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Review

Soil methane uptake by grasslands and forests in China

Yanfen Wang [a], Huai Chen [b,c,d,*], Qiuan Zhu [c,d], Changhui Peng [e,c], Ning Wu [b,d,f], Gang Yang [c,d], Dan Zhu [b,d,f], Jianqing Tian [g,d], Liuxi Tian [c,d], Xiaoming Kang [h], Yixin He [b,d], Yongheng Gao [i,d], Xinquan Zhao [b,j]

[a] University of Chinese Academy of Sciences, Beijing 100049, China
[b] Chengdu Institute of Biology, Chinese Academy of Sciences, Chengdu 610041, China
[c] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, College of Forestry, Northwest A&F University, Yangling 712100, China
[d] Zoige Peatland and Global Change Research Station, Chinese Academy of Sciences, Hongyuan 624400, China
[e] Center of CEF/ESCER, Department of Biology Science, University of Quebec at Montreal, Montreal C3H 3P8, Canada
[f] International Centre for Integrated Mountain Development, GPO Box 3226, Kathmandu, Nepal
[g] Institute of Microbiology, Chinese Academy of Sciences, Beijing 100101, China
[h] Institute of Wetland Research, Chinese Academy of Forestry, Beijing 100091, China
[i] Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China
[j] Northwest Institute of Plateau Biology, Chinese Academy of Sciences, Xining 810008, China

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ABSTRACT

Sinks of methane (CH_4) become highly variable due to both human activity and climate change. An urgent need therefore exists to budget key sinks of CH_4, such as forests and grasslands. In this study, CH_4 uptake of forests and grasslands in China was first reviewed and then estimated based upon the review itself. Total uptake from the two CH_4 sinks were 1.323 Tg CH_4 yr^{-1} in China (ranging from 0.567 to 2.078 Tg CH_4 yr^{-1}), lower than a previous estimate in China (2.56 Tg CH_4 yr^{-1}). Among the uptake, 0.650 Tg CH_4 yr^{-1} (ranging from 0.168 to 1.132 Tg CH_4 yr^{-1}) was consumed by grasslands and 0.675 Tg CH_4 yr^{-1} (ranging from 0.399 to 0.946 Tg CH_4 yr^{-1}) by forests. The largest CH_4 uptake of grasslands was found in the Qinghai-Tibetan Plateau High-Frigid Domain, which consumed 0.284 Tg CH_4 yr^{-1}, about 44% of the whole uptake of grasslands in China. The greatest CH_4 uptake (0.553 Tg CH_4 yr^{-1}) of forests took place in Eastern Humid and Semi-humid Domain of the country, which was about 82% of the total annual CH_4 uptake of forests in China. With forests and grasslands taken together, Eastern Humid and Semi-humid Domain was the largest CH_4 consumer, taking up about 0.715 Tg CH_4 yr^{-1}, accounting for 82% of the whole forest uptake and 25% of the whole grassland uptake in China. On the ecoregion scale, due to extensive forest distribution and longer growing season, Southern Asia monsoon broadleaf forest ecoregion was the greatest CH_4 uptake (0.320 Tg CH_4 yr^{-1}) of forests and grasslands in China, consuming more CH_4 than the Northeastern Arid and Semi-arid Domain combined. Our results indicated that forests and grasslands are not constant sinks of CH_4 but decreasing ones influenced by climate change and anthropogenic activity. More field data, mechanism understanding and process-based models could help better estimate and understand CH_4 uptakes of forests and grasslands in China.

1. Introduction

Methane (CH_4) is an important greenhouse gas, about 25 times more powerful in warming the atmosphere than carbon dioxide (CO_2) for the time horizon of 100 years (Denman et al., 2007). It is also involved in a number of chemical reactions which can exert strong influence over chemistry of the troposphere and the stratosphere (Cicerone and Oremland, 1988). Recently, a study reported that CH_4 emissions have larger overall impacts than current carbon-trading schemes, which modified its radiative forcing from +0.48 W m^{-2} to +0.90 W m^{-2} (Forster et al., 2007; Shindell et al., 2009). Therefore, CH_4 as an important greenhouse gas second only to CO_2, has a considerable impact on the earth's climate

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[*] Corresponding author. Chengdu Institute of Biology, Chinese Academy of Sciences, Chengdu 610041, China. Tel.: +86 28 82890543; fax: +86 28 82890536.
E-mail address: chenhuai@cib.ac.cn (H. Chen).

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system. Since the preindustrial era, atmospheric CH_4 increased significantly and reached a new high of 1813 ppb in 2011, 159% higher than the pre-industrial level (WMO, 2013). Moreover, after a near zero-growth decade from 1997 to 2006, a renewed growth in atmospheric CH_4 occurred since 2007 (Rigby et al., 2008; Dlugokencky et al., 2009). The present global CH_4 budget must therefore be determined without delay (Heimann, 2010).

Biological CH_4 oxidation in drier soil is one of the major CH_4 sinks, absorbing 26 to 34 Tg CH_4 yr^{-1} (Denman et al., 2007), making it the second largest sink after CH_4 oxidation in the troposphere (Ueyama et al., 2012; Wang et al., 2012). With the uncertainty range about ±15 Tg (CH_4) (50%), soil CH_4 oxidation is also one of the most uncertain sinks (Denman et al., 2007). The uncertainties in the global CH_4 budget come mainly from the limited observational data coverage and the great variation in the factors influencing CH_4 fluxes (Heimann, 2011). Among all, forest and grasslands soils under well-aerated conditions are recognized as a major contributor to the global soil CH_4 uptake. The contribution of forest soils to the global soil CH_4 uptake was estimated as 11.6 Tg CH_4 yr^{-1} (52%) (Dutaur and Verchot, 2007). Based on direct extrapolation of multiyear measurements, CH_4 uptake by temperate grasslands was preliminarily estimated to be 4.3 Tg CH_4 yr^{-1} (Mosier et al., 1991) and then refined as 2.3 Tg CH_4 yr^{-1} based on a literature review (Mosier et al., 1997). Thus, it would be very helpful to estimate CH_4 uptake from forests and grasslands on national, regional, as well as global scales (Mosier et al., 1991; Dutaur and Verchot, 2007; Vuichard et al., 2007; Wang et al., 2009c).

There are some estimates of national CH_4 budget in China. Anthropogenic CH_4 emission was about 34.29 Tg CH_4 yr^{-1} as presented by the People's Republic of China Initial National Communication on Climate Change (2004), which was submitted to the UNFCCC (http://unfccc.int/resource/docs/natc/chnnc1exsum.pdf). Several studies have made efforts to estimate the national emission of rice paddies (Cao et al., 1995; Kern et al., 1997; Huang et al., 1998; Khalil et al., 1998; Wang and Li, 2002; Huang et al., 2006; Cai, 2012; Chen et al., 2013), natural wetlands (Ding et al., 2004; Cai, 2012; Chen et al., 2013), and lakes (Chen et al., 2013). Based on limited measurement, aerobic soils was estimated to take up atmospheric CH_4 at a rate of 2.56 Tg CH_4 yr^{-1} (Cai, 2012). So far to the best of our knowledge, there is no synthesis study on a comprehensive CH_4 budget for either grasslands or forests in China, which is indispensable for a general CH_4 uptake estimate for this country.

Multiple studies on CH_4 fluxes of grasslands in China have already been carried out (Du and Chen, 1997; Wang et al., 1998, 2000, 2005, 2007, 2009b; Dong et al., 2000, 2005; Ma et al., 2006; Li et al., 2007; Liu et al., 2007, 2011, 2012a; Holst et al., 2008; Sun, 2008; Chen et al., 2010; Geng et al., 2010; Zhou et al., 2011; Luo and Jiao, 2012; Wei et al., 2012; Zhang et al., 2012), some even making efforts to estimate the total emission for specific regions (Du et al., 2005; Liu et al., 2009a; Wang et al., 2009c). Relatively fewer studies on CH_4 fluxes of forests in China have been published (Xu et al., 1995; Sun, 2000; Dong et al., 2003; Du et al., 2004; Mo et al., 2005; Yang et al., 2010; Liu et al., 2010b, 2012b; Guan et al., 2012; Yang, 2012). Increased knowledge concerning CH_4 uptake from forests and grasslands in China is important to understand the CH_4 budget of China as well as that of the world.

In light of such a rationale, this study had three primary objectives: 1) to review and analyze the existing studies on CH_4 uptake from grasslands and forests in China; 2) to provide estimates of the total CH_4 uptake from these two sinks; and 3) examine the existing knowledge gap and attempt to propose the future study direction to address the gaps.

2. Methods and materials

2.1. Data source and analyses

The latest information available of individual sites served as the original data sources for the map of dataset for CH_4 uptake of forests and grasslands in China (Fig. 1). We obtained the corresponding data from available published papers and dissertations including mean CH_4 uptake rates and their ranges, location site, latitude and longitude by using the "*GetData*" software (Version 2.24) and collected the available data in text format (Table S1 and Table S2). According to ecological zonation of China (Fu et al., 2001), there are three domains (Eastern Humid and Semi-humid Domain (EHSD)), Northeastern Arid and Semi-arid Domain (NASD) and Qinghai-Tibetan Plateau High-Frigid Domain (QPHD) and thirteen ecoregions in China (Fig. S1). In this study, we calculated the mean CH_4 uptake rates of forests and grasslands and their standard errors based on the data we collected, which clustered in the three domains (Fig. 1 and Fig. S1). Analysis of variance (ANOVA) was used to compare averages of CH_4 uptake rates in each domain for both forests and grasslands.

2.2. CH_4 emission estimation from grasslands and forests in China

2.2.1. CH_4 uptake calculation

The following formula was used to calculate the CH_4 uptake (MU) rate of grasslands and forests in each ecoregion of China:

$$\mathrm{MU} = \sum_i \sum_j \sum_k SR_{ijk} {}^* A_{ijk} {}^* D_{ijk}$$

Where *i* is the ecological domain (ESHD, NASD and QPHD); *j* is the growing season and non-growing season (in each domain); and *k* is the ecoregion. SR_{ijk} is the seasonal mean uptake rate under conditions of *i*, *j* and *k*. A_{ijk} is the grassland or forest area, and D_{ijk} is the duration of the growing and non-growing season. The range is calculated as from mean minus SD to mean plus SD in each ecoregion.

2.2.2. Grassland and forest area

Grassland (not including shrublands) in China is manly distributed in the NASD and QPHD. The area of grasslands in China in this study was obtained from one of the three grassland resource inventories since 1979, the one from 1981 to 1988 which covered more than 2000 counties in China (Department of Animal Husbandry and Veterinary et al., 1996). The forest inventory database was based on the Forest Resource Inventory of China since 1973, which spanned six periods: 1973–1976, 1977–1981, 1984–1988, 1989–1993, 1994–1998 and 1999–2003 (Xu et al., 2007). We used the latest inventory in this study. All area data was at the provincial scale, we added up provincial data for the total area of each ecoregion (Fig. S1). For cross-ecoregion provinces, the area of each ecoregion was calculated according to the ratio of specific ecoregions.

2.2.3. Duration of growing seasons

This study assumed that the growing season duration of grasslands is approximately 300 days for southern China and about 165 days (from early May to late October) for the arid, semi-arid northern China and the Qinghai-Tibetan Plateau, respectively. Chen et al. (2010) reported that the contribution of the non-growing season (October–April) to the cumulative annual CH_4 uptake is approximately 30% (25%–36%), so in this study we assumed that the contribution of the nongrowing uptake was about

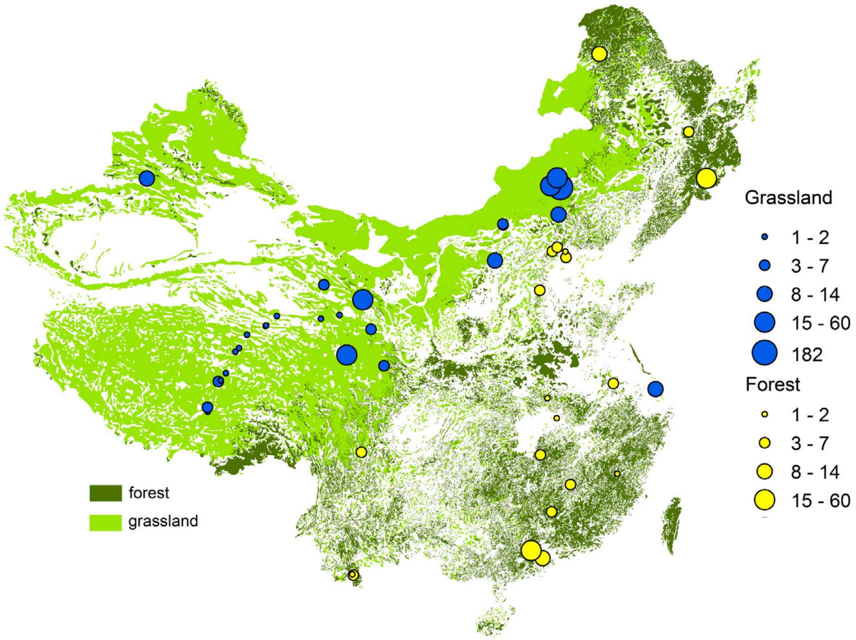

Fig. 1. Mean CH$_4$ uptake study sites from forests and grasslands in China. The size of the bubbles signifies the quantity of data about mean methane uptake in each site.

30% of the total annual uptake in the arid, semi-arid northern China and the Qinghai-Tibetan Plateau.

The duration of forest growth is generally longer in southern and eastern China than western and northern China due to a warmer climate and higher precipitation rate. This study assumed a forest growing duration of 300 days in south and southeastern China but only 165 days (5.5 months) for western and northern China. Subsequently, the non-growing season duration is approximately 60 days for the south and southeastern regions, and 200 days for the western and northern regions. Similar to that of grassland, we assumed that the contribution of the nongrowing forest uptake was about 30% of the total annual uptake in the arid, semi-arid northern China and the Qinghai-Tibetan Plateau.

3. Results and discussion

3.1. Observed CH$_4$ uptakes in grasslands in China

Grasslands of China cover 41.7% of the area of the country and 16.3% of the world's total grassland, mainly distributed in arid-semiarid northern part of China and the Qinghai-Tibetan Plateau, with a small part in central, eastern and southern regions under monsoonal warm temperate and tropical climates (Scurlock and Hall, 1998; Chen and Wang, 2002; Fan et al., 2007). During the past decades, many studies concerned about CH$_4$ fluxes from grasslands, with several reports indicating CH$_4$ emissions from wet meadows (Cao et al., 2008; Wang et al., 2009b; Chen et al., 2011; Liu et al., 2012a). Based on analyses of data taken from 50 articles (including several theses, Table S1), we obtained 465 sets of mean CH$_4$ flux rates from grasslands under different grazing and fertilizer treatments in China, and calculated a mean CH$_4$ uptake rate ($\pm$SD) of 59.62 ± 56.96 μg CH$_4$ m^{-2} h^{-1}, which is comparable with CH$_4$ uptake rates from other grasslands in the world (Mosier et al., 1991; Glatzel and Stahr, 2001; Mosier et al., 2002; Mori et al., 2008; Castaldi et al., 2010; Merbold et al., 2013). Except for only 15 data in EHSD, the majority 450 data was located in NASD and QPFD, where most of Chinese grasslands are distrusted (Fig. S1 and Fig. 2). More than three fourths of all published measurements from grasslands of China were taken in the semi-arid steppe ecoregion of the NASD. Based on 306 data collected in this region we estimated the mean CH$_4$ uptake rate by grasslands as 74.31 ± 62.51 μg CH$_4$ m^{-2} h^{-1} (Du et al., 1998; Wang et al., 1998, 2000, 2005; Ma et al., 2006; Liu et al., 2007, 2009a; Geng et al., 2010; Zhou and Hao, 2010; Luo and Jiao, 2012), which is also the highest mean CH$_4$ uptake rate of grasslands for all ecoregions in China (Fig. 2). In semi-arid desert steppe ecoregion and arid desert ecoregion, the mean CH$_4$ uptake rates were about 41.19 ± 26.01 μg CH$_4$ m^{-2} h^{-1} ($n = 21$) and 32.88 ± 27.39 μg CH$_4$ m^{-2} h^{-1} ($n = 10$), respectively. In QPFD, almost all data located in alpine steppe and meadow ecoregion, presenting a mean CH$_4$ uptake rate about 31.29 ± 21.78 μg CH$_4$ m^{-2} h^{-1} ($n = 104$) (Cao et al., 2008; Sun, 2008; Kong et al., 2009; Lin et al., 2009; Wang et al., 2009a, 2009b; Jiang et al., 2010; Wan et al., 2010; Wei et al., 2011, 2012; Liu et al., 2012a, 2012c; Zhang et al.,

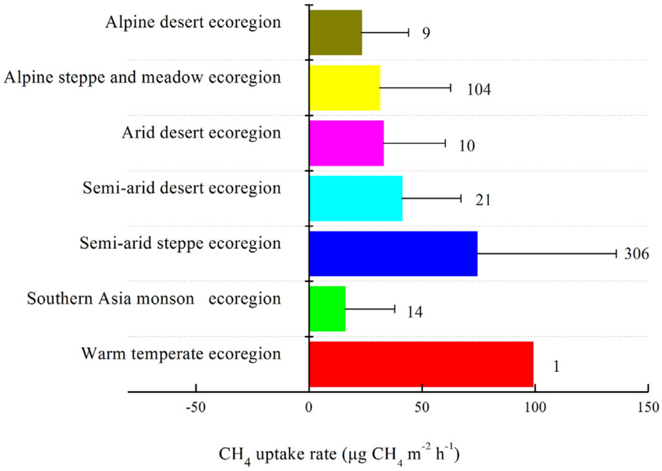

Fig. 2. Mean CH$_4$ uptake rates from grasslands in different ecoregions in China. The number at the left of each column means the total dataset of each ecoregion.

2013). In arid desert ecoregion, the mean CH_4 uptake rate was about 23.21 ± 20.80 μg CH_4 m^{-2} h^{-1}, lower than that of alpine steppe and meadow ecoregion ($n = 9$, Fig. 1). Only two studies were carried out in EHSD (Figs. 2 and 3), with one reporting considerably low CH_4 uptake rates (15.97 ± 32.46 μg CH_4 m^{-2} h^{-1} based on 14 data) from urban lawns in Shanghai (Mei, 2008) and the other a relatively higher CH_4 uptake rate (99.08 CH_4 m^{-2} h^{-1}) of grasslands in the Taihang Mountain (Liu et al., 2013b). For different types of grasslands, we found that the mean CH_4 uptake rate of steppes (71.45 ± 61.21 μg CH_4 m^{-2} h^{-1} based on 337 data) was significantly higher than that of meadows (28.45 ± 24.32 μg CH_4 m^{-2} h^{-1} based on 128 data) in China ($P < 0.01$) partly due to the higher soil water content in meadow (Fang et al., 2014).

Many studies also discussed the temporal variation of CH_4 uptake by grasslands of China (Du et al., 1997, 1998; Wang et al., 1998, 2000; Dong et al., 2000; Pei et al., 2003; Wang et al., 2003a, 2009a; Qi et al., 2004; Wei et al., 2012; Kato et al., 2013). Similar with other studies all over the world (Dengel et al., 2011; Imer et al., 2013), the maximum uptake rate is usually observed in the afternoon due to the warmest soil condition during the day (Wang et al., 2003a; Du et al., 2005; Kato et al., 2013), except for a few reporting peak values at other times (Du et al., 1997; Dong et al., 2000; Qi et al., 2004). Typical seasonal patterns have been found in Inner Mongolia (Du et al., 1997; Wang et al., 1998, 2000, 2003a; Du et al., 2005; Chen et al., 2010; Zhang et al., 2012) and on the Qinghai-Tibetan Plateau (Pei et al., 2003; Wang et al., 2009a), with larger uptake rates in summer and lower rates in winter (Liu et al., 2007; Holst et al., 2008; Chen et al., 2010). For NASD, we found that CH_4 uptake rate of the growing season (81.58 ± 65.64 μg CH_4 m^{-2} h^{-1} based on 248 data) was significant higher than that of the non-growing season (41.27 ± 34.76 μg CH_4 m^{-2} h^{-1} based on 65 data) ($P < 0.01$), similar to the results of Wang et al. (2005) due to warming condition in growing season enhancing activities of methanotrophs. The dominant factors for seasonal variation of CH_4 uptake are soil temperature and soil moisture (Jiang et al., 2010). A few studies also reported the inter-annual variation of CH_4 uptake rates, partly depending on inter-annual variation of precipitation (Wang et al., 2000, 2001; Du et al., 2005).

CH_4 uptakes from grasslands are not only influenced by natural factors but also by intensive managerial practices. In NASD and QPFD, nomadic pastoralists have grazed their livestock for thousands of years. Thus, livestock grazing may have been the most important management of grasslands on both domains. Grazing was found to have complicated effects on CH_4 uptakes by grasslands, probably due to different grazing density and grazing patterns, or accompanied by difference of weather conditions and vegetation (Du and Chen, 1997; Wang et al., 2000; Wang et al., 2001, 2003b; Qi et al., 2003; Ma et al., 2006; Li et al., 2007; Liu et al., 2007, 2012c; Lin et al., 2009; Wan et al., 2010; Zhou and Hao, 2010; Zhou et al., 2011; Jiang et al., 2012; Zhang et al., 2012). In both semi-arid steppe ecoregion and alpine steppe and meadow ecoregion, the CH_4 uptake rate of freely grazed grasslands was lower than that of fenced grasslands (Table 1), partly due to grazing-induced changes in soil bulk density by tramping, soil nutrient and biomass allocation (Du and Chen, 1997; Qi et al., 2003; Wang et al., 2003b; Liu et al., 2007). In semi-arid steppe ecoregion, we further found that the CH_4 uptake rate of winter-grazed steppes (40.82 ± 16.23 μg CH_4 m^{-2} h^{-1} based on 13 data) was significantly lower than that of fenced steppes (65.60 ± 21.69 μg CH_4 m^{-2} h^{-1} based on 10 data). The probable reason was that winter grazing may cause water stress and suppress gas diffusion, thus decrease the activity and population of CH_4-consuming bacteria, and ultimately limit CH_4 uptake (Liu et al., 2007). In semi-arid steppe ecoregion, CH_4 uptake in light grazing pastures was higher than that of the controls and that in more intense grazing pastures was lower than controls (Table 1). In alpine steppe and meadow ecoregion, Wan et al. (2010) also found the similar effect of grazing on CH_4 uptake of grasslands. Probably because trampling and mowing of intense grazing affected water diffusion from the soil surface, while light grazing might maintain the optimal soil moisture for CH_4-consuming bacteria in the semi-arid region (Wang et al., 2001). However, Wang et al. (2000) found that there was no significant variation of CH_4 uptake under different grazing densities. Excrement patches of grazing animals also play an important role in significantly decreasing CH_4 uptake (Ma et al., 2006; Lin et al., 2009). CH_4 uptake was also substantially influenced by mowing through its effect on some biotic factors (such as net primary productivity, soil microbial C/N supply and soil microbial activities) not on soil temperature nor moisture (Zhang et al., 2012). Nitrogen fertilization or deposition is another important factor influencing CH_4 uptakes from grasslands. In QPFD, Jiang et al. (2010) indicated that simulated nitrogen deposition after a short term slightly reduced CH_4 uptake of an alpine meadow. The probable reasons are: (1) CH_4 oxidation is limited by NH_4^+ due to lack of specificity of CH_4 monooxygenase (MMO) in methanotroph; (2) methanotrophic bacteria is toxically inhibited by hydroxylamine and nitrite produced by methanotrophic ammonia oxidation; (3) the activity of methanotroph can be suppressed by osmotic stress induced by nitrogen salt addition (Saari et al., 2004).

Recent studies further reported that low N addition decreased the soil water content, in result slightly promoted CH_4 uptake from alpine meadow soil, while medium and high N deposition inhibited CH_4 uptake and decreased the atmospheric CH_4 sink (Zhang et al., 2013; Fang et al., 2014). They also indicated that NO_3^-

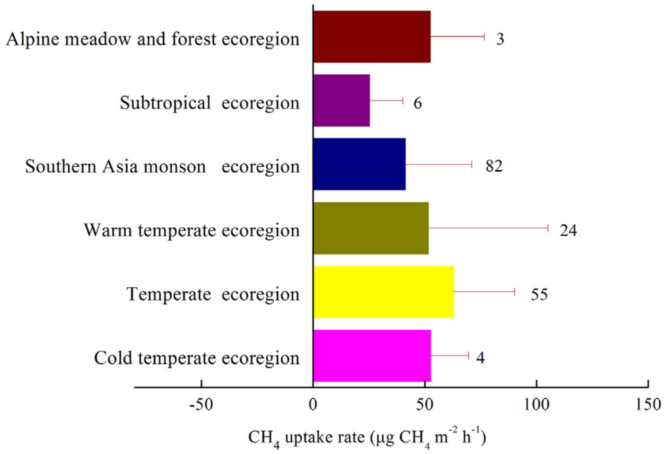

Fig. 3. Mean CH_4 uptake rates from forests in different ecoregions in China. The number at the left of each column means the total dataset of each ecoregion.

Table 1
CH_4 uptake rate of grasslands in different ecoregions under grazing treatments.

Ecoregion	Treatment	Mean	Number	Standard deviation
Semi-arid steppe ecoregion	Freely grazed	48.89	46	20.08
	Fenced	69.00	45	23.43
	Non-grazed	51.55	20	40.86
	Light grazed	89.26	19	83.85
	Moderately grazed	75.34	19	53.89
	Heavy grazed	73.41	19	49.67
Alpine steppe and meadow ecoregion	Freely grazed	75.02	3	14.44
	Fenced	80.35	4	33.53

accumulation could significantly promote CH_4 uptake in the meadow soil (Zhang et al., 2013; Fang et al., 2014). In arid desert ecoregion, nitrogen deposition tended to significantly increase CH_4 uptake (Li et al., 2012). Partly because N addition enhances soil mineralization rates and more C and N is available which also favors the activity of methanotroph in N-limited grasslands (Zhang et al., 2013; Fang et al., 2014). These results indicated that inorganic N is an important influencing factor of soil CH_4 uptake, and its promotion or inhibition to soil CH_4 uptake depends on the soil N status (Fang et al., 2014) as well as soil water regime. Moreover, climate warming is believed to increase CH_4 uptake from grasslands in Inner Mongolia (Chen et al., 2010).

3.2. *Observed methane uptakes in forests in China*

China has 175 million hectares (18.25% of the area of this country) of forests, ranging from tropical forests in the south to boreal forests in the north (Xu et al., 2007). During the past two decades, some studies reported about carbon storage of forests (Fang et al., 2001; Zhou et al., 2006b; Piao et al., 2009; Guo et al., 2010) with a few of them discussing about CH_4 fluxes from forests in China. Sporadic reports considered forests from southern China (Southern Asia monsoon humid and semi-humid evergreen broadleaf forest ecoregion) as weak CH_4 sources (Liu et al., 2010b; Li, 2011; Yang, 2012), and very few about CH_4 emissions from forests under high nitrogen addition (Mo et al., 2005). On the basis of the analyses of data taken from 32 articles (including several theses, Fig. 1 and Table S2), we obtained 174 sets of mean CH_4 flux rates from forests in China, and calculated a mean uptake rate (±SD) of 49.43 ± 333.81 μg CH_4 m^{-2} h^{-1} (Fig. 3) which is comparable with CH_4 uptake rates by other forests in the world (Peichl et al., 2010; Sousa Neto et al., 2011; Wang et al., 2013a). Except for only 3 data in QPFD, the rest 171 data was located in EHSD, where most of Chinese forests are distributed (Fig. S1 and Fig. 3). None data was available for NASD. In the alpine meadow and forest ecoregion of QPFD, the annual mean CH_4 uptake rate was about 52.43 ± 24.26 μg CH_4 m^{-2} h^{-1} ($n = 9$). In temperate humid mixed forest ecoregion, we obtained the highest mean CH_4 uptake rate about 62.89 ± 27.26 μg CH_4 m^{-2} h^{-1} ($n = 55$)(Fig. 3). The lowest mean CH_4 uptake rate was found in subtropical humid evergreen broadleaf forest region, about 25.22 ± 14.92 μg CH_4 m^{-2} h^{-1} ($n = 6$). Almost half data ($n = 82$) was distributed in Southern Asia monsoon humid and semi-humid evergreen broadleaf forest ecoregion with the mean CH_4 uptake rate about 41.69 ± 29.84 μg CH_4 m^{-2} h^{-1}, which was higher than that of Subtropical humid evergreen broadleaf forest region. Warm temperate humid and semi-humid deciduous broadleaf forest ecoregion and cold temperate conifer forest ecoregion had similar CH_4 uptake rates, about $51. 49 \pm 53.73$ μg CH_4 m^{-2} h^{-1} ($n = 24$) and 52.50 ± 15.81 μg CH_4 m^{-2} h^{-1} ($n = 4$), respectively.

The temporal variations of CH_4 uptake by forests in China were discussed in many studies (Sun, 2000; Dong et al., 2003; Du et al., 2004; Mo et al., 2006; Tang et al., 2006; Fang et al., 2009; Yang et al., 2010; Liu et al., 2010a, 2010b; Hu et al., 2011; Li, 2011; Zhang et al., 2011a; Yang, 2012; Liu et al., 2012b). Several studies reported great diurnal variations of CH_4 uptake rates with no significant relations between CH_4 uptake and soil moisture or temperature (Dong et al., 2003; Mo et al., 2005; Yang et al., 2010; Hu et al., 2011). In temperate mixed forest ecoregion and warm temperate deciduous forest ecoregion, we found that CH_4 uptake rates of the growing season was significantly higher than those of the non-growing season ($P < 0.01$) due to warmer conditions for soil methanotrophs. In temperate mixed forest ecoregion, CH_4 uptake rates were about 70.86 ± 21.64 μg CH_4 m^{-2} h^{-1} ($n = 46$) and 22.40 ± 13.20 μg CH_4 m^{-2} h^{-1} ($n = 8$) of growing season and non-growing season, respectively. In warm temperate deciduous forest ecoregion, CH_4 uptake rates were about 55.72 ± 21.62 μg CH_4 m^{-2} h^{-1} ($n = 5$) and 22.00 ± 11.20 μg CH_4 m^{-2} h^{-1} ($n = 4$) of growing season and non-growing season, respectively. Furthermore, in boreal and temperate forests of northern China or sub-alpine forests of southwestern China, peaks of CH_4 uptake are usually recorded in summer and lowest CH_4 uptake in winter (Sun, 2000; Dong et al., 2003; Du et al., 2004; Liu et al., 2010a), where seasonal variation of soil temperature is the dominant factor controlling CH_4 uptake. In tropical or subtropical forests in southern China, the seasonality of CH_4 uptake is more complicated depending on the seasonal patterns of precipitation. E.g., Mo et al. (2006) reported that the highest CH_4 uptake took place in winter rather than summer. In Southern Asia monsoon humid forest ecoregion, a CH_4 uptake rate was found to be significantly higher in the cool-dry season, about 61.29 ± 23.55 μg CH_4 m^{-2} h^{-1} ($n = 17$) than in the warm-humid season, about 45.71 ± 22.43 μg CH_4 m^{-2} h^{-1} ($n = 17$), with some CH_4 emissions in the warm-humid season (Tang et al., 2006; Werner et al., 2006; Zhou et al., 2006a; Fang et al., 2009; Liu et al., 2010b; Li, 2011; Yang, 2012). Moreover, a few studies reported annual precipitation as the dominant factor for inter-annual variations of CH_4 uptake by forests (Mo et al., 2006; Tang et al., 2006).

During the past several decades, great changes have taken place in forests in China due to human disturbances and climate changes, which may result in significant variations of CH_4 uptake of forests (Liu et al., 2010b). The main human disturbance is logging, for which China lost its natural forests. Natural forests declined to 30% of the total forest area in China (Zhang et al., 2000). In both temperate mixed forest ecoregion and alpine meadow and forest ecoregion, we found that secondary forests have relatively lower CH_4 uptakes about 36.98 ± 7.37 μg CH_4 m^{-2} h^{-1} ($n = 3$) than natural forests in the corresponding area, about 50.88 ± 24.89 μg CH_4 m^{-2} h^{-1} ($n = 3$), due to lower soil water content in natural forests (Dong et al., 2003; Werner et al., 2006; Liu et al., 2012b). Besides logging, anther human disturbance for forest in China is plantation. Due to demands of wood and the Grain to Green Project initiated since 1999, China has become the greatest forest plantation country of the world, covering about 53.3 million hectares (Lei, 2005). We found that the mean CH_4 uptake rate of natural forests (57.33 ± 32.01 μg CH_4 m^{-2} h^{-1} based on 134 data) were significantly higher than that of plantation (22.64 ± 26.83 μg CH_4 m^{-2} h^{-1} based on 40 data) in China ($P < 0.01$). Werner et al. (2006) recorded that the CH_4 uptake was only 7.6 ± 0.67 μg CH_4 m^{-2} h^{-1} in the rubber plantation and Li (2011) also observed that the CH_4 uptake as low as 1.39 μg CH_4 m^{-2} h^{-1} or even found low CH_4 emissions from another plantation in Southern Asia monsoon humid forest ecoregion (Table S2). Moreover, managerial practices, such as irrigation, fertilization and litter removals, greatly impact CH_4 uptakes of forests in China (Table 2). Werner et al. (2006) found that watered forests had significantly lower CH_4 uptakes in tropical rainforests (Table 2). Sun et al. (2011) reported with incubation experiments that increase in soil water content greatly decreased CH_4 uptakes of forest soil. Nitrogen addition or nitrogen deposition, especially of large amount, is also found to inhibit CH_4 uptakes, especially when nitrogen addition was relative high (Mo et al., 2005; Hu et al., 2011; Zhang et al., 2011a; Wang, 2012). In tropical forests with limited phosphorus (P) availability, Zhang et al. (2011a,b) found that P addition significantly stimulated CH_4 uptakes and mitigated the inhibitive effect of N deposition on CH_4 uptake due to enhanced soil methanotrophic activity by P addition. In cold temperate conifer forest ecoregion and South Asia monsoon forest ecoregion, removal of the surface litter was found to slightly decrease CH_4 uptakes (Table 2) (Tang et al., 2006; Zhou et al., 2006a), while in temperate humid mixed forest ecoregion, it significantly enhanced CH_4 uptake. Wang et al. (2013a,b) found that litter layer reduced CH_4 uptake by forest soil when soil water content was below

Table 2
CH_4 uptake rate of forests in different ecoregions under different treatments.

Ecoregion	Treatment	Mean	Number	Standard deviation
Cold temperate conifer forest ecoregion	With surface litter	55.00	4	5.77
	Without surface litter	50.00	4	23.09
Temperate humid mixed forest ecoregion	With surface litter	49.50	4	43.45
	Without surface litter	59.39	4	39.35
Warm temperate broadleaf forest ecoregion	Control	17.94	2	19.83
	High nitrogen addition	10.24	2	9.20
	Low nitrogen addition	16.59	2	17.44
	Middle nitrogen addition	12.65	2	12.25
South Asia monsoon forest ecoregion	With surface litter	56.76	18	25.32
	Without surface litter	54.75	18	18.58
Subtropical humid forest ecoregion	Control	27.02	3	17.02
	Watered	23.42	3	16.06

15.8%, and increased CH_4 uptake when soil water content was above this value in the subtropical region. Litter layer may serve as a moisture-induced bidirectional buffer for atmospheric CH_4 uptake by forest soils (Wang et al., 2013b). This is the reason that we found different effect of surface litter on CH_4 uptake by forest soils in different ecoregions. In temperate humid mixed forest ecoregion, warming, elevated CO_2 and their interaction were found to decrease CH_4 uptakes of forests (Guan et al., 2012).

3.3. *Estimated methane uptake in grasslands of China*

Among the many studies concerning about the CH_4 uptake by grasslands in China, a few focused on estimating the CH_4 budget of grasslands in Inner Mongolia and Qinghai-Tibetan Plateau (Liu et al., 2009a; Wang et al., 2009c; Chen et al., 2010; Kato et al., 2011) with only one estimating the total CH_4 uptake of grasslands and shrublands with low vegetation cover on the country scale, about 1.73 ± 0.64 Tg CH_4 yr^{-1} (Cai, 2012). Liu et al. (2009a,b) estimated that the CH_4 uptake by all upland grassland soils of the Baiyinxile Livestock Farm (covering about 290 661 ha) consumed about 298 ± 56 tons C growing season^{-1} (May–September, 153 days). Based on high frequent measurement, Chen et al. (2010) indicated that the contribution of the non-growing season to the cumulative annual CH_4 uptake was approximately 30%. Wang et al. (2009a,b) reported that grazed steppe of the Xilin River catchment (covering about 8208.1 km^2) in central Inner Mongolia consumed about 2.67 Gg CH_4 yr^{-1}. Based on limited measurement, Kato et al. (2011) preliminarily estimated that the grasslands on the Qinghai-Tibetan Plateau consumed about 0.185 Tg CH_4 during the summertime. However, Cao et al. (2008) indicated that *Kobresia* meadows on the Qinghai-Tibetan Plateau emitted about 0.13 Tg CH_4 yr^{-1}, possibly contributed by alpine plants, which was questioned by their colleagues (Wang et al., 2009b).

Based on the data collection and detailed calculation, this study estimated the total CH_4 uptake of grasslands in China about 0.650 Tg CH_4 yr^{-1} (ranging from 0.168 to 1.132 Tg CH_4 yr^{-1}), with 0.459 Tg CH_4 consuming during the growing season and 0.191 Tg CH_4 during the non-growing season (Table 3). This estimate was about 18%–49% of the total CH_4 uptake by temperate grasslands (Born et al., 1990; Mosier et al., 1991, 1997). This is lower than a previous study about 1.73 ± 0.64 Tg CH_4 yr^{-1} partly because more specific data of CH_4 uptake rates were used in this study and partly because we did not included shrublands in our estimate (Cai, 2012). The largest CH_4 uptake of grasslands was found in QPFD, which consumed about 0.284 Tg CH_4 yr^{-1}, about 44% of the whole uptake of grasslands in China. The CH_4 uptake by grasslands on the Qinghai-Tibetan Plateau was higher than the previous study because the previous study only calculated CH_4 uptake in the growing season and neglected the 30% during the non-growing season (Kato et al., 2011). The second CH_4 uptake of grasslands was observed in NASD, about 0.204 Tg CH_4 yr^{-1}. The lowest CH_4 uptake of grasslands was by EHSD, about 0.162 Tg CH_4 yr^{-1}. On the ecoregion scale (Fig. 4), due to its extensive coverage of grassland, alpine steppe and meadow ecoregion on the Qinghai-Tibetan Plateau and semi-arid steppe ecoregion in Inner Mongolia ranked the first and second largest CH_4 uptake of grasslands in China, about 0.151 Tg CH_4 yr^{-1} and 0.097 Tg CH_4 yr^{-1}, respectively. Alpine desert and semi-desert ecoregion ranked the third largest CH_4 uptake of grasslands in China, about 0.075 Tg CH_4 yr^{-1}. Due to large grassland distribution, arid desert ecoregion also consumed a substantial amount of CH_4 (0.066 Tg CH_4 yr^{-1}). In the tropical and subtropical China, there are three ecoregions including Southern Asia monsoon broadleaf forest ecoregion, tropical humid forest ecoregion and subtropical broadleaf forest ecoregion (Fig. S1). Due to relatively low uptake rate and grassland distribution, these ecoregions together consumed only 0.036 Tg CH_4 yr^{-1}. In the temperate region of Eastern Humid and Semi-humid Domain, three ecoregions together consumed 0.126 Tg CH_4 yr^{-1}. The ecoregion with lowest CH_4 uptake was also located there, consuming about 0.0007 Tg CH_4 yr^{-1}.

3.4. *Estimated methane uptake in forests of China*

Forests are usually regarded as important CH_4 sinks (Potter et al., 1996; Dutaur and Verchot, 2007) with temperate forests consuming about 3.3 Tg CH_4 yr^{-1} (Potter et al., 1996). With the many studies concerning about CH_4 uptake of forests in China, only

Table 3
Total CH_4 uptake (Gg CH_4 yr^{-1}) during growing season and non-growing season for different domains of China.

Domain	Grassland uptake			Forest uptake		
	Growing season	Non-growing season	Annual	Growing season	Non-growing season	Annual
Eastern Humid and Semi-humid Domain	117.24	44.82	162.06	424.12	128.58	552.70
Northeastern Arid and Semi-arid Domain	142.46	61.05	203.51	29.28	12.55	41.83
Qinghai-Tibetan Plateau High-Frigid Domain	199.04	85.31	284.35	54.77	23.48	78.25
Total	458.74	191.18	649.92	513.09	161.89	674.98

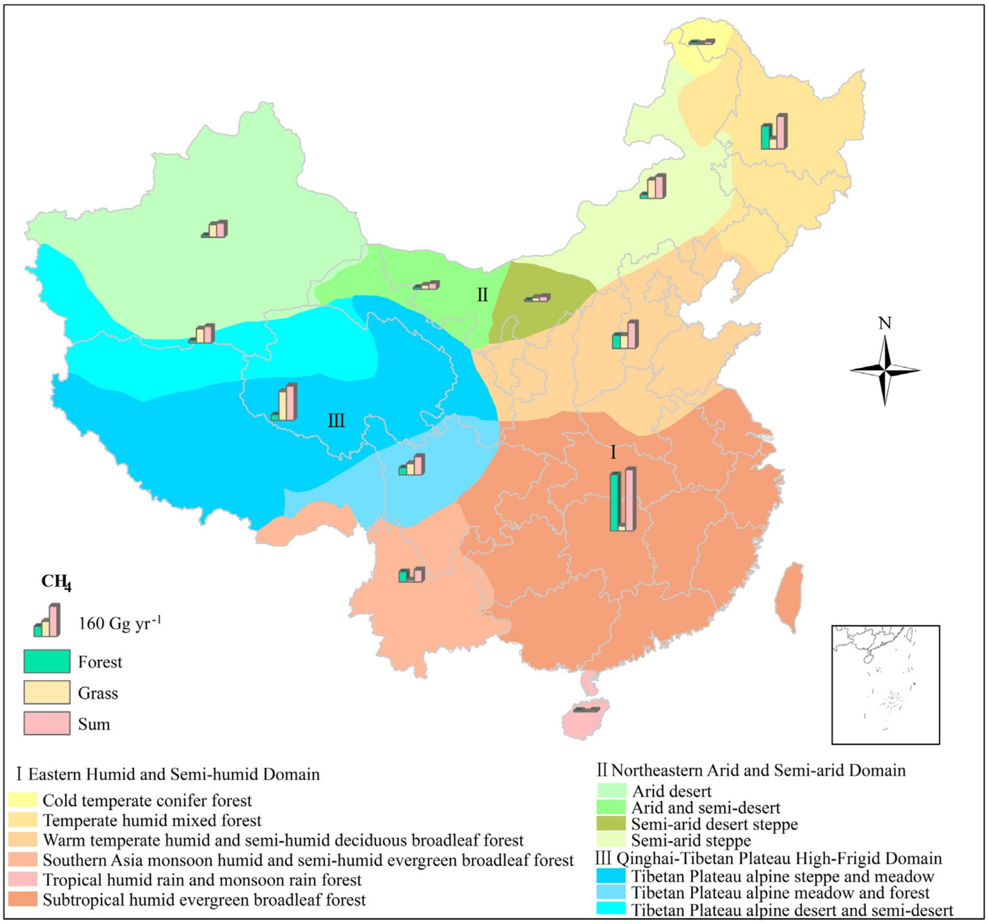

Fig. 4. Annual CH_4 uptakes from forests and grasslands located within the different ecoregions of China.

one preliminarily estimated the total CH_4 uptake of forests as 0.60 ± 0.19 Tg CH_4 $yr^{-1}$with great uncertainties (Cai, 2012).

With more complete data and detailed calculation, this study estimated the total CH_4 uptake by forests in China as 0.675 Tg CH_4 yr^{-1} (ranging from 0.399 to 0.946 Tg CH_4 yr^{-1}), with 0.513 Tg CH_4 consumed during the growing season and 0.162 Tg CH_4 during the non-growing season (Table 3), which is close to the previous estimate (Cai, 2012) and slightly higher than that of European forests (0.60 Tg yr^{-1}) (Dobbie et al., 1996). Due to extensive distribution of forests, CH_4 uptake by forests was found varying among regions with the greatest annual CH_4 uptake about 0.553 Tg CH_4 yr^{-1} taking place in EHSD, which was accounting for about 82% of the total annual CH_4 uptake of forests in China. The QHFD consumed about 0.078 Tg CH_4 yr^{-1}, and the lowest annual uptake about 0.042 Tg CH_4 yr^{-1} was observed in NASD. On the ecoregion scale (Fig. 4), due to great distribution of forests and relatively longer growing season, the Southern Asia monsoon broadleaf ecoregion had the largest CH_4 uptake of forests about 0.295 Tg CH_4 yr^{-1}, which is around 44% of the whole forest uptake. Due to great distribution of forests and higher uptake rate, temperate humid mixed forest ecoregion and warm temperate broadleaf forest ecoregion ranked the second and third, consuming about 0.119 Tg CH_4 yr^{-1} and 0.068 Tg CH_4 yr^{-1}. Due to large distribution of forests and longer growing season, subtropical evergreen broadleaf forest ecoregion also served as a relatively strong CH_4 sink of about 0.055 Tg CH_4 yr^{-1}. Tropical rain forest ecoregion consumed only 0.008 Tg CH_4 yr^{-1} because of limited area and low uptake rate. On the Qinghai-Tibetan Plateau, due to relatively large distribution of forest, alpine meadow and forest ecoregion ranked the first CH_4 uptake of forests (0.036 Tg CH_4 yr^{-1}). The lowest CH_4 uptake of forests (0.008 Tg CH_4 yr^{-1}) was observed in arid and semi-arid desert ecoregion due to its low forest coverage and cold climate.

3.5. *The total CH_4 uptake of forests and grasslands in China*

Through abovementioned review and estimates, we preliminarily estimated the total CH_4 uptake of forests and grasslands as 1.323 Tg CH_4 yr^{-1} in China (ranging from 0.567 to 2.078 Tg CH_4 yr^{-1}), with a certain level of uncertainty in soil water regime and spatial variation, equivalent about 5.0% of the total uptake of global aerobic soils (based on the average of global soil uptakes summarized in Table 4). This estimate is relatively lower than a previous estimate in China (2.56 Tg CH_4 yr^{-1}) for CH_4 uptake of forests and grasslands only based on limited measurement with more uncertainties (Cai, 2012). Total CH_4 uptake of forests and grasslands could offset about 49% of CH_4 emissions from natural wetlands of China (Chen et al., 2013). On the domain scale, EHSD was the greatest CH_4 uptake (0.715 Tg CH_4 yr^{-1}) of forests and grasslands in China, with 82% of the whole forest uptake and 25% of the whole grassland uptake in China. QHFD ranked the second CH_4 uptake (0.363 Tg CH_4 yr^{-1}) of forests and grasslands in China, probably due to its great grassland and forest distribution. The lowest CH_4 uptake (0.245 Tg CH_4 yr^{-1}) of forests and grasslands in China was observed in NASD. On the ecoregion scale (Fig. 4), due to the extensive forest distribution and long growing season,

Table 4
Estimates in relation to CH_4 uptake from grasslands and forests from nations or regions around the world.

Estimate (Tg CH_4 yr^{-1})	Systems	Region	Methods	References
12.4 (modified)	Forest	Temperate and boreal	Based on measurement	(Steudler et al., 1989)
0.02–1.8	Grassland	Temperate	Based on measurement	(Born et al., 1990)
0.5–5.6	Grassland	Temperate	Based on measurement	(Mosier et al., 1991)
0.6	Forest	Europe	Based on measurement	(Dobbie et al., 1996)
21(17–24)	Aerobic soils	Global	Biogeochemical modeling	(Potter et al., 1996)
2.7	Grassland	Temperate	Review	(Mosier et al., 1997)
7.4	Forest	Tropical	Review	(Mosier et al., 1997)
12.1	Forest	Temperate	Review	(Mosier et al., 1997)
2.4	Forest	Boreal	Review	(Mosier et al., 1997)
26	Aerobic soils	Global	Inverse modeling	(Hein et al., 1997)
29(7–100)	Aerobic soils	Global	Review	(Smith et al., 2000)
34	Aerobic soils	Global	Inverse modeling	(Wang et al., 2004)
30	Aerobic soils	Global	Biogeochemical modeling	(Denman et al., 2007)
22 ± 12	Aerobic soils	Global	Inventory	(Dutaur and Verchot, 2007)
6.2	Forests	Tropical	Inventory	(Dutaur and Verchot, 2007)
3.3	Forests	Temperate	Inventory	(Dutaur and Verchot, 2007)
28(9–47)	Aerobic soils	Global	Modeling	(Curry, 2007)
5.4	Forests	Temperate	Review	(Ishizuka et al., 2009)
0.185	Grassland	Qinghai-Tibetan Plateau	Based on measurement	(Kato et al., 2011)
2.56	Aerobic soils	China	Review	(Cai, 2012)
32–36	Aerobic soils	Global	Biogeochemical modelling	(Zhuang et al., 2013)

Southern Asia monsoon broadleaf forest ecoregion was the greatest CH_4 uptake (0.320 Tg CH_4 yr^{-1}) of forests and grasslands in China, which was higher than that of the whole uptake of NASD. Alpine steppe and meadow ecoregion ranked the second uptake (0.181 Tg CH_4 yr^{-1}) of forests and grasslands in China due to extensive grasslands distribution and high uptake rate. Temperate mixed forest ecoregion ranked the third uptake of forests and grasslands in China (0.172 Tg CH_4 yr^{-1}) due to high uptake rate and extensive natural forest distribution. Warm temperate broadleaf forest ecoregion ranked the fourth uptake (0.136 Tg CH_4 yr^{-1}) with a half from grasslands and the other half from forests in China. Due to extensive steppe distribution and higher uptake rate, semi-arid steppe ecoregion also consumed substantial amount of CH_4 about 0.115 Tg CH_4 yr^{-1}. Due to limited area of forests and grasslands as well as low uptake rate, tropical humid and monsoon rainforest ecoregion had the lowest CH_4 uptake (0.008 Tg CH_4 yr^{-1}).

Grasslands and forests are not stable sinks of CH_4, but instead variable owing to global change and anthropogenic activity (Zhuang et al., 2013). Besides, increasing atmospheric CH_4 concentrations could also enhance uptake. In China, climate warming is obvious in the past decades and most probably going on in the future, especially for the northern China (Piao et al., 2010). Such warming could stimulate the activity of methanotrophs in grassland and temperate soils, resulting in an increase in CH_4 uptake. Moreover, longer growing season under climate warming would result in extra increase in the total annual CH_4 uptake. However, in China, precipitation is quite variable. Drier northern China has had a 12% decline in precipitation during summer and autumn since 1960 (Piao et al., 2010), which may increase CH_4 uptake of forests and grasslands in this region. By contrast, wetter southern China experienced more rainfall in summer and winter (Piao et al., 2010), which might decrease the CH_4 uptake of forests and grasslands in this area. To quantify the changes of the CH_4 uptake of grasslands and forests we need more data from more specific regions and modeling. There are some pilot studies about modeling methane uptakes from uplands (Zhuang et al., 2013). For our knowledge, there is no modeling for CH_4 uptakes of forests and grasslands in China, despite the several modeling studies for methane emissions from rice paddies and natural wetlands (Li et al., 2010; Zhang et al., 2011b). In the past two years, our group has developed a process-based CH_4 model (TRIPLEX-GHG) to model CH_4 emissions from natural wetlands on the global scale (Zhu et al., 2013). We are planning to develop a sub-model of TRIPLEX-GHG model to model CH_4 uptakes from forests and grasslands in China. Furthermore, a recent paper indicated an enhanced nitrogen deposition over China, with the average annual bulk deposition of N increased by 8 kg of nitrogen per hectare between the 1980s and the 2000s, and higher deposition in the industrialized and agriculturally intensified regions of China (Liu et al., 2013a). Such enhanced nitrogen deposition might decrease CH_4 uptake in China, especially for nitrogen-limited regions. As an example, a study on Qinghai-Tibetan Plateau reported that low-level nitrogen deposition significantly inhibited CH_4 uptake from the soil of an alpine meadow (Fang et al., 2014). The industrialized and agriculturally intensified regions are usually located in EHSD (Fig. S1). Higher nitrogen deposition there might further decrease the uptake rate of soil.

Besides global change, managerial practices have greatly influenced CH_4 uptake of grasslands and forests in China. For grasslands, grazing may have been the most important anthropogenic impact factor on CH_4 uptake. Due to rising populations of both humans and livestock during the past decades in China, heavy grazing not only caused grasslands degrading (Liu et al., 2009a) but also decreased CH_4 uptake of grasslands (Du and Chen, 1997; Qi et al., 2003; Wang et al., 2003b; Liu et al., 2007). However, grazing exclosure and sedentarization of pastoral nomads (Liu et al., 2009b) would partly alleviate grazing, enhancing CH_4 uptake of grasslands (Wang et al., 2002; Liu et al., 2007; Wei et al., 2012). Fertilization, aiming to improve grassland production, further decreased CH_4 uptake of grasslands (Liu et al., 2012c; Fang et al., 2014). During the last 50 years, China has experienced pervasive logging of natural forests and countrywide afforestation (Zhao and Shao, 2002). Loss of natural forests would decrease the CH_4 uptake of forests because natural forests usually have relatively higher uptake rates than plantations or farmlands (Werner et al., 2006; Liu et al., 2012b). The Natural Forest Conservation Program (NFCP, initiated in 1998) conserved natural forests through logging bans and afforestation, which increased the CH_4 uptake of forests in China. The Grain to Green Program (GTGP, initiated in 1999) converts cropland on steep slopes to forest. Such reforestation on slopes would also increase CH_4 uptake of forests in China due to the greater CH_4 uptake than cropland (Dong et al., 2000). Furthermore, mean CH_4 uptake was found to increase significantly with stand age due to reduced soil water content (Hiltbrunner et al., 2012). These implicated that the

CH_4 sink of afforestation and reforestation would increase with time in China.

4. Conclusions

The estimates of this study have inevitable limitations and uncertainties. First, limited measurements were assumed to represent national conditions, which caused overestimation or underestimation of uptakes of forests and grasslands. In some ecoregions, we did not have enough data to represent the mean uptake CH_4 rate of the whole ecoregion. Second, great temporal and spatial variations in CH_4 uptakes of the vast country also led to uncertainty in estimation, especially for the EHSD, where the uptake rate varied greatly. Third, with no eddy covariance tower data (continuous high-frequent data) available in China, all data were based on closed chamber method (intermittent low-frequent data), which was another factor for bias in estimation. Fourth, uncertainty of each parameter also led to uncertainty in calculation of our estimate. E.g. duration of the growing season is quite variable in China and uncertainties in its estimate would lead to a level of uncertainty in our estimate. At last, sparse data about effect of management of forests and grasslands on CH_4 uptake is another source of uncertainty.

Furthermore, there are some key knowledge gaps for CH_4 cycling of forests and grasslands in China. As we know, soil water content and temperature are dominant factors controlling CH_4 cycling of forests and grasslands. Under climate change, soil water content and temperature significantly changes all over the world. However, studies focusing on the effect of simulated warming or drought on CH_4 uptake in forests and grasslands in China are far too few. Even less is focused on microbial mechanism about such effects as well as changes in structure and activity of methanotrophs. As mentioned before, besides mechanisms, although there are several modeling studies for CH_4 emissions from rice paddies and natural wetlands, not a single model was developed to simulate CH_4 uptakes of forests and grasslands in China. Based on meta-analyses and modeling of CH_4 uptakes of forests and grasslands in China and other countries in Asia, further upscaling such results to the whole Asia would be very important.

Therefore, new research directions may need to be proposed for future research upon discussion of these key issues in relation to (1) collecting greater amount of observational field data on various temporal and spatial scales through establishing research network of Chinese CH_4 fluxes from different ecosystems; (2) developing improved process-based CH_4 models in consideration of different sinks and sources of CH_4, calibrated and validated by a new model-data fusion framework (Peng et al., 2011); (3) quantifying the effect of land use change and climate change on the national CH_4 budget through inverse models and process-based models; (4) understanding variations in the structure and activity of methanotrophic community of forests and grasslands under global change; (5) introducing new approaches and methods to increase CH_4 uptake of forests and grasslands in China; and (6) through modeling or inventory, estimating CH_4 uptake of forests and grasslands in Asia.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.soilbio.2014.02.023.

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