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Evaluation of anthropogenic CH_4 emissions over China using bottom-up inventories

Xiaohui Lin[1*], Wen Zhang[1*], Monica Crippa[2], Shushi Peng[3], Pengfei Han[4], Ning Zeng[5], Lijun Yu[1], Guocheng Wang[1]

[1]State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
[2]European Commission, Joint Research Centre (JRC), Ispra, Italy
[3]Sino-French Institute for Earth System Science, College of Urban and Environmental Sciences, Peking University, Beijing, China
[4]State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
[5]Department of Atmospheric and Oceanic Science, and Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland, USA

[*] *Correspondence to*: linxh@mail.iap.ac.cn; zhw@mail.iap.ac.cn.

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Abstract

Atmospheric methane (CH_4) is a potent greenhouse gas that is strongly influenced by several human activities. China, as one of the major agricultural and energy production countries, e.g., rice cultivation, ruminant feeding and coal production, contributes considerably to the global anthropogenic CH_4 emissions. Understanding the characteristics of China's CH_4 emissions is necessary for interpreting source contributions and for further climate change mitigation. However, the scarcity of data from some sources or years and spatially explicit information pose great challenges to completing an analysis of CH_4 emissions. This study provides a comprehensive evaluation of China's anthropogenic CH_4 emissions by synthesizing most of the currently available data (12 inventories). The results show that anthropogenic CH_4 emissions differ widely among inventories, with values ranging from 41.9-57.5 Tg CH_4 yr^{-1} in 2010. The discrepancy primarily resulted from the energy sector (27.3-60.0% of total emissions), followed by the agricultural (26.9-50.8%), and waste treatment (8.1-21.2%) sectors. Temporally, emissions among inventories stabilized in the 1990s, but increased significantly thereafter, with annual average growth rates (AAGRs) of 1.8-3.9% during 2000-2010, but slower AAGRs of 0.5-2.2% during 2011-2015. Spatially, the growth of CH_4 emissions could be attributed mostly to an increase in emissions from the energy sector (mainly from coal mining) in the northern and central inland regions, followed by waste treatment in the southern and eastern regions. The availability of detailed activity data for sectors or subsectors and the use of region-specific emission factors play important roles in understanding source contributions, and reducing the uncertainty of bottom-up inventories.

Keywords: Anthropogenic CH_4 emissions; bottom-up inventories; uncertainty analysis; source and contribution.

1 Introduction

Atmospheric methane (CH_4) is a potent greenhouse gas with a warming potential that is 28 fold higher than that of CO_2 over a 100-year time horizon (Myhre et al., 2013). The dry air mole fraction of atmospheric CH_4 was 1873.7 parts per billion by volume (ppb) in Frebruary 2020 (https://www.esrl.noaa.gov/gmd/ccgg/trends_ch4). However, CH_4 has a relatively short atmospheric lifetime of ~10 years, and reducing CH_4 emissions is considered an efficient option to lower radiative forcing in the short term (Montzka et al., 2011; Shindell et al., 2012). The global CH_4 budget is strongly influenced by several human activities, including food production (ruminant and rice), waste (sewage and landfills), and fossil fuel production and use (coal, oil and gas) (Bruhwiler et al., 2014; Menon et al., 2007). Global anthropogenic CH_4 emissions (~357 Tg CH_4 yr^{-1}) contributed approximately 60% of total emissions, as estimated by atmospheric inversions (Saunois et al., 2020). According to the latest report from a global methane project, emissions from agriculture contributed most (44%) to global anthropogenic sources, followed by fossil fuel (35%) and waste (12%) (Saunois et al., 2020). Control of anthropogenic CH_4 emissions has become a promising target in the effort to mitigate climate change at short timescales (Höglund-Isaksson, 2012; Henne et al., 2016; Saunois et al., 2016). Therefore, understanding the levels and trends of anthropogenic CH_4

emissions and their drivers is extremely crucial for global change research and mitigation.

The estimation of anthropogenic CH_4 emissions is more challenging than the estimation of CO_2 emissions due to the greater uncertainty and fewer global estimates (IPCC, 2014). The current estimates of global anthropogenic emissions ranged from 334 to 375 Tg CH_4 yr^{-1} by top-down approaches and from 348 to 392 Tg CH_4 yr^{-1} by bottom-up approaches during 2008-2017 (Saunois et al., 2020). Top-down (atmospheric inversions) approaches provide a good picture of global and continental CH_4 emissions (Alexe et al., 2014). However, for small-scale regions, inversions largely depend on prior emission inventories and are still limited by their coarse spatial resolutions (Alexe et al., 2014; Henne et al., 2016). Bottom-up emissions estimates are based on source-specific information on activity data and emission factors. The analyses of source-specific emissions help us understand the relationship between emissions and the underlying socioeconomic and sociodemographic driving processes (Miller and Michalak, 2017; Zhou and Gurney, 2011). Bottom-up inventories are essential in terms of providing baseline information on emission characteristics, and reliable emission estimates can further help with optimizing mitigation strategies (Cheng et al., 2014; Sheng et al., 2019). Due to the quality of activity data and the variability of emission factors caused by discrepancies in socioeconomic characteristics in both space and time, there are still several challenges in relation to the use of bottom-up estimates (Barkley et al., 2017; Bergamaschi et al., 2010).

As an area with widespread rice and coal production areas and a growing human population with billions of people, China is a large emitter of CH_4 (Ito et al., 2019; Janssens-Maenhout et al., 2019; Oreggioni et al., 2020). However, insufficient attention has been given to CH_4 emissions in China, although CH_4 has greater short-term impacts than CO_2 and contributes significantly to climate change (Zhang et al., 2016; Zhang et al., 2018). The main anthropogenic sources of CH_4 in China in 2014, as reported by the National Communication on Climate Change (NCCC) of the People's Republic of China, were from agriculture (40% of anthropogenic emissions), waste (12%) and energy (45%). However, anthropogenic CH_4 emissions differ widely among inventories with differences as high as 17 Tg CH_4 found for 2010 (Ito et al., 2019), of which paddy and coal mining emissions contributed a large part of the variability (Cheewaphongphan et al., 2019). Due to the scarcity of data from some sources or years and spatially explicit information, a quantitative analysis of China's CH_4 emissions remains a great challenge. Several studies have quantified the emissions from rice paddies in China by using process-based modeling approaches (Huang et al., 1998; Li et al., 2002; Tian et al., 2011; Zhang et al., 2011). However, there are considerable differences in the modeling estimates, which range from 3.8 to 9.8 Tg (Zhang et al., 2017). As the largest coal producer worldwide, China's coal mine CH_4 emissions are still poorly quantified, and estimates vary significantly from 14 to 28 Tg CH_4 yr^{-1} (Sheng et al., 2019). In addition, emissions from waste treatment are mainly focused on wastewater in China (Du et al., 2018; Zhao et al., 2019). However, there have been few studies on the comprehensive evaluation of China's anthropogenic CH_4 emissions, although one or several representative emission sources have been studied at the provincial level or in certain regions are studied (Chen et al., 2011; Huang et al., 2019; Liu et al., 2016; Ren et al., 2011; Yue et al.,

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2012; Zhang and Chen, 2014). A systematic estimate is urgently needed to understand China's contribution to the global CH_4 budget and to furhter mitigate climate warming.

Based on a comprehensive literature review of previous studies, we collected most of the available datasets (12 global and regional inventories) to characterize the anthropogenic CH_4 emissions in China. We presented a detailed evaluation of the major emission sectors, including agricultural activities (rice cultivation and livestock), energy activities (fossil fuel production and use), and waste management (wastewater and landfill), in the existing inventories (Table 1). The specific objectives of this study were to (1) adequately understand the characteristics and dynamics of anthropogenic CH_4 emission in China and identify its sectoral and regional contributions; (2) understand sources of discrepancies among inventories and provide helpful suggestions for further improvements in estimations and policy-making related to the control of CH_4 emissions.

2 Data and methods

Here, we collected 12 global and regional bottom-up inventories for anthropogenic CH_4 emissions over mainland China (listed in Table 1), including 4 gridded datasets and 8 statistical datasets. To analyze the spatiotemporal patterns and discrepancies among inventories, specific anthropogenic sectors were aggregated into 3 categories (i.e., agriculture, energy, and waste) (Table S1). Specifically, the 4 gridded inventories were collected from the fuel combustion inventory from Peking University (PKU-CH4-China-v1) (Peng et al., 2016), Emissions Database for Global Atmospheric Research (EDGAR v5.0) (Crippa et al., 2019), Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS/ECLIPSE v5a CLE baseline) (Höglund-Isaksson, 2012), and Regional Emission inventory in ASia (REAS 2.1) (Kurokawa et al., 2013; Ohara et al., 2007). The 8 statistical tabular data sets used in this study were from research institutes and published literature, including the Environmental Protection Agency (EPA) of the United States; Food and Agriculture Organization (FAO); National Communication on Climate Change (NCCC) of the People's Republic of China; Global Methane Budget (GMB) released by the Global Carbon Project (Saunois et al., 2020); published literature data from Yue et al. (2012), Huang et al. (2019), Zhang and Chen (2014), Zhang et al. (2016), Zhang et al. (2018), and China High Resolution Emission Database (CHRED) (Cai et al., 2018).

The three gridded emissions (i.e., EDGAR, GAINS, and REAS) are generally based on country-specific socioeconomic statistics and with country-level or Intergovernmental Panel on Climate Change (IPCC) default emission factors (Crippa et al., 2019; Höglund-Isaksson, 2012; Kurokawa et al., 2013; Ohara et al., 2007), which are widely used as priori emissions for atmospheric research. The PKU inventories considered regional discrepancies by applying province-level activity data and region-specific emission factors when data availability allowed, especially for provinces with large differences in economic development (Peng et al., 2016).

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Table 1 Key features of gridded emissions inventories

Item	PKU (PKU-CH4-China-v1)	EDGAR (EDGARv5.0)	GAINS (ECLIPSE V5a)	REAS (REAS 2.1)
Year	1980-2010	1970-2015	1990-2050 at 5-year intervals	2000-2008
Domain	Global	Global	Global	East, Southeast, South, and Central Asia
Spatial resolution	0.1°	0.1°	0.5°	0.25°
Temporal resolution	Annual	Annual	Annual	Annual
Sources of activity data				
Agriculture	Provincial agriculture statistics (NBS)	FAO	FAO	FAO
Energy	Provincial energy statistics (NBS)	IEA	IEA	IEA, Provincial energy statistics (NBS)
Waste	Provincial environmental statistics (NBS)	UNFCCC	UNFCCC, FAO	NA
Data access	http://inventory.pku.edu.cn/home.html	https://edgar.jrc.ec.europa.eu/overview.php?v=50_GHG	https://iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5a.html	http://www.nies.go.jp/REAS/index.html#data%20sets
Reference	Peng et al. (2016)	Crippa et al. (2019)	Höglund-Isaksson (2012)	Kurokawa et al. (2013)

*The complete list of data sources can be found in the References.

110 **3 Results and Discussion**

3.1 Temporal variations of anthropogenic CH_4 emissions

The anthropogenic CH_4 emissions from China differ widely among inventories, but are still broadly within the minimum-maximum range of the GMB for 2000-2009 and 2003-2012 (Fig. 1). The emission estimates from these data sets are in the ranges of 28.5-46.3 and 41.9-57.5 Tg CH_4 yr^{-1} for 1990 and 2010, respectively. During 2000-2010, the emissions were dominated by emissions from the energy sector (27.3-60.0% of the total emissions), followed by emissions from agricultural activities (26.9-50.8%), and waste treatment (8.1-21.2%). A considerable discrepancy was found between REAS and the other inventories in terms of the magnitude and variation, with a difference as high as 35.8 Tg CH_4 in 2008. Furthermore, emissions from the energy sector in REAS were ~2 times greater than those from other inventories (22-24 Tg CH_4 yr^{-1}). The trend in REAS was mostly triggered by a fast increase in energy sector emissions, with AAGRs greater than 10% during 2000-2008. This result was probably due to the fact that the coal consumption trend was adjusted to a higher value according to the GOME satellite (Ohara et al., 2007). The CH_4 emissions estimated from EDGAR were 13.2% higher than those from NCCC, in the respective corresponding periods. These results may be due to the higher estimates of agriculture and energy emissions obtained by using high emission factors in rice cultivation and coal mining in EDGAR (Cheewaphongphan et al., 2019; Peng et al., 2016). Emissions derived from PKU were 12.2% lower than those from NCCC, which resulted from the lower emission factors in livestock and coal mining.

The existing inventories show rather consistent temporal trends. CH_4 emissions stabilized in the 1990s but increased significantly thereafter, with AAGRs of 1.8% (EPA) - 3.8% (GAINS) during 2000-2010, and slower AAGRs of 0.5% (EDGAR) - 2.2% (FAO) during 2011-2015. Specifically, agricultural activities were the main contributors to national CH_4 emissions before 2000 (46.1-60.0% of the total emissions), expect as reported by the FAO. Emissions from agriculture were rather stable and showed slight decreases during 2000-2010, with AAGRs of -0.7~-0.5% among the inventories. This result may be caused by the decreasing trend of emissions from rice production and livestock, with AAGRs of -0.03~-0.8% and -0.5~-0.7%, respectively. However, EDGAR presented an increasing trend in agriculture (AAGR = 0.2%) in the same period, which resulted from the combined effect of emissions growth in rice production (AAGR=0.9%), and a reduction in livestock (AAGR = -0.6%). Over the study period, energy source emissions showed substantial variability, ranging from 11.5 ±3.0 Tg CH_4 yr^{-1} in 1990 to 22.6 ±3.6 Tg CH_4 yr^{-1} in 2010. After 2000, emissions from energy increased significantly and became the leading source (AAGR: 5.9-9.0%, 2000-2010). This increase was mainly driven by the rapid growth of coal production in China, with an AAGR up to 9.0% in the 2000s, while it was only 2.6% in the 1990s according to the official data released by the National Bureau of Statistics of China (CSY, 2019). Additionally, discrepancies exist in the magnitude of waste sector emissions, although the value continued to increase steadily during 2000-2010 (AAGR: 2.1-3.4%), except as reported by the EPA (AAGR = 0.4%).

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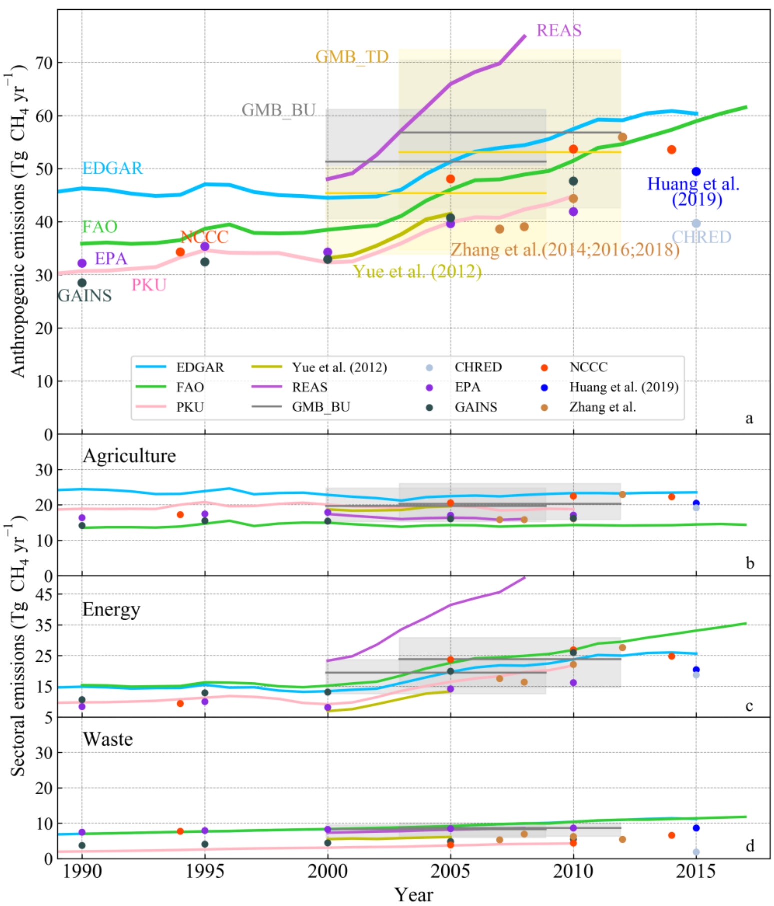

Fig. 1 The temporal variation in China's total (a) and sector-specific (c-d) CH_4 emissions since 1990. Gray and yellow lines indicate the mean of the bottom-up and top-down estimates of CH_4 emissions from GMB, respectively. Shaded areas represent the min-max value of emissions from GMB.

3.2 Spatial patterns of anthropogenic CH_4 emissions

Available gridded emissions remain limited; thus, the spatial pattern analysis of CH_4 emissions was performed on the PKU, EDGAR, GAINS, and REAS inventories (Fig. 2, Table 1). In 2010, China's CH_4 emissions were dominated by emissions from the energy sector (41-67% of total emissions), followed by emissions from agricultural activities (21-42%), and waste treatment (10-18%). Remarkable regional disparities were observed among inventories. The spatial patterns had a close relationship with regional urbanization and economic activities, because of the associated increased energy production, livestock and waste sector emissions. High-emissions areas (e.g., emitting grids > 40 g CH_4 m^{-2} yr^{-1}) were generally located in densely populated areas (such as Beijing and Shanghai), energy production regions (such as Shanxi), and rice cultivation

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areas in south-central China as well as livestock-dominated regions in the North China Plain and Northeast China. The western regions showed low emissions (e.g., emitting grids < 1 g CH_4 m^{-2} yr^{-1}). Intense emissions from large cities were attributable to industrial activities, transportation, and solid waste in landfills (Ito et al., 2019). The expansive areas of rice paddy and double-cropping systems in southern and central China were recognized as being large contributions to the corresponding high emissions (Chen et al., 2013; Zhang et al., 2011). Due to massive emissions from coal mining, provinces such as Shanxi, Ningxia, Henan, Guizhou, Chongqing, and Sichuan were emissions hotspots, with emitting grids higher than 60 g CH_4 m^{-2} yr^{-1}.

There were substantial discrepancies in the magnitude and distribution of sector-specific emissions among the inventories. For example, the amount of CH_4 emissions from agriculture in EDGAR was 24.2-45.7% higher than those from PKU, REAS, and GAINS. The spatial pattern of agricultural emissions in EDGAR was similar to the corresponding distribution in PKU because the emission factors used in EDGAR were updated with those in PKU (Janssens-Maenhout et al., 2019). Grids with high estimations (10-40 g CH_4 m^{-2}) were mainly located in the Yangtze River valley (Fig. 2e) and the eastern part of the Beijing-Tianjin-Hebei region accounted for nearly half of the agricultural emissions (with values that were 22.7-39.3% higher than the others, Fig. 2q). The higher CH_4 emissions estimated from EDGAR in Beijing may be due to the higher number of livestock from FAO statistics (5.5 million cattle) (Gilbert et al., 2018), which was considerably higher than the number provided by NBS (0.3 million cattle) in 2010 (CSY, 2019). Additionally, EDGAR tended to allocate more emissions from energy to the North China Plain (such as Shanxi and Shandong provinces, Fig. 2f). More than 75% of the energy emissions from EDGAR were allocated in high-emitting grids (>60 g CH_4 m^{-2} yr^{-1}, Fig. 2r), which covered less than 0.8% of the total number of grids. This result implied that EDGAR may provide lower estimates in other areas. PKU had a distinct spatial pattern for energy emissions, which was attributable to the fact that emissions from coal exploitation were located using the geolocation (latitude and longitude) of 4264 coal mines from Liu et al. (2015). Emissions from waste treatment were mostly located in more developed areas, such as the North China Plain, Yangtze River Delta and Pearl River Delta. Zhang and Chen (2014) also found that emissions from waste treatment were related to the size of the economies of the regions and their urban population scales to a certain extent. The emissions from waste treatment estimated by EDGAR were 20.7-142.9% higher than the values from other inventories. Moreover, EDGAR tended to have higher emissions from waste treatment in urban areas, whose emission hotspots (> 40 g CH_4 m^{-2} yr^{-1}) were highly consistent with the distribution of provincial capitals (Fig. 2g).

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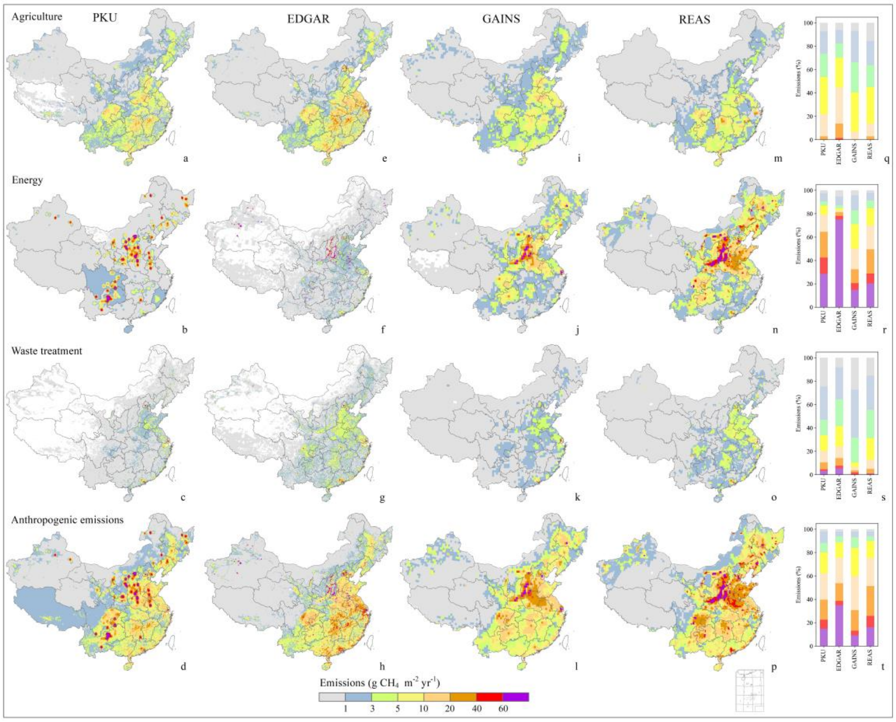

Fig. 2 The spatial distribution of sectoral and total anthropogenic CH_4 emissions from PKU (a-d), EDGAR (e-h), GAINS (i-l) in 2010 and REAS (m-p) in 2008, and emissions frequency (q-t).

3.3 Changes in the spatial pattern of anthropogenic CH_4 emissions from 2000 to 2010

From 2000 to 2010, anthropogenic CH_4 emissions increased considerably in China, and this increase was mainly driven by increased emissions from energy exploitation (especially in coal mining) in the northern and central regions, followed by waste treatment in the southern and eastern regions and agriculture in the northeastern region (Fig. 3). The growth was profoundly affected by urbanization and economic development. The decrease in CH_4 emissions from PKU in southern and southeastern China was attributed to a decline in rice cultivation and livestock feeding (Peng et al., 2016), and similar results were also observed in REAS (Fig. 3a,m). Since the 1980s and perhaps earlier, most Chinese farmers have adopted the practice of draining paddy fields in the middle of the rice-growing season, which halts most of the methane releases from the fields (Qiu, 2009). Additionally, emissions from livestock in southeastern China have decreased due to the reduction in the buffalo population (Yu et al., 2018). These changes in livestock and rice cultivation contributed to mitigation in CH_4 emissions. In EDGAR, a decreasing trend was found for energy emissions was found in the central regions and in the North China Plain (Fig. 3f), while a similar trend was not found in the other inventories during 2000-2010. These results were attributed to the reduced emissions in the subsector of energy for buildings (RCO, Fig. S1). In addition, Shanxi province

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had a larger contribution to the changes in energy emissions in EDGAR (40%) than to those in other inventories (18-23%), which may have omitted emissions in other regions.

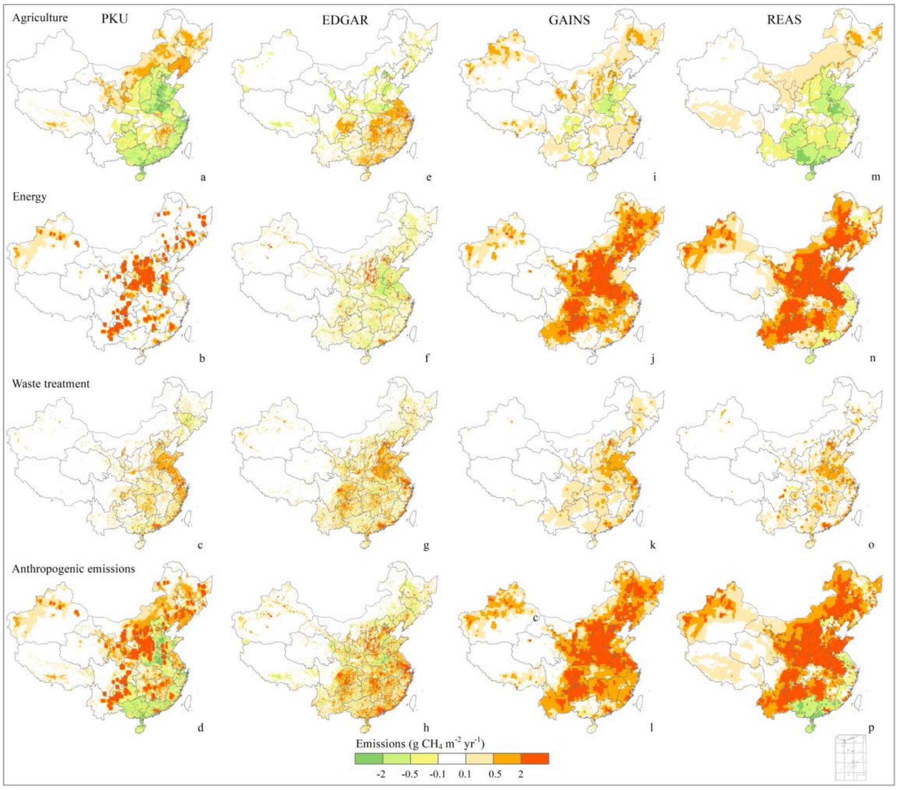

Fig. 3 Changes in sectoral and total anthropogenic CH_4 emissions from PKU (a-d), EDGAR (e-h), GAINS (i-l) from 2000 to 2010, and REAS (m-p) from 2000 to 2008.

3.4 Further comparison with other inventories at the subsector level

To further evaluate the quality of existing inventories, independent and more detailed subsector datasets were collected to improve our understanding of the uncertainty in total amounts and spatial patterns among different inventories. Based on the data availability, three subsectors of major emissions sources are displayed, i.e., rice cultivation, livestock, and coal mining (Fig. 4). These three subsectors accounted for 70-85% of the total emissions in China in 2010. The data used for comparison were collected from Zhang et al. (2017) (for rice cultivation), Lin et al. (2011) (for livestock), and Sheng et al. (2019) (for coal mining). Zhang et al. (2017) compiled the NCCC inventory of rice by using a semiempirical model (CH4MOD). The CH4MOD model is a semiempirical model simulating CH_4 production and emissions at daily steps. Inputs into the CH4MOD include daily air temperature, percentage of sand in the paddy soil, rice grain yield, type and amount of organic matter applied, and water management used for rice irrigation (Zhang et al., 2011). Lin et al. (2011) estimated emissions

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from livestock based on county-level statistical data and region-specific emission factors. Sheng et al. (2019) estimated emissions from coal mining based on more than 10000 operating coal mines reported by the Chinese State Administration of Coal Mine Safety (SACMS).

For the rice cultivation subsector, the amount from PKU was 7.3 Tg CH_4 yr^{-1}, which was comparable to the value of 8.2 Tg CH_4 yr^{-1} reported for 2010 by Zhang et al. (2017) (Fig. 4j). However, EDGAR tended to provide higher estimates, with a value of 13.9 Tg CH_4 yr^{-1} (Fig. 4d). This difference could be seen from the larger contribution of high-emitting grids (> 10 g CH_4 m^{-2} yr^{-1}, Fig. 4m) in EDGAR (6.7 Tg CH_4 yr^{-1} or 48.7% of total emissions), while the values in the other inventories were ranging from 17~34% (1.2~2.8 Tg CH_4 yr^{-1}). The higher estimates from EDGAR were primarily located in the Yangtze River (e.g., Hunan and Jiangxi). According to the study of Cheewaphongphan et al. (2019), EDGAR used a higher proportion of continuous floods, leading to a higher emission factor than that produced in intermittent flood conditions. In contrast, REAS tended to provide a lower estimate (6.7 Tg), especially in the Yangtze River and Northeast China (Fig. 4g). This discrepancy was partly because emissions from rice cultivation in REAS2.1 were from 2008, while others were from 2010. Moreover, emissions in 2008 from REAS2.1 were extrapolated from REAS1.1 in 2000 (Kurokawa et al., 2013), which may not have captured the emission changes caused by the increases in rice cultivation area. As reported by the NBS, areas of rice cultivation have increased by 5900 km^2 in Anhui, Hunan, Jiangsu and Jiangxi provinces, and 12,514 km^2 in Northeast China (i.e. Heilongjiang, Jilin, and Liaoning provinces) from 2000 to 2008 (CSY, 2019).

For the livestock subsector, the amount ranged from 9.2 (REAS) to 11.4 (PKU) Tg CH_4 yr^{-1}. The bottom-up inventory based on detailed county-level activity data estimated the 2010 emissions to be 12.4 Tg CH_4 yr^{-1} (Lin et al., 2011). A consistent spatial pattern from livestock sources was found among inventories. However, REAS tended to underestimate emissions in the North China Plain (such as in Shandong and Henan), Tibetan Plateau and Northeast China, which missed large numbers of high-emitting grids compared to other inventories (Fig. 4h). In addition, higher emissions in the northeastern part of Beijing were reported by EDGAR, with grids emitting more than 20 g CH_4 m^{-2} yr^{-1} (Fig. 4e). This results was caused by the high estimated number of livestock obtained from FAO statistics (Gilbert et al., 2018).

For the coal mining subsector, the amounts from PKU and EDGAR were 17.3 and 19.0 Tg CH_4 yr^{-1} in 2010, respectively, which were comparable to the values of 16.7 Tg CH_4 yr^{-1} in 2011 from Sheng et al. (2019) and 16.0 Tg CH_4 yr^{-1} in 2010 from Zhu et al. (2017). However, emissions from REAS showed a large difference with those in the other inventories, with values up to 38.4 Tg CH_4 yr^{-1} in 2008. Spatially, more than 92% of emissions from coal mining in EDGAR were located in high-emitting grids (>60 g CH_4 m^{-2}, Fig. 4d), which covered less than 0.5% of the total grid number. This result may be due to the limited number of coal mines (~ 4000) used in EDGAR (Crippa et al., 2019; Sheng et al., 2019). The allocation of national total emissions to limited mine locations leads to incorrect spatial patterns and artificial emission hot spots (Sheng et al., 2019). These spatial errors would cause bias in the analysis of trends and source attribution in inversions, and mislead

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mitigation strategies in coal exploitation (Sheng et al., 2019). Additionally, emissions from coal mining in PKU showed a relatively consistent pattern with that in Sheng et al., (2019); however, PKU tended to have similar proportions among emitting grids (Fig. 4o). This result could be because the locations of coal mines used in PKU may have a coarser spatial resolution than 0.1˚.

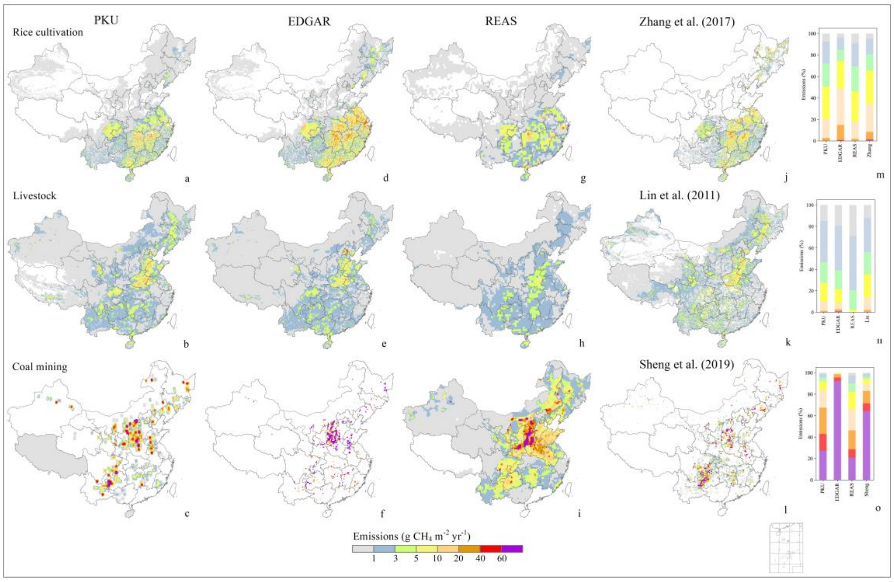

Fig. 4 The spatial distribution of sub-sectoral CH_4 emissions among inventories in 2010. Emissions from coal mining in EDGAR were aggregated to a spatial resolution of 0.2˚.

3.5 Estimates and uncertainties of total and sectoral emissions

Considering the comparability of different inventories, subsector emissions were collected for five datasets (i.e., PKU, EDGAR, EPA, NCCC, and Zhang et al. (2016)). In 2010, the total emissions in China were estimated to be 48.7±5.2 Tg CH_4 yr^{-1} (mean ± standard deviation (SD), hereafter the same) among inventories (Fig. 5a). The mean emissions from agricultural activities were 18.6±3.1 Tg CH_4 yr^{-1}, of which livestock contributed 11.0 Tg CH_4 yr^{-1} and rice cultivation contributed 7.8 Tg CH_4 yr^{-1}. Among all the agricultural activities, rice cultivation showed a relatively large range from 5.9 Tg CH_4 yr^{-1} in EPA to 13.9 Tg CH_4 yr^{-1} in EDGAR (Fig. 5b). The CH_4 emissions from rice paddies are among the most uncertain estimates in rice-growing countries (Huang et al., 2006). High spatial heterogeneity and inadequate data on rice cultivation introduce large uncertainties to inventories (Yan et al., 2009; Yan et al., 2003; Zhang et al., 2014). Furthermore, the uncertainty of emission factors related to rice practices is high in China (Peng et al., 2016). In addition, energy activities play an important role in national emissions, with a mean value equal to 23.3 Tg CH_4 yr^{-1} and an SD of 3.5 Tg CH_4 yr^{-1}. Coal mining is the largest emission source, accounting for 77% (17.9 Tg CH_4 yr^{-1}) of the total energy emissions (Fig. 5a). Estimated emissions

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from coal mining ranged from 14.3 Tg CH_4 yr^{-1} in EPA to 22.9 Tg CH_4 yr^{-1} in NCCC, while estimates from PKU, EDGAR, and Zhang et al. (2016) showed only a small difference (17.3-19.3 Tg CH_4 yr^{-1}) (Fig. 5b). EDGAR revised emission factors for coal mining with local data from PKU, and weighted the emissions by coal mine activity per province (Janssens-Maenhout et al., 2019). Emissions from waste treatment were 7.1±2.5 Tg CH_4 yr^{-1}, which contributed a relatively small share of the national total emissions (14%). However, a notable discrepancy exists in emissions from waste treatment, which can be classified into two groups (Fig. 5b). Estimates from PKU, NCCC, GAINS, and Zhang et al. (2016) were 4.3-6.2 Tg CH_4 yr^{-1}, respectively, while estimates in the others were 8.6-10.4 Tg CH_4 yr^{-1} in 2010. These differences were mainly induced by the different estimates for wastewater. Higher estimates for wastewater probably resulted from a higher CH_4 correction factor for wastewater treatment plants or a higher chemical oxygen demand (Peng et al., 2016).

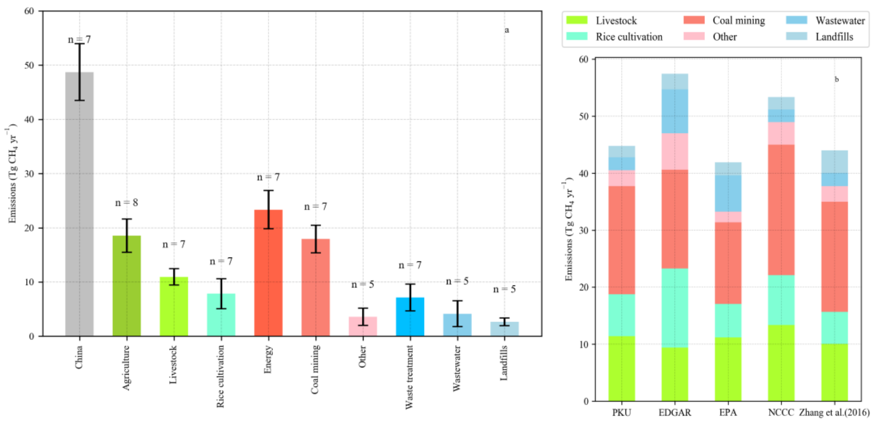

Fig. 5 The mean (bar plot in (a)) and standard deviation (error bar in (a)) of sector and subsector CH_4 emissions, and total anthropogenic CH_4 emissions by subsector (b) among different inventories in 2010.

4 Conclusions

As one of the major rice cultivators and coal producers, China is a large emitter of CH_4. Quantifying China's contribution to the global CH_4 budget is important and can provide helpful support for policy-making related to mitigating CH_4 emissions. We collected and analyzed the available datasets to comprehensively evaluate China's anthropogenic CH_4 emissions. This study, to the best of our knowledge, provides the first quantitative analysis of the amount and spatiotemporal patterns of CH_4 emissions in China. China's CH_4 emissions were largely associated with economic development and urbanization. High emissions were generally located in densely populated areas, energy production regions, and agriculture-dominant regions. Temporally, emissions stabilized in the 1990s but increased significantly thereafter, with AAGRs of 1.8-3.9% during 2000-2010, and slower AAGRs of 0.5-2.2% during 2011-2015. Spatially, increased emissions were mainly driven by the increased emissions from energy activities in the northern and central inland regions, followed by the emissions from waste treatment in the southern and eastern regions. During 2000-2010, anthropogenic CH_4 emissions from China differed widely among inventories, of which the energy sector contributed the most to the total emissions, followed by the agricultural activities, and waste treatment. Large discrepancies mainly resulted from rice cultivation in agricultural sector, coal mining in the energy sector, and wastewater in the waste treatment sector. We suggest data developers should make the detailed activity data for sectors and subsectors publicly available; furthermore, they should use the local optimized emission factors instead of the default emission factors to reduce the level of uncertainty.

Author contributions. XHL and WZ conceived and designed the study. XHL collected and analyzed the data sets. XHL led the paper writing with contributions from all coauthors.

Competing interests. The authors declare that they have no conflicts of interest.

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