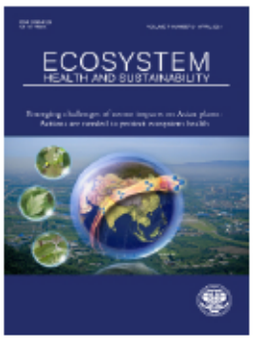

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Methane emissions from livestock in East Asia during 1961–2019

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ABSTRACT

Context: East Asia is a crucial region in the global methane (CH4) budget, with significant contributions from the livestock sector. However, the long-term trend and spatial pattern of CH4 emissions from livestock in this region have not been fully assessed.

Methods: Here, we estimate CH4 emissions from 10 categories of livestock in East Asia during 1961 – 2019 following the Tier 2 approaches suggested by the 2019 Refinement to the IPCC 2006 Guidelines.

Results: livestock-sourced CH4 emission in 2019 was 13.22 [11.42 – 15.01] (mean [minimum% maximum of 95– confidence interval] Tg CH4 yr-1, accounting for an increase of 231% since 1961. The contribution of slaughtered populations to total emissions increased from 3% in 1961 to 24% in 2019. Spatially, the emission hotspots were mostly distributed in eastern China, South Korea, and parts of Japan, but they tend to shift northward after 2000.

Conclusion: It is necessary to use dynamic emission factors and include slaughtered populations in the estimation of livestock CH4 emissions. Regions including Northern China, Mongolia, and South Korea deserve more attention in future CH4 mitigation efforts.

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CH4 emissions; livestock; dynamic emission factors; live and slaughtered populations; East Asia

Introduction

Methane (CH4) is the second most important greenhouse gas in terms of radiative forcing (Ciais et al. 2014; Saunois et al. 2016). Globally, CH4 emissions grew rapidly in recent years and the mean mole fraction of atmospheric CH4 reached 1850 ppb in 2017, about 2.6 times that before the industrial revolution (Saunois et al. 2020; Nisbet et al. 2019). The rapid growth is largely due to human activities, which contributes approximately 60% of global total CH4 emissions (Tian et al. 2016; Saunois et al. 2020; Tian et al. 2015). Therefore, reducing anthropogenic CH4 emission can be an effective approach to mitigate the greenhouse effect (Kirschke et al. 2013; Saunois et al. 2016; Xu et al. 2019). The livestock sector has been widely recognized as a major contributor to anthropogenic CH4 emissions (Dangal et al. 2017; Herrero et al. 2016; Peng et al. 2016; Chang et al. 2019). It is estimated that CH4 emissions from livestock sector were 111 Tg CH4 yr-1 in the 2008 – 2017 decade, which accounted for 30% of global total anthropogenic emissions (Saunois et al. 2020).

East Asia is one of the hot spots for global livestock CH4 emissions, due to the large and rapidly increasing livestock population and production in this region (Dangal et al. 2017; Tubiello et al. 2013; Yamaji, Ohara, and Akimoto 2003; Herrero et al. 2016). The total number of livestock (including ruminants and non-ruminants) in East Asia has increased by 167%, from 0.31 billion heads in 1961 to 0.82 billion heads in 2019 (FAOSTAT. 2020). Moreover, livestock populations in this region are expected to keep increasing in the coming decades driven by the increasing demand of dairy products and meat associated with human population growth, rising incomes and dietary changes (Herrero et al. 2016; Thornton 2010). Increases in livestock population and changes in production systems would have significant impacts on CH4 emissions. However, there is limited understanding of how changes in both ruminants and non-ruminants' populations and livestock production system have altered the long-term trajectory and spatial patterns of CH4 emissions in East Asia.

Previous inventories of livestock CH4 emissions in East Asia were mostly based on constant emission factors, without considering their temporal variations (Höglund-Isaksson 2012; Yamaji, Ohara, and Akimoto 2003; Tubiello et al. 2013; Ito et al. 2019; US EPA 2012). But in fact, livestock characters have substantially changed over the past few decades, which may result in significant changes in emission factors (IPCC 2019). For example, the carcass weight of cattle in Japan and China had increased by 157% and 52%, respectively,

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Supplemental data for this article can be accessed here

from 1961 to 2019 (FAOSTAT. 2020) . The temporal dynamics of emission factors can be quantified using the IPCC Tier 2 approach, which requires more detailed information on livestock, including livestock characteristics, feeding systems and manure management approaches (IPCC 2006). Recently, Yu et al. (2018) and Xu et al. (2019) used Tier 2 method to evaluated livestock CH4 emissions in China, and found the results were clearly inconsistent with estimates based on constant emission factors. Globally, Dangal et al. (2017) estimated CH4 emissions from ruminant livestock including cattle, sheep and goat, and found the results based on Tier 2 method can be 9 – 35% higher than those based on Tier 1 default emission factors during 1961 – 2014. Thus, using the Tier 2 approach with dynamic emission factors may help to better understand and accurately quantify the long-term CH4 emissions from livestock (IPCC 2019).

Driven by increased human demand for meat, the number of slaughtered livestock has increased rapidly in recent decades (FAOSTAT. 2020). The IPCC have pointed out that animals should be included in the estimate of greenhouse gas emissions even if they are slaughtered (IPCC 2019). However, most existing studies only used the population of live animals as activity data (e.g., Janssens-Maenhout et al. 2017; Tubiello et al. 2013), the contribution of slaughtered population to CH4 emissions has been relatively neglected. In China, some studies have included annual slaughtered population in CH4 estimates and found that this will help improve the representativeness of activity data (e.g., Peng et al. 2016; Yu et al. 2018). Moreover, due to the difference in feeding length, the average life span (ALS) of different animals may not be equal (Peng et al. 2016). The actual emission duration (i.e., months when animals emit CH4 within a year) could be shorter than one year for some animals (IPCC 2019). Generally, the ALS of large animals (e.g., cattle and buffalo) will be longer than that of small ones (e.g, sheep and goat) (Peng et al. 2016). For the same livestock category, the ALS of adult animals is longer than that of the young ones (Yu et al. 2018). Therefore, incorporating the ALS into estimates will help improve estimation accuracy of the annual CH4 emissions from livestock (Yu et al. 2018; IPCC 2019).

In this study, we followed the most recent revised IPCC guidelines (IPCC 2019) to estimate livestock CH4 emissions in East Asia from 1961 to 2019 (the latest year for which data are available). The estimates were primarily based on Tier 2 method with dynamic emission factors. Tier 1 method with constant emission factors was also used to make a comparison. The impact of ALS and the contribution from slaughtered animals were taken into account. Our objectives were to (1) provide latest inventory of CH4 emissions from livestock in East Asia based on the most recent IPCC guidelines; (2) quantify the temporal evolution of livestock CH4 emissions in nearly sixty years; (3) reveal the spatial pattern of livestock CH4 emissions; (4) make a comparison between our estimates and other inventories (e.g., EPA and EDGAR).

Materials and methods

The annual total CH4 emissions from livestock are the sum of emissions from enteric fermentation and manure management (IPCC 2019). Mathematically,

$$E_t = E_e + E_m \tag{1}$$

$$E_e = \sum_i N_i \cdot EF_{ei} \cdot ALS_i/12 \tag{2}$$

$$E_m = \sum_i N_i \bullet EF_{mi} \bullet ALS_i/12 \tag{3}$$

where, Et = annual total CH4 emissions from livestock; Ee = CH4 emissions from enteric fermentation; Em = CH4 emissions from manure management; i = livestock category or subcategory; N = number of livestock; EFe = emission factor of enteric fermentation; EFm = emission factor of manure management; ALS = average life span of livestock within 1 year, that is, months when livestock emit CH4 in a calendar year.

Livestock numbers

In this study, a total of ten categories of livestock were taken into account, including ruminants such as dairy cattle, nondairy cattle, buffalo, sheep, goat and camel, non-ruminants such as pig, horse, mule and ass. For each livestock category, the year-end live population and annual slaughtered population were both included in estimation of CH4 emissions (Peng et al. 2016). The year-end live population refers to the number of animals still alive at the end of the year. It is generally obtained from the end-of-year inventory of live animals (NDRCC 2014). The annual slaughtered population refers to the total number of slaughtered animals within a year. Including the slaughtered population in estimation will help reveal the actual number of livestock that emits CH4 within a year (IPCC 2019). We first collected official census data at sub-national level in each country. If sub-national data were missing, national statistics from FAO were collected. For mainland China, we obtained live population (1978 – 2019) of each livestock category at provincial level from the National Bureau of Statistics of China (NBSC, http://data.stats.gov.cn/easyquery.htm?cn=E0103). Since NBSC only provided the total number of cattle, the proportion of dairy cattle, nondairy cattle and buffalo was extracted from the China Agricultural Statistical Yearbook, and then divided the total cattle population into three categories.

Moreover, the provincial livestock numbers during 2000 – 2005 were adjusted proportionally to match national statistics, taking into account the inconsistency between national and provincial inventories in this period. Statistics for Taiwan, Hong Kong and Macao were obtained from FAO database (FAOSTAT. 2020). For Mongolia, the live population (1970 – 2019) were obtained for each province (aimag) from the National Statistics Office of Mongolia (NSOM, http://1212.mn/tables.aspx?TBL_ID = DT_NSO_1001_021V1). For missing years without provincial statistics in mainland China and Mongolia during 1961 – 2019, we extracted the proportion of livestock for each province based on existing inventory and then allocated country-level FAO data into provincial level (Dangal et al. 2017). Since there are lack of provincial census data for the slaughtered population in mainland China and Mongolia, we collected country-level data from FAO and then allocated the data to provincial level in the same proportion as the live population. For Japan, South Korea, and North Korea, the national statistics of live and slaughtered population of each livestock category were extracted from FAO. According to the IPCC Tier 2 approach, the live population was divided into three subcategories: Breeding female, Young, and Other (Table. S1). Considering the breeding females and young animals are rarely slaughtered, the slaughtered population was not classified into subcategories in this study.

Emission factors

According to the Tier 2 approach from IPCC (2019), the emission factors of enteric fermentation and manure management can be calculated as follows,

$$EF_e = \left[\frac{GE * \left(\frac{Y_m}{100}\right) * 365}{55.65}\right] \quad (4)$$

where EFe = emission factors of enteric fermentation. GE = gross energy intake of each livestock category/subcategory, M head-1 day-1. GE is the sum of energy for maintenance, activity, growth, lactation, work and production of livestock, which can be estimated based on information on body weight, milk and wool production, working times and feed quality, etc. Ym = convention factor showing percentage of feed energy converted to CH4. The convention rate are associated with several factors including animal genetics, feed characteristics, production practices, etc. IPCC (2019) listed default values of Ym for each livestock category by production yield and feed quality. In this study, we mostly adopted the IPCC default values with adjustment according to country specific production yield and feed quality (Table S2). The factor 55.65 is the energy content of CH4, MJ kg-1 CH4.

$$EF_m = (VS \bullet 365) * \left[B_o \bullet 0.67 \bullet \sum_{S,k} \frac{MCF_{S,k}}{100} \bullet AWMS_{(S,k)}\right] \quad (5)$$

$$VS = \left[GE \bullet \left(1 - \frac{DE\%}{100}\right) + (UE \bullet GE)\right] \bullet \left[\left(\frac{1 - ASH}{18.45}\right)\right] \quad (6)$$

where EFm = emission factors of manure management. VS = daily volatile solid excreted, kg dry matter anima-1 day-1. 365 = basis for calculating annual VS production, days year-1. Bo = maximum CH4 producing capacity for manure produced, m3 CH4 kg-1. 0.67 = conversion factor of m3 CH4 to kilograms CH4, Kg m-3. MCF(S,k) = CH4 conversion factors for each manure management system S by climate region k, %. AWMS(S,k) = fraction of manure handled using manure management system S in climate region k, dimensionless. GE = gross energy intake, MJ head-1 day-1. DE = feed digestibility, %. UE = urinary energy expressed as a fraction of GE. ASH = the ash content of manure calculated as a fraction of the dry matter feed intake. 18.45 = conversion factor for dietary GE per kg of dry matter, MJ kg-1. See Text S1 for more details on the Tier 2 estimation.

In this study, we calculated the Tier 2 emission factors for the main contributors of CH4 emissions, including dairy cattle, nondairy cattle, buffalo, sheep and goat. In order to make a comparison, the Tier 1 emission factors were also used for those livestock categories. Due to the lack of information on livestock characteristics and corresponding coefficients, the emissions from pig, camel, horse, mule and ass were estimated following Tier 1 method from IPCC (2019), see Text S2 for details.

Average life span

The ALS information on different livestock categories/subcategories was extracted from publications (Table S3). For live population, the ALS was assumed to be 12 months for adult (including subcategories of Breeding female and Other) large animals (including dairy cattle, nondairy cattle, buffalo, camel, horse, mule and ass), 6 months for young large animals, 9 months for adult small ruminates (sheep and goat), 2.5 months for young small ruminates, and 6 months for pigs, respectively (Yu et al. 2018; Peng et al. 2016). In this study, livestock were assumed to be slaughtered evenly in twelve months in a calendar year, then for slaughtered population, the ALS of large animals, small ruminants, and pigs were estimated as 6, 5.6 and 3 months, respectively (Yu et al. 2018).

Development of gridded CH4 emissions

To produce gridded maps of CH4 emissions from livestock, the country/provincial level CH4 emissions can

be allocated into the grid level according to spatial proxy data extracted from Gridded Livestock of the World database (GLW) (e.g., Janssens-Maenhout et al. 2017; Yu et al. 2018; Saunois et al. 2016). In this study, we used the GLW 3 as the spatial proxy data (Gilbert et al. 2018). The recent version of GLW database provides absolute livestock numbers per pixel (0.0833° × 0.0833°) of the majority of CH4 producers, including cattle, buffalo, sheep, goat, pig and horse. To allocate the CH4 emissions to grid level for each livestock category, we first obtained the total number of livestock at province/country level based on GLW 3, then calculated the percentage of livestock number in each grid cell to get spatial patterns of livestock population in each administrative region. We then distributed the province/country level CH4 emissions to grid level follow the spatial patterns of the population. As the GLW database is for the live population of livestock, in this study, the spatial pattern of slaughtered population was assumed to be the same as that of the live population.

Uncertainty analysis

In this study, the uncertainty of CH4 emissions was estimated from uncertainties in activity data and emission factors. The uncertainties in activity data were associated with data source, e.g., the uncertainties in livestock population extracted from national statistics and FAOSTAT were assumed to be ±5% and ±20%, respectively (NDRCC 2014; IPCC 2019). Uncertainties in Tier 2 emission factors were evaluated by the uncertainties in various parameters including Ym, DP, DE, Bo, AWMS, ASH. For each parameter, the uncertainty range was estimated by measurements from publications or based on default IPCC uncertainty ranges (Table S8). Uncertainty in Tier 1 emission factors was assumed to be ±30% based on IPCC (2019). Then the uncertainties in activity data, parameters and emission factors were combined using error propagation equations from IPCC Guidelines to show 95% uncertainty intervals of our estimates (IPCC 2019; Tubiello et al. 2013).

Results

Temporal trend in CH4 emissions

Our results showed that the total CH4 emission from livestock in East Asia was 13.22 [11.42 – 15.01] (mean [minimum–maximum of 95% confidence interval]) Tg CH4 yr-1 in 2019, accounting for an increase of 231% since 1961 (3.99 [3.44 – 4.54] Tg CH4 yr-1) (Figure 1(a)). Over the study period, livestock-sourced CH4 emissions experienced three phases: a significant increase at a rate of 0.11 Tg CH4 yr-1 ($p < 0.01$) during 1961 – 1979, followed by a rapid increase at a rate of 0.42 Tg CH4 yr-1 ($p < 0.01$) during 1980 – 1999, and then a roughly stable trend during 2000 – 2019 ($p = 0.18$). In 2019, CH4 emissions associated with enteric fermentation and manure management was

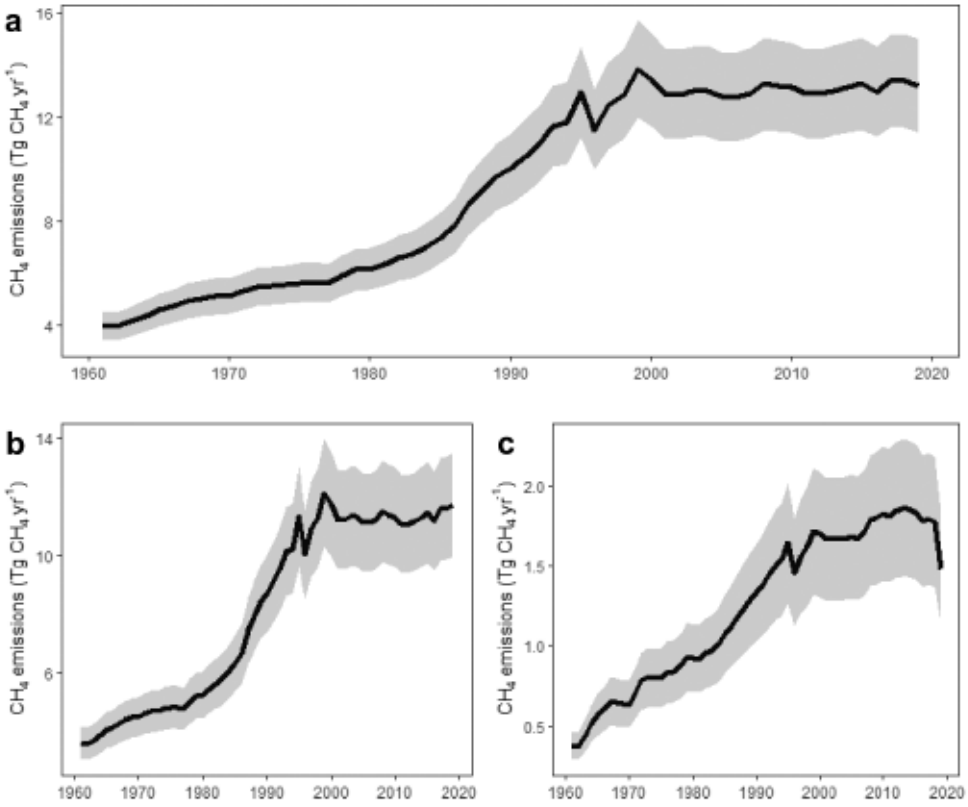

Figure 1. Temporal trends in (a) total CH4 emissions and CH4 emissions from (b) enteric fermentation and (c) manure management in East Asia during 1961 – 2019. The shaded area shows the 95% confidence interval of our estimates.

11.73 [9.97 – 13.50] Tg CH4 yr-1 and 1.48 [1.14 – 1.82] Tg CH4 yr-1, respectively. Temporal trends of emissions associated with the two processes are different. Enteric fermentation emissions increased rapidly before 2000 and then remained roughly stable (Figure 1(b)). However, manure management emissions increased consistently over the study period except for year 2019 (Figure 1(c)). Throughout the study period, enteric fermentation shared approximately 87% of the total emissions, and manure management shared approximately 13%.

CH4 emissions by livestock categories

Across different livestock categories, nondairy cattle was the main source of the total CH4 emissions during 1961 – 2019, accounting for 52% of the total emissions, followed by pig (11%), goat (10%), sheep (8%), buffalo (8%), dairy cattle (7%) and horse (2%). The contributions of camel, mule and ass were less than 1% (Figure 2(a)). In total, the ruminants and non-ruminants contributed 85% and 15%, respectively. From 1961 to 2019, CH4 emissions from dairy cattle increased approximately 17 times. And emissions from buffalo, nondairy cattle, sheep, pig and goat increased by 26%, 181%, 384%, 453% and 482%, respectively. However, CH4 emissions decreased by 10%, 24%, 36% and 55% for horse, camel, mule and ass (Figure 2(a)). With respect to live and slaughtered populations, live population shared the majority of the total emissions over the study period. But the emissions from slaughtered population increased significantly. Its contribution increased from 3% in 1961 to 24% in 2019 (Figure 2(b)). And the increase mainly occurred in the period 1980 – 2019, with an annual increment of 0.09 Tg CH4 yr-1 ($p < 0.01$).

Country-level CH4 emissions

In 2019, CH4 emissions in China, Japan, South Korea, Mongolia and North Korea were 11.67 [9.92 – 13.42] Tg CH4 yr-1, 0.47 [0.38 – 0.57] Tg CH4 yr-1, 0.31 [0.25 – 0.38] Tg CH4 yr-1, 0.69 [0.57 – 0.82] Tg CH4 yr-1 and 0.07 [0.05 – 0.08] Tg CH4 yr-1, respectively (Figure 3). The contribution from manure management varies in different countries. For example, the manure management contributed ~14% of the total CH4 emissions in China, but in Mongolia it only contributed ~2% over the study period. During 1961 – 2019, China accounted for the majority of the total emissions (89%) in East Asia, followed by Japan (5%), Mongolia (4%), South Korea (2%) and North Korea (1%). Compared to the 1961, CH4 emissions in 2019 increased by 242%, 131%, 556%, 147% and 54% in China, Japan, South Korea, Mongolia and North Korea, respectively. However, the emissions in different countries showed different trends after the year 2000, with China and Japan producing 5% and 11% less

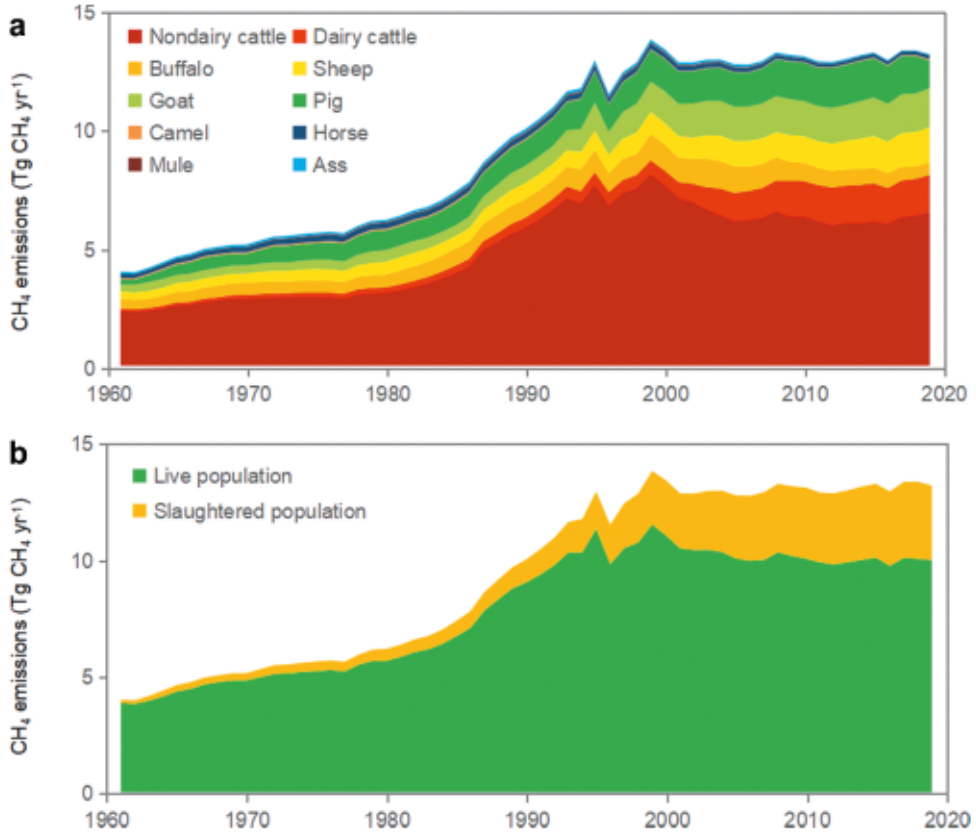

Figure 2. Changes in CH4 emissions from (a) different livestock categories and (b) live and slaughtered populations in East Asia during 1961 – 2019.

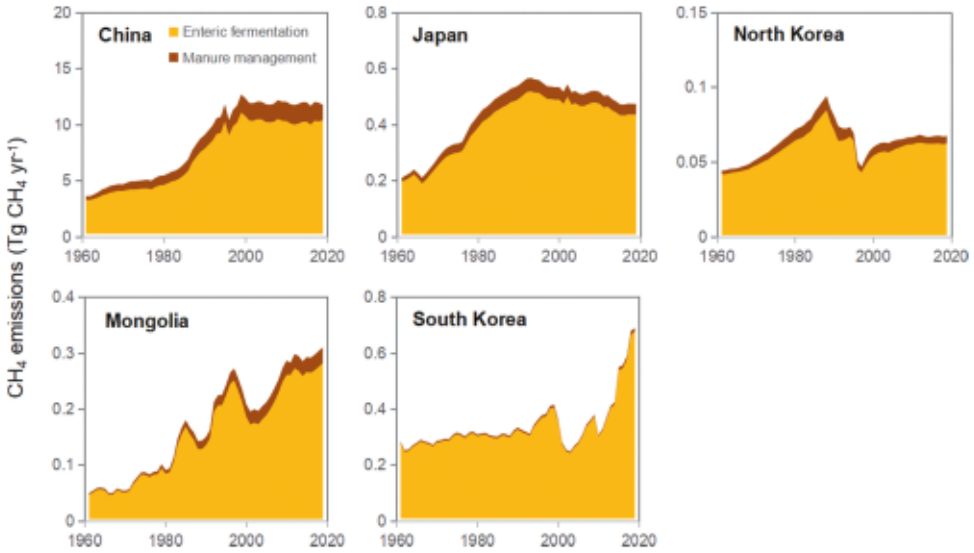

Figure 3. Changes in CH4 emissions from livestock in different countries in East Asia during 1961 – 2019.

emissions in the 2019 than in the 2000, while Mongolia, North Korea and South Korea producing 92%, 13% and 49% more over the same period. This led Mongolia to surpass Japan to rank second place in 2019.

Spatial patterns of CH4 emissions

In 2019, the hot spots of CH4 emissions were mostly distributed in eastern China, South Korea and parts of Japan, which are mainly dominated by spatial distribution of cattle, buffalo and pig (Figure 4(a), S5). Compared to the year 1961, CH4 emission in 2019 mostly increased in vast area of eastern China, as well as in most of South Korea and parts of Japan (Figure 4 (b)), mainly due to increasing population of dairy and nondairy cattle, pig and goat (Figure S1, S2, S5). In addition, there was an increase in CH4 emission in parts of northern China, which was mostly attributed to more cattle and sheep (Figure 4(b), S5). The emission hot spots tend to shift northward after 2000. Compared to the year 2000, CH4 emission in parts of central China, southern China and Japan were significantly reduced in 2019 (Figure 4(c)), as a result of the decreasing population of buffalo and nondairy cattle (Figure S1). By contrast, the emission increased in parts of northern China and northeastern China, South Korea and most parts of Mongolia from 2000 to 2019, which was mainly related to more sheep, goat, nondairy cattle and pig (Figure 4(c), S1, S2, S5).

Discussion

Trends in livestock CH4 emissions

Using the Tier 2 method from IPCC (2019), we estimated CH4 emissions from East Asian livestock was 13.22 [11.42 – 15.01] Tg CH4 yr-1 in 2019, accounting for ~12% of the emissions from global livestock (Saunois et al. 2020). Compared to 1961, the emissions in 2019 had increased by 231% (Figure 1(a)). The increment in CH4 emissions mainly occurred before 2000, mostly in the 1980s and 1990s, which was largely due to the rapid increase in livestock numbers (Figure S1 and S2) driven by the increasing consumption of livestock products, e.g., meat and milk (Xu et al. 2019; Herrero et al. 2013). Since 2000, the total emissions had remained roughly stable. This is primarily caused by the combined effect of changes in livestock numbers and emission factors. For example, the live population of nondairy cattle in China and Japan had decreased since the late 1990s, which can led to a lower emissions in East Asia(Figure S1). However, the emission factors of some categories of animals (e.g., dairy cattle, nondairy cattle and sheep in China and Japan) continued to increase (Figure S4), which can partly offset the decline in CH4 emissions caused by the shrinking livestock population. Additionally, to meet the growing meat consumption, more and more animals were slaughtered (Figure S2), making the slaughtered population to be an important role on CH4 emissions (Figure 2(b)). It is worth noting that, since the late 1990s, the increase in slaughtered animals has been mainly achieved by increasing extraction rate (slaughtered population/total population) rather than raising more animals. For example, from 1996 to 2017, the slaughtered population of beef cattle in China increased by 88% while the total population decreased by 21% (Li, Yan, and Zan 2018). This also explains why beef production in East Asia can increase significantly (FAOSTAT. 2020) without increasing the CH4 emissions from nondairy cattle (Figure 2(a)). Driven by rising demands for meat, the number of slaughtered animals is expected to continue increasing in the coming decades (Garnett 2009; Alexandratos

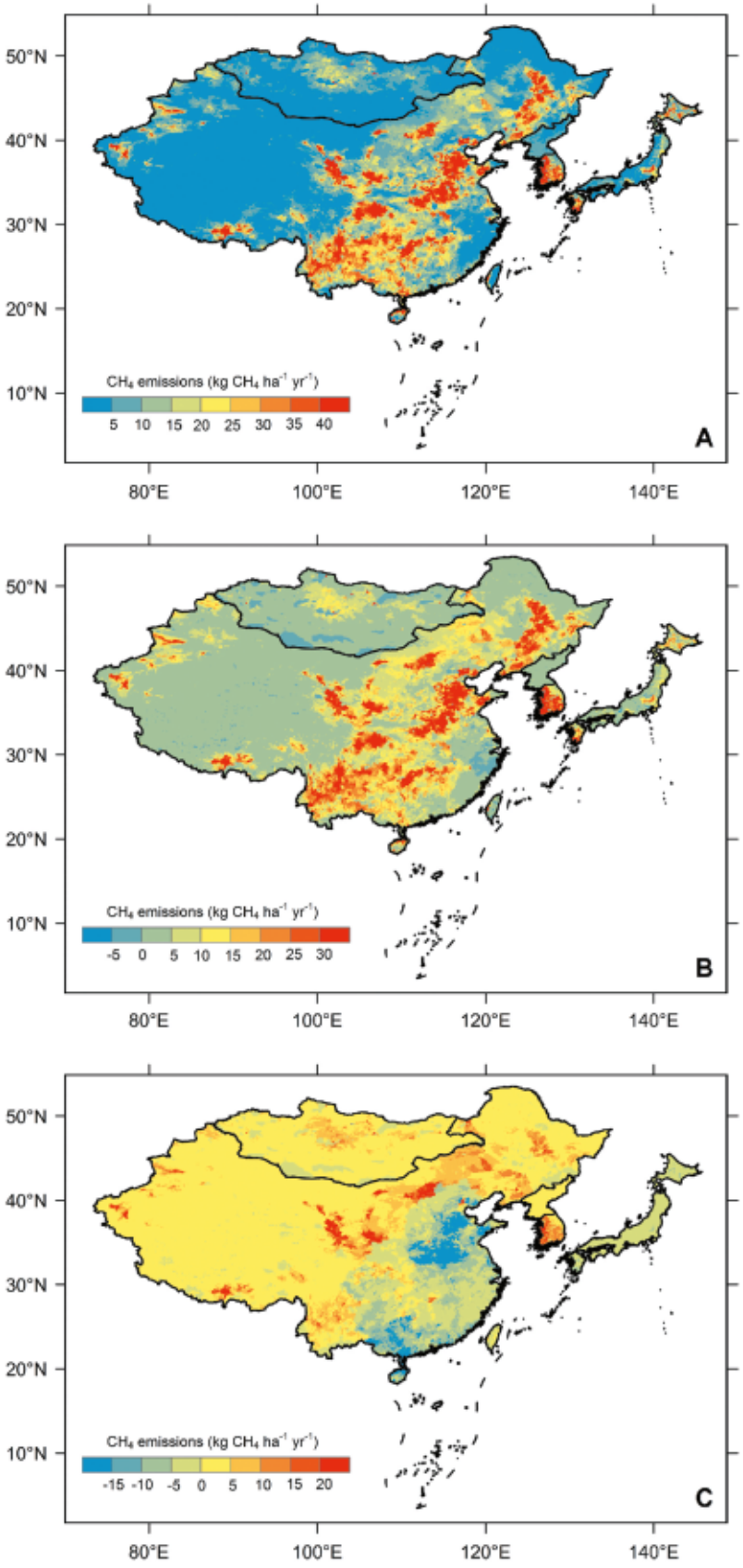

Figure 4. Spatial patterns of (a) CH4 emissions in 2019, and changes in CH4 emissions between (b) 2019 and 1961 and (c) 2019 and 2000.

and Bruinsma 2012), which would ultimately release more CH4 to the atmosphere. Therefore, the slaughtered population should not be overlooked in future inventories of CH4 emissions.

For different processes, we found that the temporal trends of CH4 emissions associated with enteric fermentation and manure management are different. The enteric fermentation emissions increased first then remained stable (Figure 1(b)), while the manure management emissions continued to increase over the study period except for a drop in 2019 (Figure 1(c)). This is because the enteric fermentation emissions were mainly from ruminant animals, but the manure management emissions were mainly from pig. Over the study period, pig population in East Asia had continued to rise until 2019, when there was a sharp decline caused by swine fever (Liu et al. 2020).

At the country level, China shared the majority (89%) of livestock CH4 emissions in East Asia during 1961 – 2019, followed by Japan (5%), Mongolia (4%), South Korea (2%) and North Korea (1%) (Figure 3), which is consistent with estimates from Yamaji, Ohara, and Akimoto (2003), and largely associated with livestock numbers (Figure S1 and S2). Compared with 1961, the 2019 emissions had increased significantly in all countries. And the increment were mainly occurred in densely populated areas, such as eastern China, South Korea and parts of Japan (Figure 4(b)). This is due to these areas raise a large number of livestock and have high consumption demand for livestock products (Gilbert et al. 2018; Herrero et al. 2013; Xu et al. 2019). After 2000, CH4 emissions showed different trends in different countries. The emissions in Japan dropped significantly due to the decreasing livestock populations (Figure 4(c), S1). However, the emissions in Mongolia showed a rapid increase, lending Mongolia to surpass Japan as the second largest producer of livestock CH4 emissions in 2019 (Figures 3, 4(c)). This sudden growth is associated with the collapse of Soviet Union, which liberalized economic policies and stimulated the development of Mongolian animal husbandry (Rao et al. 2015). A significant increment in CH4 emissions was also found in South Korea, which is mostly attributed to the increase in number of nondairy cattle driven by the growing demand of beef consumption (Chung et al. 2018). In China, CH4 emissions have been spatially differentiated since 2000. Specifically, the emissions decreased in central and southern regions but increased in northern regions (Figure 4(c)). Similar results were also found in Xu et al. (2019). This northward shift is mainly affected by the spatial patterns and changes of animal populations. For example, the buffalo population, which is mainly distributed in southern China, had declined dramatically since the late 1990s (Figure S1, S5) resulting in less emissions in southern China. And nondairy cattle in central China also decreased after about 2000 (Li, Yan, and Zan 2018). However, in northern China, sheep numbers continued to increase, which causes more emissions (Figure S5).

The temporal trend of CH4 emissions in East Asia is different from that in the world. Globally, the livestock emissions have continued to increase for more than half a century (Tubiello et al. 2013; Patra 2014; Chang et al. 2019; Dangal et al. 2017). And the growth rate was found to be higher in developing countries than in developed countries (Patra 2014; Caro et al. 2014). For example, the average growth rate (AGR) of enteric fermentation emissions from global livestock was 0.9% over the period 1961 to 2010, but that was 1.1% for Indian livestock (Patra 2014). However, the emissions in East Asia increased first and then roughly stabilized after 2000 (Figure 1(a)). The change in temporal trend in East Asia was primarily driven by the decreasing emissions in China (Figures 3, 5), which were mostly triggered by the decline in nondairy cattle and buffalo populations in recent decades (Figure S1). In the past, nondairy cattle (mainly Chinese yellow cattle) and buffalo in China were commonly used as draft animals. However, due to the economic development in recent decades, this role has been largely replaced by agricultural machinery, resulting in a dramatic decline in buffalo and nondairy cattle population (Xue, Wang, and Yan 2014). Another reason for the decline in China's emissions might be the rapid increase in meat import. Based on statistics from FAO, beef import to China has grown exponentially in recent decades and reached approximately 2.2 million tones in 2019 (Figure S6). This large quantity of imported meat could occupy the market shares of local meat to some extent. However, considering the huge beef consumption and the uncertainty of import policies in the future (Li, Yan, and Zan 2018), we predict that cattle population in China may rise again, thereby driving an increase in CH4 emissions in East Asia.

Comparison with other estimates

We compared our estimates to six previous inventories of CH4 emissions (Figure 5): 1) the United States Environmental Protection Agency (US EPA) (US EPA 2012), 2) Emission Database for Global Atmospheric Research (EDGAR) v4.3.2 (Janssens-Maenhout et al. 2017), 3) FAO (Tubiello et al. 2013), 4) National Communications or Biennial Update Reports reported to United Nations Framework Convention on Climate Change (UNFCCC) (UNFCCC 2020), 5) Yamaji, Ohara, and Akimoto (2003) and, 6) Peng et al. (2016) (for China only). In addition, we also made a comparison with the Tier 1 estimates .

In East Asia, our estimates are generally consistent with estimates from EPA but ~30% and ~20% higher than those of FAO and EDGAR v4.3.2 after 1980. This discrepancy is mainly due to (1) inventories from FAO

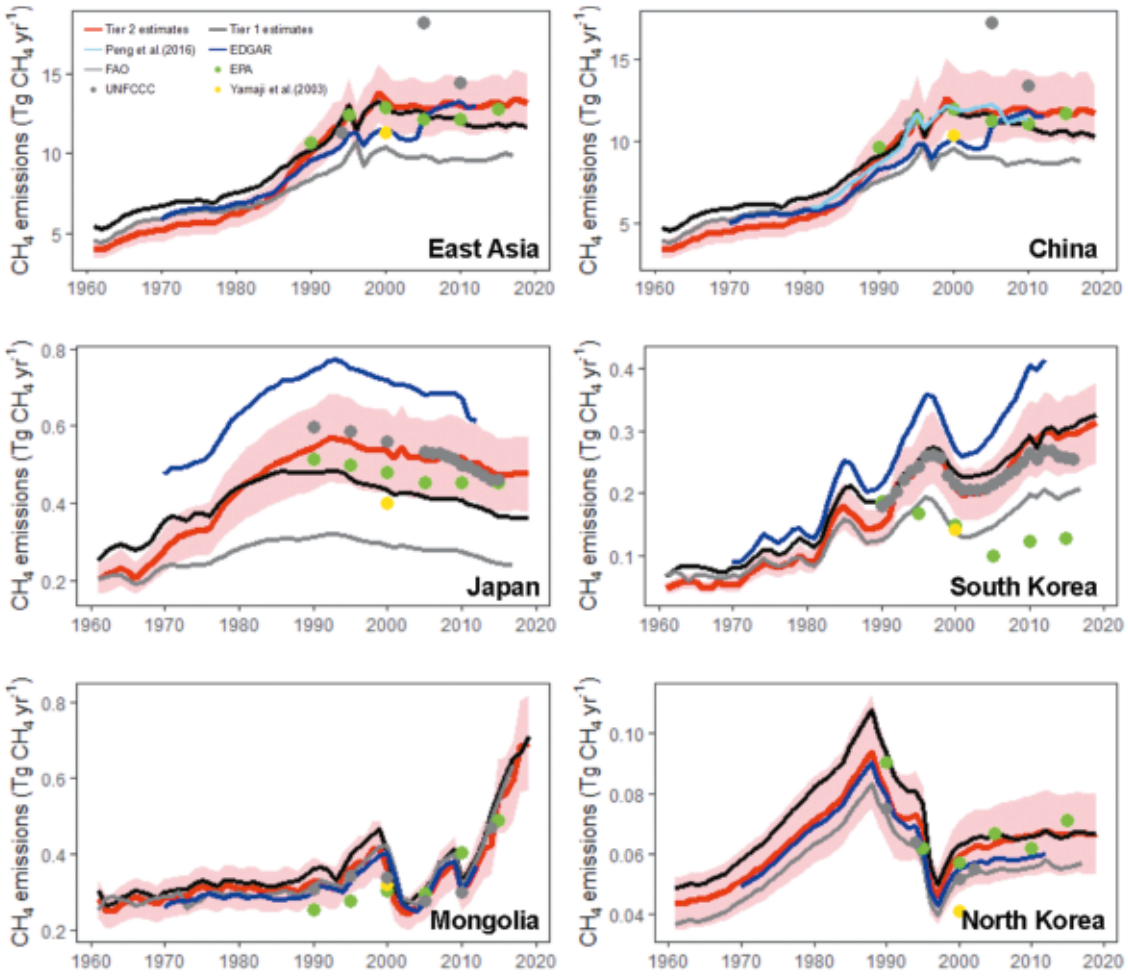

Figure 5. Time series of CH4 emissions from livestock in East Asia and countries from this study and other inventories including US EPA (.US EPA 2012), EDGAR v4.3.2 (Janssens-Maenhout et al. 2017), FAO (Tubiello et al. 2013), UNFCCC (2020), Yamaji, Ohara, and Akimoto (2003) and Peng et al. (2016) (for China only). The shaded area shows the 95% confidence interval of the Tier 2 estimates. Tier 1 estimates refers to estimates using default emission factors from IPCC (2019)

and EDGAR v4.3.2 do not incorporate slaughtered livestock, which produce more CH4 emissions mostly after 1980 (Figure 2(b)); and (2) the impact of increased body weight and milk yield of dairy and nondairy cattle was considered in EDGAR v4.3.2, but not in FAO which helps explain the smaller difference between our study and EDGAR v4.3.2. Our estimates and FAO found the China's emissions increased first and then roughly stabilized after 2000. However, EDGAR v4.3.2 showed that China's emissions continued to increase. This is mainly attributed to differences in activity data and estimation approaches. The activity data used in EDGAR v4.3.2 were extracted from FAOSTAT which is inconsistent with National Bureau of Statistics of China (NBSC) on some livestock categories. For example, NBSC shows a significant drop in buffalo population after 2000, but FAOSTAT shows keeping increase in buffalo population in China over the study period (Yu et al. 2018). This helps explain why an increasing trend after 2000 was found in EDGAR v4.3.2 but not in our estimates. FAO used same activity data with EDGAR v4.3.2 but adopted temporal constant emission factors without considering growth in emission factors caused by increased milk yield and livestock body weight (Tubiello et al. 2013). Thus, FAO's estimates remained stable rather than increasing after 2000. Our results were similar to inventory from UNFCCC in 1994 and 2010, but were 30% lower than UNFCC estimates in 2005. The inconsistencies are largely due to the difference in emissions from China, which was estimated using higher emission factors in UNFCCC inventory (NDRCC 2014; Peng et al. 2016). Compared to Yamaji, Ohara, and Akimoto (2003), our results are 20% higher in 2003, which could be associated with the exclusion of slaughtered livestock in estimates of Yamaji, Ohara, and Akimoto (2003). Our estimates for emissions in China are generally consistent with the findings of Peng et al. (2016). Across different countries, there is a greater disparity between inventories in developed countries (Japan and South Korea) than in other ones. For example, the estimates from EDGAR v4.3.2 is 130% higher than that from FAO in Japan, but the corresponding difference is only 8% in North Korea. The inconsistencies can be largely attributed to two reasons. First, livestock characteristics (e.g, body weight and milk yield) in Japan and South Korea are

significantly higher than those in other Asian countries but similar to that in North America (Kikuhara, Kumagai, and Hirooka 2009; Ji and Park 2012). Thus, the estimates based on default emission factors of Asia, such as inventory from FAO (Tubiello et al. 2013), should be much lower than that relying on emission factors derived from native livestock characteristics. Second, there are intensive feeding systems and higher feed digestibility in Japan and South Korea, which lowers CH4 emissions intensity compared to extensive feeding systems (Mitsumori et al. 2012; Bayaru et al. 2001; Santoso et al. 2003; Hosoda et al. 2006). Studies that ignore the emissions-reducing effects of these factors (e.g., EDGAR v4.3.2) might overestimate CH4 emissions to some extent.

Compare to Tier 1 estimates, the Tier 2 estimates are 10 – 20% lower before 1990, but 5 – 10% higher after 2000. This is because Tier 2 approaches can reflect the impact of changes in animal productivity on CH4 emissions while Tier 1 cannot. In more than half a century, the milk yield and body weight of livestock have increased significantly in East Asia, resulting an increment in emission factors (Figure S3, S4). Compared with the Tier 1 emissions factors, the Tier 2 emissions factors are lower at first but higher later (Figure S4). With the improvement of breeding technique and feeding management, livestock body weight and production yield are likely to increase in future decades (Herrero et al. 2016; Thornton 2010; Garnett 2009), which will lead to an increase in emission factors in the absence of responsive mitigation measures. Thus, the gap between two calculated results might be further widened in the future without considering the corresponding mitigation efforts.

Uncertainties and future research needs

In this study, we estimated the CH4 emissions based on IPCC Tier 2 method. The dynamic emission factors were derived for different livestock categories and subcategories. Even though we have considered the uncertainties from activity data and uncertainties from several parameters (e.g., Ym, DP, ASH) related to emission factors, there are still some uncertain sources are not included in our estimates. First, the feed digestibility, manure management systems and average life span of livestock may change over time (Herrero et al. 2013; Yu et al. 2018), while these factors are assumed to be temporal constant in our study. Second, our estimates were mostly based on country level livestock information, however, there should be differences in livestock systems within the country (Xu et al. 2019; NDRCC 2014; Herrero et al. 2013). Third, we allocated the country level emissions to grid level based on livestock density data for year 2010 (Gilbert et al. 2018). But the livestock density pattern might change overtime from 1961 to 2019, which will increase uncertainty of the spatial variations of CH4 emissions. To overcome those uncertainties, more investigation should be conducted on the detailed information of livestock feeding and manure management systems in the future. Additionally, the development of long-term series of livestock density data sets will help to accurately assess the spatial changes in livestock CH4 emissions.

Conclusion

Using the Tier 2 approach from IPCC (2019), we provided a long-term inventory of CH4 emissions from livestock in East Asia. The result shows livestock CH4 emissions experienced three phases and increased from 3.99 [3.44 – 4.54] to 13.22 [11.42 – 15.01] Tg CH4 yr-1 during 1961 – 2019. CH4 emissions associated with enteric fermentation and manure management accounted for 87% and 13% of the total, respectively. Nondairy cattle was the main emission source, followed by pig. At the country level, China contributed most of the CH4 emissions, followed by Mongolia and Japan. Since 2000, there was a slight decline in CH4 emissions in central China, southern China and Japan but a remarkable increase in Mongolia and South Korea, resulting the emission hotspots in East Asia tend to shift northward. CH4 emissions from slaughtered populations increased rapidly driven by a sharp increase in the population of slaughtered animals. Compared to the Tier 1 estimates, the Tier 2 estimates are lower before 1990 but higher after 2000, resulting from the significant increase in livestock productivity (e.g., milk yield and body weight) in recent decades. Our study demonstrates that using the dynamic emission factors and incorporating the slaughtered population in estimates are critical for accurate quantification of livestock CH4 emissions. Regions where CH4 emissions have increased rapidly since 2000, including northern China, Mongolia and South Korea, deserve more attention in future CH4 mitigation efforts.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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