weight) CH_4 over growing season and 1.76 Tg CH_4 per year (Ding et al. 2004). However, the huge spatial and seasonal variations in CH_4 emission from natural wetlands are observed in the mentioned monitoring stations, and regional differences can be significant, even when the sites are similar in climate, vegetation, and topography (Yavitt et al. 1988; Ding et al. 2004). Improving the assessment of CH_4 emissions from natural wetlands of China, requires having additional field measurements of CH_4 fluxes in various kinds of vegetation and climate conditions as well as additional information about the various wetland areas.

This study estimates the spatial distribution of CH_4 release from natural wetlands (excluding water surface) around China based on existing investigations on CH_4 fluxes from the 1990s and 2000s. The investigations were conducted in 2007 and 2008 at Xiaoxing'anling (128°38′E, 48°7′N), from 1995 to 1996, and from 2001 to 2004 at Sanjing Plain (133°13′E, 47°35′N), in 2000 at Liaohe Delta (121°35′E, 40°52′N), in 2001 and 2002 at Ruoergan Plateau (102°32′E, 32°47′N), from 2005 to 2007 at Wetland National Nature Reserve of Zoige (102°52′E, 33°56′N), in 2006 and 2007 at Huahu (102°2′E, 33°6′N), in 1997 at Huashixia (98°48′E, 35°39′N), in 2002 at Luanhaizi (102°12′E, 37°29′N), in 2003 and 2004 at Taihu (120°E, 31°N), in 2004 and 2005 at Yangtze Estuary (121°30′E, 31°39′N), in 2007 at Min River Estuary (119°34′ – 119°40′E, 26°32′ – 26°36′N), from 1995 to 1999 at Kuandu (120°27′E, 25°7′N) and Kangnan (120°53′E, 24°45′N) of Taiwan, in 1997 at Hainan (110°24′E, 19°51′N), in 2003 at Wuliangsu (108°43′ – 108°57′E, 40°47′ – 41°3′N), and from 2003 to 2005 at Xilin River basin (115°32′ – 117°12′E, 43°26′–44°39′N). This analysis was made to supply the national greenhouse gas inventories, giving updated background information about CH_4 released from natural sources in China, and it also could improve the estimates of the global carbon levels, and provide helpful information that could enhance carbon sequestration capacity in China.

Materials and methods

Databases

As any area is considered as fully natural state, for this study, "natural" covers all wetlands as determined 2000 National Land Survey Data from the Data Sharing Network of Earth System Science (http://www.geodata.cn). The land cover map is derived from remotely sensed data with a spatial resolution of 1 km × 1 km. The values for the land cover map range from 0 to 100 %, representing the percentage of this kind of land cover in every 1 km × 1 km plot. Three types of wetland-related land cover data are extracted: tidal beaches, bottomland, and marshes, with areas of 6,424, 82,068, and 44,417 km^2, respectively.

China is divided into 7 physicogeographical regions, considering the conditions of vegetation, climate, soil, and landform. These geophysical regions are named as the Northeast, North, Central, South, and Northwest China, Inner Mongolia, and Qinghai-Tibet Plateau (Fig. 1). In addition, The Shuttle Radar Topographic Mission digital elevation model (DEM) data set (http://eros.usgs.gov/#Find_Data/Products_and_Data_Available/gtopo30_info) is used to generate topographic data in China, and helped to identify wetland types.

Method

To obtain the spatial distribution of CH_4 emission in China, the pix-based wetland information (http://www.geodata.cn) is used. Methane emission (ME) at each pixel is calculated based on the following equation:

$$\mathrm{ME}_{(i,j,m)} = \mathrm{MEG}_{(i,j,m)} + \mathrm{MENG}_{(i,j,m)} \tag{1}$$

where $\mathrm{ME}_{(i,j,m)}$ is CH_4 flux at the pixel location ($i. j$) in the geophysical region m. $\mathrm{MEG}_{(i,j,m)}$ and $\mathrm{MENG}_{(i,j,m)}$ is CH_4 flux during growing season and non-growing season, respectively.

Then, CH_4 emission during growing season could be estimated by the equation as follows:

$$\mathrm{MEG}_{(i,j,m)} = \mathrm{FG}_m A_{(i,j,m)} D_m \tag{2}$$

where $A_{(i,j,m)}$ is the area of pixel at the location (i, j), which is provided by the land use map. FG_m and D_m is the mean CH_4 flux (mg CH_4 m^{-2} h^{-1}) and the duration (h) of plant growth period in m geophysical region, respectively.

CH_4 flux shows strong variations from different vegetation types in different geophysical regions. Therefore, the averaged CH_4 flux during measured period was calculated by the following equation:

$$\mathrm{FG}_m = \sum_{n=1}^{N} \mathrm{AP}_n F_{mn} \tag{3}$$

where AP_n is the area proportion of plant n in the geophysical region m, and F_{mn} is the measured CH_4 flux from plant n in geophysical region m.

If there is no references on vegetation proportion in a geophysical region, mean CH_4 values in each study are adopted. And then, these values are averaged again by different studies within the geophysical region as mean CH_4 flux.

Results and discussion

Spatial distribution of natural wetlands in China

The study area was all of China - 9,600,000 km^2. About 1.4 % of that area consists of wetlands, which spreads throughout the whole country. As for topographical conditions, natural wetland is found not only at the sea level in the eastern part of China but also on the plateau with an elevation of more than 3,000 m in southwestern part of China. Most of the natural wetlands are located in Northeast, Southeast China, and Inner Mongolia. Specifically, about 30.62 % is located in Northeast China, 28.27 % in Qinghai-Tibet Plateau, and 16.44 % in Inner Mongolia. The North, Central, Northwest, and South China has

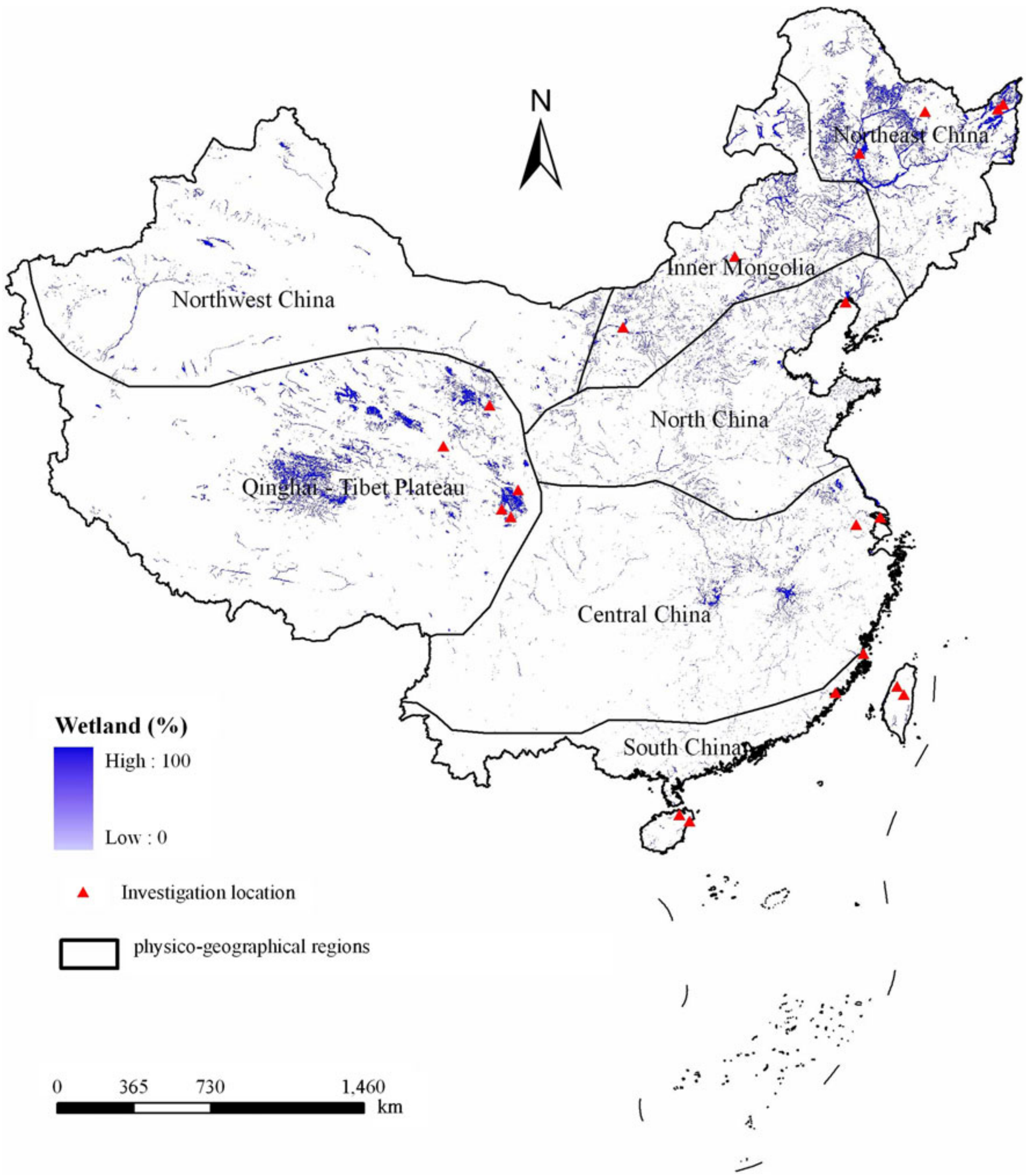

Fig. 1 Spatial distribution of natural wetland and measurements on CH_4 fluxes conducted in China

relative low proportion of natural wetland, and the ratio is 8.14, 7.8, 7.61, and 1.12 %, respectively (Table 2).

In the study of Ding, mentioned that the total area of natural wetland used to estimate CH_4 emission is 94,000 km^2, of which 51.15 and 30.29 % of natural wetland is located in Qinghai-Tibet highland and Northeast China, respectively (Ding et al. 2004). The big difference in the wetland areas between this study and Ding et al. (2004) might be that the total natural wetland excludes floodplain in Ding et al. (2004), while are included in this study. If the floodplain is not included, the natural wetland in this study is 82,068 km^2.

CH_4 release factor and duration of plant growth

Wetland plants play an important role in the three main aspects of methane emissions: (a) providing conduits for methane transportation, (b) supplying substrates for methanogens through root exudation, and (c) delivering O_2 to oxidize methane through roots to rhizosphere (Schütz et al.

Table 2 Statistics of the natural wetland (excluding water surface) area by geographical regions in China

Physico-geographical regions	Area (km^2)	Proportion (%)
South China	1,143	0.86
South China—Mangrove	352	0.26
Central China	10,109	7.61
Qinghai-Tibet Plateau	37,577	28.27
Northwest China	10,360	7.80
Inner Mongolia	21,848	16.44
North China	10,818	8.14
Northeast China—mountain area	10,019	7.54
Northeast China—plain	30,684	23.09
Total	132,909	100.00

1991). Therefore, strong variations in CH_4 release existed among various plant types.

There are five main wetland types in mountain areas in Northeast China. The CH_4 release from marsh, thicket swamp, and coniferous forested swamp is calculated from *Carex schmidtii* and *Calamagrostis angustifolia*, *Betula ovalifolia*, *Larix gmelinii—C. schmidtii*, respectively (Table 1). The emitted CH_4 fluxes from the other two wetlands of deciduous forested swamp and forested peatland are estimated according to the averaged CH_4 releases from *Alnus sibirica* and *Betula platyphylla*, and *Larix gmelini—Moss* and *L. gmelinii—sphagnum* spp., respectively. The area proportion of marsh, thicket swamp, coniferous forested swamp, deciduous forested swamp, and forested peatland is 60.43, 17.52, 19.37, 1.01, and 1.66 %. Thus, F_{mn} in mountain area (DEM > 300 m) of Northeast China is 11.60 mg CH_4 m^{-2} h^{-1} following Eq. 3 (Table 2). Since there is only one observation reported in this area, the maximum and minimum release factor is the same with the mean value.

Based on the measurements on CH_4 emissions in Sanjiang Plain (Table 1), the averaged CH_4 flux from *Carex hair*, *C. pseudocuraica*, and *Deyeuxia angustifolia* is 13.16 mg CH_4 m^{-2} h^{-1}, 4.03 mg CH_4 m^{-2} h^{-1}, and 10.80 mg CH_4 m^{-2} h^{-1}. The maximum CH_4 flux from the above three kinds of plants is 19.65 mg CH_4 m^{-2} h^{-1}, 6.48 mg CH_4 m^{-2} h^{-1}, and 10.80 mg CH_4 m^{-2} h^{-1}, and the minimum value is 10.45 mg CH_4 m^{-2} h^{-1}, 1.59 mg CH_4 m^{-2} h^{-1}, and 10.80 mg CH_4 m^{-2} h^{-1}. Among herbaceous swamp areas in Sanjiang Plain, *C. hair*, *C. pseudocuraica*, and *D. angustifolia* account for 81.90, 10.50, and 7.60 %, respectively, in Sanjiang Plain. Thus, CH_4 emission from herbaceous swamp is 12.03 mg CH_4 m^{-2} h^{-1}, with a maximum value of 17.59 mg CH_4 m^{-2} h^{-1} and a minimum value of 9.55 mg CH_4 m^{-2} h^{-1}.

In Qinghai-Tibet Plateau, CH_4 flux measurements are taken on many vegetation types. The regional mean CH_4 flux is firstly calculated for each study, and then the averaged value from different studies is deemed as the averaged CH_4 flux. In Chen study (2008), the coverage of *Carex muliensis*, *Eleocharis valleculosa*, and *Kobresia tibetica* accounts for the study area is 30, 25, and 45 %, respectively; thus, the averaged CH_4 flux is 13.44 mg CH_4 m^{-2} h^{-1}. In Huahu Lake, the area for *G. maxima*, *K. tibetica*, *H. vulgaris*, *C. muliensis*, *Bare shore*, and *P. amphibium* accounts for 25, 15, 10, 15, 20, and 15 %, respectively, and the mean CH_4 flux is 15.21 mg CH_4 m^{-2} h^{-1} (Chen et al. 2009b). In Luanhaizi wetland, *Carex allivescers V. Krez*, *Scirpus distigmaticus* L., *Hippuris vlugaris* L., and *Potamogeton pectinatus L.* make up 3.4, 20.5, 2.6, and 73.5 % of the study area (Hirota et al. 2004), and the mean CH_4 flux is 3.57 mg CH_4 m^{-2} h^{-1}. In the study of Ding et al. (2004) and Jin et al. (1999), the mean CH_4 flux is calculated by averaging values from the different vegetation types, which is 2.97 and 1.69 mg CH_4 m^{-2} h^{-1}, respectively. When compared to each other, there was a large gap in CH_4 flux between Chen et al. (2008, 2009a) and the other studies by Ding et al. (2004), Jin et al. (1999), and Hirota et al. (2004). This gap might have been caused by different vegetation types and environmental factors, since mean CH_4 fluxes from *vulgaris* are very close, 11.1 mg CH_4 m^{-2} h^{-1} in Chen et al. (2009b) and 12.1 mg CH_4 m^{-2} h^{-1} in Hirota et al. (2004). Finally, the CH_4 flux in Qinghai-Tibet Plateau is 7.38 mg CH_4 m^{-2} h^{-1} by averaging the five CH_4 fluxes from the five aforementioned studies, the maximum CH_4 release is 15.21 mg CH_4 m^{-2} h^{-1}, and the minimum value is 1.69 mg CH_4 m^{-2} h^{-1} (Table 2).

In South China, mangroves are mainly distributed along seaside. The tidal beach marked on the land cover map along seaside is deemed as the mangrove wetland, and the others are considered as herbaceous swamp. Mangrove trees are mainly distributed in Fujian, Guangdong, Guangxi, Taiwan, and Hainan. The measured CH_4 release factor of 0.03 mg CH_4 m^{-2} h^{-1} from mangroves in Hainan province by Lu group Lu et al. (1999) is used as the CH_4 emission rate from mangroves in South China. Tidal beaches in the five provinces are located in South China. The mean CH_4 fluxes from herbaceous swamp are obtained by averaging the measured CH_4 fluxes in Min River Estuary and in Taiwan, and the averaged value is 2.18 mg CH_4 m^{-2} h^{-1}, with maximum of 4.57 mg CH_4 m^{-2} h^{-1} and the minimum of 0.14 mg CH_4 m^{-2} h^{-1}.

In the three geophysical regions of North China, Central China, and Inner Mongolia, mean CH_4 flux is calculated by averaging the measured CH_4 fluxes from wetlands in their respective regions. Since there is no investigation into CH_4 fluxes in Northwest China, the measurements in Wuliangsu Lake are used for the CH_4 release from wetlands (Duan et al. 2005), where the environmental conditions are similar with that in Northwest China. The detailed information about CH_4 release factors in the three geophysical regions is listed in Table 3.

The estimates made in the growing season indicate only a ratio of the measured CH_4 flux, as an assumption that is emitted during the unmeasured period (Ding et al. 2004). In Sanjiang Plain, the mean CH_4 fluxes (November–April) are 0.5 and 0.18 mg CH_4 m^{-2} h^{-1} for *Carex Lasiocarpa* and *D. angustifolia*, respectively (Zhang et al. 2005), which are about 4.35 and 2.88 % of the measured fluxes for the two plants in Song et al. (2008). The averaged contribution of 3.61 % is used to calculate CH_4 fluxes during non-growing season in Northeast, North, and Northwest China and Inner Mongolia. In Qinghai-Tibet Plateau, the area-weighted mean CH_4 flux is 0.36 mg CH_4 m^{-2} h^{-1}, which accounted for 3.00 % of the measured CH_4 fluxes by Chen et al. (2008).

The duration of wetland plant growth is a key factor to influence estimation results. It is assumed to be 165 days in plain wetland in Northeast China and 150 days in mountainous area in Northeast China and in Qinghai-Tibet Plateau (Jin et al. 1999). In North, Northwest, South, and Central China, and Inner Mongolia, the measurement period is used as the plant growth duration. In South and Central China, the measurements are conducted around a year; thus, 365 days are used as plant growth period.

Estimate of annual CH_4 emission from natural wetland in China

The spatial distribution of annual CH_4 emission from natural wetland is described in Fig. 2. The estimated CH_4 emissions range from 0 to 5,702.8 kg per pixel with the area of 1 km^2. It is obvious that high CH_4 emissions occurred in the North and Northeast area of China, while low values are in the south and east regions. Specifically, the northeast China has the highest contribution to the total CH_4 emissions from natural wetland in China (39 %), Inner Mongolia and Qinghai-Tibet highland account for about 25 % and 21 %, respectively, and the other 15 % of released CH_4 is in northwest, north, central, and south China (Table 4).

The spatial variation in CH_4 emissions is strongly correlated with that of the area proportion of wetlands, and their correlation coefficient reaches to 0.90. This indicates that the spatial variation in CH_4 released from natural wetlands is mainly controlled by the area of wetlands. From Tables 2 and 4, the percentages of wetland in Northeast China—plain, Inner Mongolia, Northwest China, and Northeast China—mountain area are lower than their corresponding proportion of CH_4 emissions. This might be because of the combined influences of plant types, duration of plant growth, and climatic conditions.

The total CH_4 release from Chinese natural wetlands ranges from 3.48 to 7.16 Tg $year^{-1}$, with the mean value of 4.94 Tg CH_4 per year. This showed that China had a 4.5 % contribution to global natural wetland CH_4 emission levels (110 Tg CH_4) (Matthews and Fung 1987). Our estimates are much higher than that by Ding et al. (2004, 1.78 Tg CH_4 $year^{-1}$), and even the minimum value is about twice by Ding et al. (2004). This was mainly because this study adopted almost twice the wetland area as well as higher CH_4 factors. CH_4 release factor in Qinghai-Tibet Plateau is 7.38 mg CH_4 m^{-2} h^{-1} used in this study and 2.96 mg CH_4 m^{-2} h^{-1} in Ding et al. (2004). In South China, the CH_4 release factor is 0.05 mg CH_4 m^{-2} h^{-1} for mangrove wetland and 2.18 mg CH_4 m^{-2} h^{-1} for herbaceous swamp in this study, while 0.05 for all of the wetland in Ding et al. (2004). There are also some studies on estimating CH_4 emissions in local areas. In Qinghai-Tibet

Table 3 CH_4 fluxes from natural wetlands and duration of plant growth in China

Geophysical region	Mean/maximum/minimum CH_4 fluxes during growth period (mg CH_4 m^{-2} h^{-1})	Duration of measurement period (days)/begin–end (months)	Mean/maximum/minimum CH_4 fluxes during non-growth period (mg CH_4 m^{-2} h^{-1})	Duration of non-measured period (days)
Northeast China—Mountain area	11.60/11.60/11.60	150/5–10	0.42/0.42/0.42	215
Northeast China—Plain	12.03/17.59/9.55	165/5–10	0.43/0.64/0.34	200
North China	0.52/0.52/0.52	240/4–11	0.02/0.02/0.02	125
Qinghai-Tibet Plateau	7.38/15.21/1.69	150/5–9	0.22/0.46/0.05	215
Northwest China	8.75/8.75/8.75	210/4–10	0.32/0.32/0.32	154
Inner Mongolia	10.97/13.18/8.75	210/4–10	0.40/0.48/0.32	154
Central China	2.2/3.35/1.05	365/1–12		0
South China—mangroves	0.03/0.03/0.03	365/1–12		0
South China—herbaceous swamp	2.18/4.57/0.14	365/1–12		0

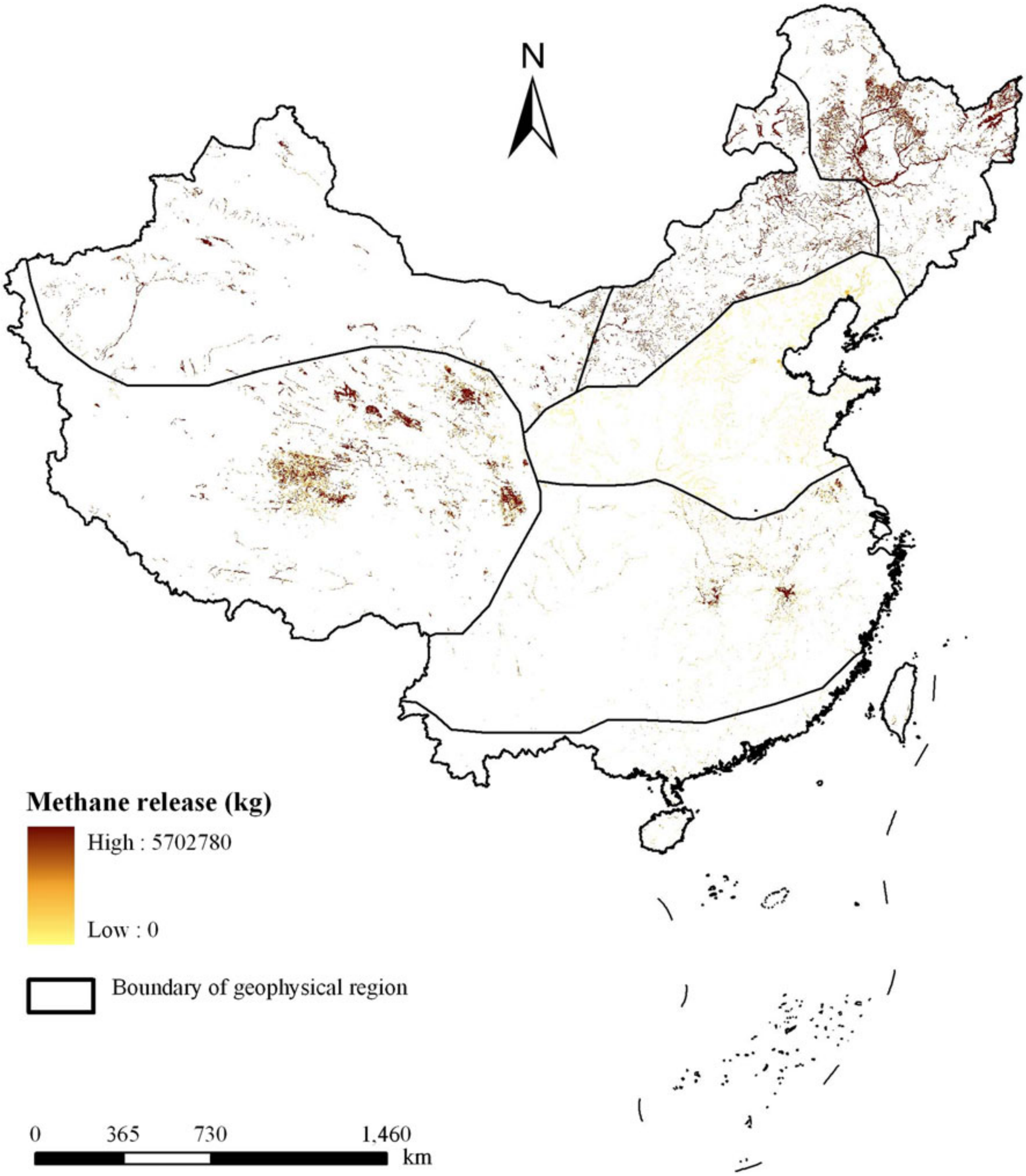

Fig. 2 Spatial distribution of estimated CH_4 emissions

Plateau, the annual CH_4 release is 0.90 Tg from 133,000 km^2 wetlands by Jin et al. (1999), 0.56 Tg from 48, 073 km^2 wetlands by Ding et al. (2004), and 1.04 Tg from 37,577 km^2 wetlands in this study. The two latter estimates are conducted only based on their measurements, while our estimate involves these two measurements and other investigations in recent results. Wang et al. (2005) also reported that the averaged CH_4 emission rate for riparian mires in semiarid area was at the upper end of the range reported previous studies of natural wetlands in China, and if their 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 year^{-1}.

Compared with the earlier estimation, this study contains several improvements. First, the natural wetland map is used to estimate CH_4 releases at per km^2, and the spatial distribution of CH_4 emissions is firstly obtained in China. Second, the simplified differentiation of wetland types by Ding et al. (2004) does not fit to estimate CH_4 efflux, since CH_4 emissions is also greatly influenced by plant, climate, and other environmental factors. In the current approach,

Table 4 Statistics of CH_4 release from natural wetland (excluding water surface) area by geographical regions in China

Physico-geographical regions	CH_4 emissions (Gg year^{-1})	Proportion (%)
South China	17.08	0.35
South China—Mangrove	0.27	0.01
Central China	191.66	3.88
Qinghai-Tibet Plateau	1,040.86	21.09
Northwest China	468.90	9.50
Inner Mongolia	1,237.06	25.06
North China	31.90	0.65
Northeast China—mountain area	440.09	8.92
Northeast China—plain	1,507.79	30.55
Total	4,935.61	100.00

geophysical regions and vegetation portion are considered to take into account the effects of climate and plant on CH_4 efflux. Finally, CH_4 release factor is updated with the recent scientific literature. In Ding et al. (2004), only four measurements were used to estimate CH_4 emission levels in China, while in this study, more than 25 investigations are used to calculate the total emissions. These 25 investigations are distributed around China, not only located in Qinghai-Tibet and Northeast China. These new measurements are not supplementary to the existed measurements on CH_4 emission in Northeast China and Qinghai-Tibet Plateau, but also provide new information in the unmeasured areas. For example, in Ding et al. (2004), CH_4 emission from salt marsh was not included since there were no measured CH_4 fluxes. However, CH_4 emission from salt marsh is not insignificant and so should not be negligible (Magenheimer et al. 1996; Tong et al. 2010).

Uncertainty analysis and future research needs

Due to the simplified nature of CH_4 release calculations, the uncertainty of the final efflux estimation could be evaluated only qualitatively. This evaluation is performed using the scale created for atmospheric emissions. The uncertainty scale C is defined as that an estimate based on a number of measurements made at a small number of representative facilities, and the typical error rate is 50–150 %; scale D is defined as that an estimate based on single measurements, and typical error rate is 100–300 % (UNECE 2004). According to the definitions on uncertainty scale, the estimates on CH_4 emissions in North, Northwest, mountain areas in Northeast China belong to uncertainty scale D, and the others are scale C. Although the Chinese territory is divided into 7 geophysical regions to represent the regional difference between climate and soil condition, strong variations are also found in measured CH_4 effluxes in each region. Therefore, with additional field measurements of CH_4 flux, an improved assessment of CH_4 emission from natural wetlands of China may be possible.

The uncertainties of CH_4 release estimates arise from uncertainties in the prediction of the area of natural wetland. The areas of natural wetland (including water surface) in China show large gaps from different sources and by different studies, 152,000 km^2 determined by Changchun Institute of Geography, Chinese Academy of Sciences, 256,878 km^2 extracted from 2000 National Land Survey Data, 224,568 km^2 by East China Normal University, and 359,478 km^2 identified from remote sensing data (Niu et al. 2009). The strong variations in natural wetland areas are directly important causes of the gaps, which estimated CH_4 emissions in China between different studies. Moreover, China's natural wetlands are disappearing even faster than feared, 33 % of which were lost between 1978 and 2008 (Gong et al. 2010). In this study, the 2000 National Land Survey Data is used, and by now the wetland might have decreased further, and the annual CH_4 release might be higher estimated in this study.

In this study, the influence of soil conditions on CH_4 release is not considered. Methane emission from wetlands results from the interaction between several biological and physical processes in the soil, which is strongly regulated by the amount and quality of available substrate, pH, and temperature (Yavitt and Lang 1990; Westermann 1996). Moreover, 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 different riparian sites (Wang et al. 2005). In further study in estimating CH_4 emissions from natural wetland, a detailed soil map on physical characteristics should be provided.

Conclusion

As mentioned in Introduction section, numerous studies are conducted to measure the rate of CH_4 fluxes in different regions, but just few estimates about overall geographical CH_4 emissions in China. Based on the spatial distribution of wetland, plant types, duration of plant growth, and geophysical divisions, this study firstly estimates the spatial variations in annual CH_4 emissions from natural wetlands excluding water surface in China, with the pixel size of 1 km × 1 km. The estimated annual CH_4 emissions range from 0 to 5702.8 kg per pixel with the area of 1 km^2, and the spatial variation in CH_4 emissions is strong correlated with that of wetlands. The total CH_4 emission from natural wetland in China was 4.94 Tg year^{-1}, higher than that by Ding et al. (2004) since the larger areas of natural wetland and higher CH_4 release factor are used. The wetland in northeast China had the highest contribution to the total CH_4 emissions in China, Inner Mongolia and Qinghai-Tibet highlands had the second highest contribution, and northwest, north, central, and south China had the least.

Acknowledgments Funding support was from the Specialized Research Fund for the Doctoral Program of Higher Education of China (20100091120017), National Natural Science Foundation of China (41101315 and 41171324), funding of visiting scholar project by CSC(201208320130), Fundamental Research Funds for the Central Universities, and the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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