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RESEARCH ARTICLE

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A 130-year global inventory of methane emissions from livestock: Trends, patterns, and drivers

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Abstract

Livestock contributes approximately one-third of global anthropogenic methane (CH_4) emissions. Quantifying the spatial and temporal variations of these emissions is crucial for climate change mitigation. Although country-level information is reported regularly through national inventories and global databases, spatially explicit quantification of century-long dynamics of CH_4 emissions from livestock has been poorly investigated. Using the Tier 2 method adopted from the 2019 Refinement to 2006 IPCC guidelines, we estimated CH_4 emissions from global livestock at a spatial resolution of 0.083° (~9 km at the equator) during the period 1890–2019. We find that global CH_4 emissions from livestock increased from 31.8 [26.5–37.1] (mean [minimum–maximum of 95% confidence interval) Tg CH_4 yr^{-1} in 1890 to 131.7 [109.6–153.7] Tg CH_4 yr^{-1} in 2019, a fourfold increase in the past 130 years. The growth in global CH_4 emissions mostly occurred after 1950 and was mainly attributed to the cattle sector. Our estimate shows faster growth in livestock CH_4 emissions as compared to the previous Tier 1 estimates and is ~20% higher than the estimate from FAOSTAT for the year 2019. Regionally, South Asia, Brazil, North Africa, China, the United States, Western Europe, and Equatorial Africa shared the majority of the global emissions in the 2010s. South Asia, tropical Africa, and Brazil have dominated the growth in global CH_4 emissions from livestock in the recent three decades. Changes in livestock CH_4 emissions were primarily associated with changes in population and national income and were also affected by the policy, diet shifts, livestock productivity improvement, and international trade. The new geospatial information on the magnitude and trends of livestock CH_4 emissions identifies emission hotspots and spatial–temporal patterns, which will help to guide meaningful CH_4 mitigation practices in the livestock sector at both local and global scales.

KEYWORDS
CH_4 emissions, IPCC 2019 refinement, livestock, long-term variations, Tier 2

1 | INTRODUCTION

Methane (CH_4) is the second most important anthropogenic greenhouse gas (GHG), contributing approximately 0.5 °C to observed global warming (2010–2019 relative to 1850–1900) as assessed from radiative forcing studies (IPCC, 2021). The atmospheric CH_4 concentration was stable at ~600–700 ppb over the last millennium, but it has increased almost exponentially since the start of the industrial era, reaching ~1892 ppb in 2021, a threefold increase over the past two centuries (Dlugokencky, 2021; Turner et al., 2019). Moreover, global CH_4 emissions and atmospheric concentrations are projected to rise continuously until at least 2050 in the absence of strong mitigation measures (Bergamaschi et al., 2018; Saunois et al., 2020), which could threaten the achievement of the Paris Agreement goals, given the significant contribution of CH_4 to global warming (IPCC, 2021).

The abundance of CH_4 in the atmosphere is closely related to livestock, which accounts for ~30% of global anthropogenic CH_4 emissions (Jackson et al., 2020; Saunois et al., 2020; Tian et al., 2016). Global livestock herds have tripled over the past century (Dangal et al., 2017; FAO, 2021b; Mitchell, 1993, 1998a, 1998b) and are projected to further expand in coming decades (FAO, 2018; Godfray et al., 2018; Thornton, 2010). While the modern and future CH_4 emission patterns are derived from their historical evolvement (Patra, 2014; Turner et al., 2019). Understanding the historical emissions can help to identify where the best opportunities for mitigation are, while being sensitive to the fact that trends and strength of emissions pathways vary due to differences in the level of economic development and animal husbandry (Caro, Davis, et al., 2014; Dangal et al., 2017; Robinson et al., 2011). Additionally, historical CH_4 emissions also have a legacy, although shorter than other long-lived greenhouse gases, on changes in the climate system (Bergamaschi et al., 2018; Turner et al., 2019).

Methane emissions from livestock are produced from two processes, that is, enteric fermentation and manure management (IPCC, 2019; Kumari et al., 2020). Enteric fermentation accounts for the majority (~90%) of global CH_4 emissions from livestock (Caro, Davis, et al., 2014; FAO, 2021b; Kumari et al., 2020; Tubiello, 2019). Among different livestock categories, ruminants take the main share of livestock CH_4 emissions at the global scale as well as in most countries, due to the preponderance of enteric fermentation in the total (Chang et al., 2019; Dangal et al., 2017; FAO, 2021b). In some countries and regions, however, nonruminant emissions are significant through manure production and management processes (Chang et al., 2021). In the case of pigs, there are about 970 million heads in the world, and nearly half of them in China (FAO, 2021b). The large pig population produces considerable amounts of CH_4 emissions (Xu et al., 2019; Zhang, Tian, et al., 2021), although the national total livestock emissions are dominated by enteric fermentation from cattle (FAO, 2020).

To derive CH_4 emissions from livestock, the Intergovernmental Panel on Climate Change Guidelines on National greenhouse gas inventories (IPCC, 2019) recommends methods for making estimates using three tiers of increasing complexity, namely Tier 1, 2 or 3. Tier 1 represents the IPCC “default” method, which can be used when national information is not available, in order to facilitate reporting. Tier 1 equations and emissions coefficients are therefore quite simplified, that is, they use as input activity data a rather simplified description of livestock herds, while the emissions factors are time-invariant, globally applicable constants, with only limited regional specificity for some processes. Conversely, Tier 2 and Tier 3 coefficients are based on more nuanced, nationally derived information, with Tier 3 coefficients also incorporating more sophisticated knowledge, including models and data produced with geospatial and time-dependent approaches (IPCC, 2019). Previous studies on CH_4 emissions from global livestock are mostly based on IPCC Tier 1 default emission factors (e.g., Caro, Davis, et al., 2014; EPA, 2012; FAO, 2020; Tubiello, 2019; Tubiello et al., 2013). It is known that Tier 1 approaches, by using coefficients reflecting an average period around the time when the IPCC (2006) was published, tend to overestimate emissions earlier in a time series and overestimate emissions in more recent decades (Chang et al., 2019; Tubiello, 2019). This is because they do not capture the change in technological advancements, especially in livestock productivity, which increases over time (FAO, 2021b; Thornton, 2010) and at the same time is a major driver of livestock CH_4 emissions per unit animal (IPCC, 2019). For example, the body weight of beef cattle in China was estimated to have increased by ~40% in last three decades (Yu et al., 2018), and cow milk yield in the United States grew by ~19% from 2003 to 2014 (Niles & Wiltshire, 2019).

Dangal et al. (2017) used the Tier 2 method from IPCC (2006) to estimate the impacts of changing productivity on CH_4 emissions from enteric fermentation and manure management at a global scale. However, only four categories of ruminants including dairy cattle, nondairy cattle, sheep, and goats were considered. Using the same method, Chang et al. (2019) provided an inventory on CH_4 emissions from global ruminants, but only considering the emissions associated with enteric fermentation, and still using the IPCC, 2006 guidelines, which have now been improved by a refinement version which offers new approaches and emission factors (IPCC, 2019).

Compared to the 2006 guidelines (IPCC, 2006), the 2019 guidelines (IPCC, 2019) updated the Tier 1 enteric emission factors, revised the Tier 1 and 2 methods for estimating manure management emissions, and updated some parameters for estimating enteric emissions in the Tier 2 method. Recently, Chang et al. (2021) investigated the differences between estimates by the two guidelines (IPCC, 2006; IPCC, 2019) and the methodological tiers (Tier 1 and Tier 2) for the period of 2000–2018. However, long-term estimates of global livestock CH_4 emissions using the refined IPCC (2019) coefficients have not yet been carried out.

Here, we estimate global livestock CH_4 emissions from 1890 to 2019, following the new IPCC (2019) guidelines. A total of 10 categories of livestock (including dairy cattle, nondairy cattle, buffaloes, sheep, goats, pigs, camels, horses, mules, and donkeys) were assessed. We establish long-term population sequences at national scale for livestock and provided grid maps of livestock CH_4 emissions at a resolution of 0.083° (~9 km at the equator). Specifically, this study aims to assess the long-term trends and spatial patterns of livestock CH_4 emissions at multiple scales from local to regional to global over the past 130 years.

2 | MATERIALS AND METHODS

In this study, we followed the IPCC 2019 refinement guidelines (IPCC, 2019) to estimate CH_4 emissions from global livestock. Compared to the IPCC 2006 guidelines (IPCC, 2006), the IPCC, 2019 refinement guidelines have several improvements including: (1) update of the Tier 1 enteric emission factors by considering the differences between high and low productivity systems; (2) improvement of the Tier 1 and 2 methods for estimating manure management emissions by incorporating more variables and also the differences in livestock productivity systems; and (3) revision of some Tier 2 parameters based on more sophisticated livestock information (Figure 1). These efforts aim at reducing uncertainty of estimates by providing more up-to-date scientific knowledge in the refined guidelines (Amon et al., 2021; IPCC, 2019).

Here, we used the Tier 2 methods to derive CH_4 emissions from the major emitters including dairy cattle, nondairy cattle, buffaloes, sheep, and goats. For other animals, including pigs, horses, camels, mules, and donkeys, Tier 1 methods were used due to the lack of more detailed information. The livestock CH_4 emissions were calculated as:

$$\text{Emissions} = \sum N_i \bullet EF_{ef/mm,i} \tag{1}$$

where, *Emissions* is the annual total CH_4 emissions from livestock; *N* is the annual livestock population of category *i*, $EF_{ef/mm,\,i}$ is the emission factor of enteric fermentation or manure management for livestock category *i*.

2.1 | Livestock population data

The annual livestock population by country and over the period 1961–2019 was mostly obtained from FAOSTAT (FAO, 2021b), which has

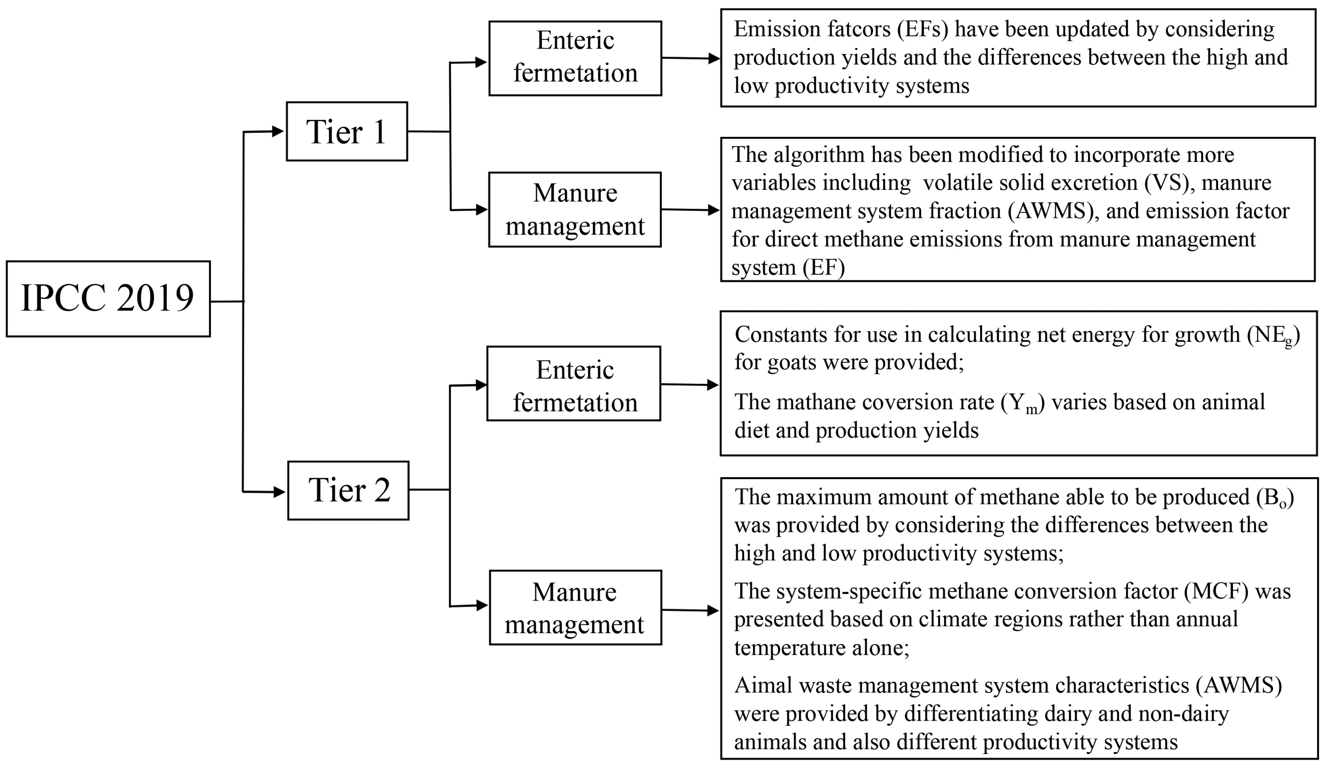


FIGURE 1 Updates in the estimation of livestock CH_4 emissions in the IPCC 2019 refinement guidelines as compared to the IPCC 2006 guidelines.

been widely used in estimates of livestock sourced CH_4 emissions (e.g., Caro, Davis, et al., 2014; Chang et al., 2019; Dangal et al., 2017; FAO, 2021a; Saunois et al., 2020; Tubiello et al., 2013). Considering the significant differences in livestock populations between the FAOSTAT and the national statistics in China (Yu et al., 2018), we replaced the FAOSTAT data on livestock in China with data from the China Statistical Yearbook (NBSC, 2021) for the period 1978–2019, by assuming the national source more realistic. As required by the IPCC guidelines (IPCC, 2019), we divided the total population into dairy and nondairy populations by subtracting dairy animal population from the total population (Caro, Davis, et al., 2014; Dangal et al., 2017; FAO, 2021b). For the period of 1890–1960, we generated the annual livestock population based on the HYDE data set. (https://themasites.pbl.nl/tridion/en/themasites/hyde/landusedata/livestock/index-2.html). The HYDE provided a 10-year interval livestock data set for 17 regions of the world since 1890 (Dangal et al., 2017; Mitchell, 1993, 1998a, 1998b). To develop annual time series of livestock population in each country, we first linearly interpolated the regional 10-year interval data, then calculated the number of livestock in each country as a percentage of the total livestock in the region based on FAOSTAT 1961 value, and then allocated the regional livestock population to countries accordingly. After that, we combined the sequences from FAOSTAT and those from HYDE to obtain the full-time series of country-level population data during 1890–2019 for different livestock categories. To meet the demand of the Tier 2 estimation, we further divided the population of dairy cattle, nondairy cattle, buffaloes, sheep, and goats into three subcategories: milking animals, replacement animals, and other animals (Chang et al., 2021). The numbers of milking animals were extracted from FAOSTAT (FAO, 2021b). The population of replacement animals (N_{rep}) was derived following the equation:

$$N_{\text{rep}} = N_{\text{milk}} \cdot R_{\text{rep}} \tag{2}$$

where N_{milk} is the number of milking animals, the R_{rep} is the ratio of replacement animals to the total population of milking animals, which was extracted from Table 2.4–2.11 of the GLEAM 2.0 documentation (FAO, 2017). After deriving the replacement population, the population of other animals was obtained by subtracting the numbers of milking animals and replacement animals from the total livestock population.

The GLW3 database provides gridded livestock population maps for a reference year of ca. 2010, at a spatial resolution of 0.083° for cattle (including dairy and nondairy cattle), buffaloes, sheep, goats, pigs, and horses (Gilbert et al., 2018). For lack of information of the time dependence of currently available livestock maps, we assumed the same spatial pattern of livestock as GLW3 throughout the study period and distributed the national livestock numbers to grid cells (Chang et al., 2019; Dangal et al., 2017). For livestock with no gridded maps, such as camels, mules, and donkeys, the spatial distribution pattern of horses was used. To distribute the national livestock population to grid level for each category/subcategories, we calculated the proportion of livestock population for each grid cell within each specific country based on the GLW 3 data. Mathematically:

$$P_{GLW(i,j,k)} = \frac{N_{GLW(i,j,k)}}{\sum_{i \in j} N_{GLW(i,j,k)}} \tag{3}$$

where, the $P_{GLW(i,j,k)}$ is the proportion of GLW3 livestock population of category k in grid cell i within country j. $N_{GLW(i,j,k)}$ is the GLW3 livestock population of category k in grid cell i within country j. Then, we distributed the national livestock numbers to grid level using:

$$N_{GRD(i,j,k)} = N_{CNY(j,k)} \cdot P_{GLW(i,j,k)} \tag{4}$$

where, the $N_{GRD(i,j,k)}$ is the livestock numbers of category k in grid cell i within country j. $N_{CNY(j,k)}$ is the national livestock numbers obtained from FAOSTAT for category k in country j.

2.2 | Emission factors of enteric fermentation and manure management

For livestock with the Tier 2 estimates, emission factors of enteric fermentation were estimated following IPCC (2019) Volume 4, Chapter 10, Equation 10.21:

$$EF_{ef} = \left[\frac{GE \cdot \left(\frac{Y_m}{100} \right) \cdot 365}{55.65} \right] \tag{5}$$

where, EF_{ef} is emission factor of enteric fermentation. *GE* is gross energy intake of livestock, which can be derived based on animal body size, energy requirement and feed characteristics (see Text S1 for details). The factor *55.65* is the energy content of CH_4. *365* is number of days in a year. Y_m is convention factor indicating percentage of feed energy converted to CH_4. The Y_m is closely related to feed quality (Herrero et al., 2016; IPCC, 2019). Generally, the higher the feed digestibility the lower Y_m. Here, we used the method from Opio et al. (2013) to calculate the Y_m in different regions, following the equation:

$$Y_m = 9.75 - 0.05 \cdot DE \tag{6}$$

where, *DE* is the feed digestibility which can be extracted regional level values from Opio et al. (2013) Table B13.

The Tier 2 emission factors of manure management were estimated following IPCC (2019) Volume 4, Chapter 10, Equation 10.23:

$$EF_{mm} = (VS \cdot 365) \cdot \left[B_o \cdot 0.67 \cdot \sum_{s,k} \frac{MCF_{(s,k)}}{100} \cdot AWMS_{(s,k)} \right] \tag{7}$$

where, EF_{mm} is emission factor of manure management. VS is daily volatile solid excreted. B_o is maximum CH_4 producing capacity for manure produced. 0.67 is conversion factor of m^3 CH_4 to kilograms CH_4. $MCF_{(s,k)}$ is CH_4 conversion factors for each manure management systems by climate region k. $AWMS_{(s,k)}$ is fraction of manure handled using manure management system s in climate region k. In this study, the climate zones were classified according to the approach provided by IPCC (2019) and improved by Chang et al. (2021) (Text S1). The values of B_o, *MCF*, and *AWMS* were extracted from Tables 10.16, 10.17, 10.A6 – A9 in IPCC (2019), respectively. The VS were calculated following IPCC (2019) Volume 4, Chapter 10, Equation 10.24:

$$VS = \left[GE \bullet \left(1 - \frac{DE}{100}\right) + (UE \bullet GE)\right] \bullet \left[\left(\frac{1 - ASH}{18.45}\right)\right] \quad (8)$$

where, the *GE* is the gross energy intake which has been estimated above; *DE* is the feed digestibility with default values extracted from Opio et al. (2013) Table B13; *UE* is the coefficient indicating the urinary energy as a fraction of *GE*, which is set to be 0.04 according to IPCC (2019). *ASH* is the ash content of feed with a value of 0.06.

For livestock with the Tier 1 estimates, we used the adjusted Tier 1 emission factors to estimate the enteric emissions. The temporal changes in body weight of pigs were incorporated in the estimation. To differentiate the productivity systems of livestock sector, we assumed that the developed countries/regions have the high productivity system. For other countries, the fraction of high productivity system (F_{high}) was calculated using the method suggested by Chang et al. (2021), following the equation:

$$F_{high} = \frac{W_{mean} - W_{low}}{W_{high} - W_{low}} \quad (9)$$

where, W_{mean}, W_{high}, and W_{low} are mean livestock body weight, livestock body weight of in the high productivity systems, and that in low productivity systems, respectively. The default values of livestock body weight can be extracted from Table 10A.5 in IPCC (2019). For manure management emissions, the Tier 1 estimates were based on IPCC (2019) Volume 4, Chapter 10, Equation 10.22. More details about the Tier 1 estimates were listed in Text S2.

2.3 | Uncertainty analysis

The uncertainty in our estimates was assessed by combining the uncertainties associated with activity data and emission factors of enteric fermentation and manure management (IPCC, 2019). The uncertainty range of livestock number data was assumed to be ±20% (IPCC, 2006; IPCC, 2019). For emission factors of enteric fermentation, the uncertainties in Tier 2 estimates were derived from the Y_m uncertainties with values of ±20%, ±13%, and ± 18%, respectively, for bovine animals (including dairy cattle, nondairy cattle, and buffaloes), sheep, and goats (IPCC, 2019). And the uncertainties in Tier 1 estimates were assumed to be ±40% (the median of uncertainty range ±30–50% suggested by IPCC, 2019). For emission factor of manage management, the uncertainties in Tier 2 estimates were estimated based on uncertainties from the B_o and *MCF* with values of ±15% and ±30%, respectively (IPCC, 2019), and the uncertainties in Tier 1 estimates were assumed to be ±30%. Then we combined all the uncertainties to show 95% confidence interval of estimates by using the IPCC error propagation equations (IPCC, 2019; Tubiello et al., 2013; Wolf et al., 2017).

3 | RESULTS

3.1 | Temporal changes in global CH_4 emissions from livestock

Our estimate shows that CH_4 emissions from global livestock increased from 31.8 [26.5–37.1] Tg CH_4 yr^{-1} in 1890 to 131.7 [109.6–153.7] Tg CH_4 yr^{-1} in 2019, a 314% increase. In the past 130 years,

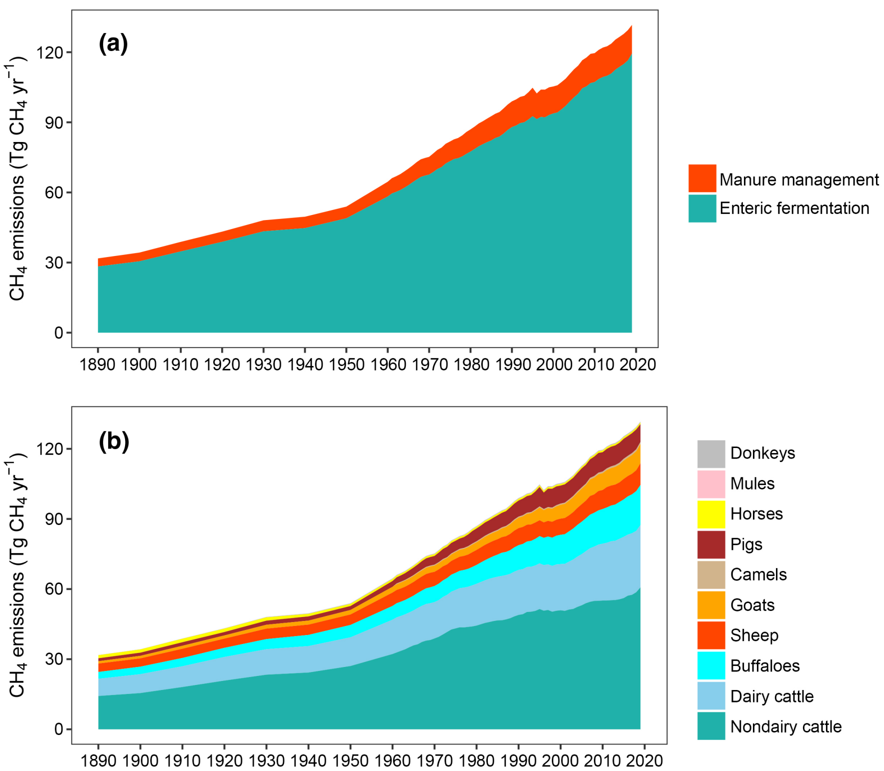


FIGURE 2 Temporal changes in global CH_4 emissions from livestock by (a) manure management and enteric fermentation and (b) animal categories during 1890–2019. [Colour figure can be viewed at wileyonlinelibrary.com]

CH_4 emissions experienced two main phases (Figure 2). During 1890–1949, emissions increased slowly at a rate of 0.4 Tg CH_4 yr^{-2} ($R^2 = 0.99$, $p < 0.01$). During 1950–2019, emissions increased rapidly at a rate of 1.1 Tg CH_4 yr^{-2} ($R^2 = 0.99$, $p < 0.01$), that was nearly three times the previous one. Almost 80% of the total increase of CH_4 emissions in the past 130 years occurred during 1950–2019. The emissions associated with enteric fermentation accounted for the majority (88%–91%) of the total global CH_4 emissions over the study period, and the emissions associated with manure management were responsible for the remaining (Figure 2a, Tables S3 and S4). Among different livestock categories, nondairy cattle were the largest CH_4 producer, accounting for about half (~49%) of the total global emissions in the past 130 years, followed by dairy cattle (~21%), buffaloes (~10%), sheep (~8%), pigs (~5%), goats (~4%), and horses (~2%). Other animals including camels, mules, and donkeys each contributed less than 1% of total emissions. Over the whole study period, emissions from all categories of livestock except horses have increased. The nondairy cattle emissions showed the fastest increase, contributing 45% of the total increased global livestock emissions between the 1890s and 2010s, followed by dairy cattle (20%), buffaloes (14%), pigs (8%), goats (7%), and sheep (6%). By contrast, horses had a negative contribution (−1%) (Figure 2b).

3.2 | Regional and country-level livestock CH_4 emissions

CH_4 emissions from livestock varies among different regions and countries (Figures 3, 4). To better show the regional and national CH_4 emissions and its temporal changes, we divided the world into 19 parts, namely Canada (CAN), the USA (US), Eastern Europe (EEU), Western Europe (WEU), Russia (RUS), Central Asia (CAS), Korean Japan (KAJ), China (CHN), Southeast Asia (SEAS), South Asia (SAS), Middle East (MIDE), Oceania (OCE), Northern Africa (NAF), Equatorial Africa (EQAF), Southern Africa (SAF), Central America (CAM), Northern South America (NSA), Brazil (BRA), and Southwest South America (SSA) (Figure S1).

In the 1890s, the largest emissions were found in South Asia (8.2 Tg CH_4 yr^{-1}), followed by the United States (5.3 Tg CH_4 yr^{-1}) and Western Europe (4.7 Tg CH_4 yr^{-1}). All other regions emitted less than 2.0 Tg CH_4 yr^{-1} (Figure 3). Across different countries, India had the highest emissions (6.5 Tg CH_4 yr^{-1}), followed by the United States, Russia (1.3 Tg CH_4 yr^{-1}), Brazil (1.3 Tg CH_4 yr^{-1}), China (1.2 Tg CH_4 yr^{-1}), and Argentina (1.0 Tg CH_4 yr^{-1}). African countries had much lower emissions (less than 0.3 Tg CH_4 yr^{-1}) (Figure 4a). Overall, the emissions from developed and developing countries accounted for 44% and 56% of the global total, respectively (Figure 3).

In the 2010s, South Asia had the largest emissions (34.7 Tg CH_4 yr^{-1}), followed by Brazil (12.0 Tg CH_4 yr^{-1}), Northern Africa (11.6 Tg CH_4 yr^{-1}), and China (11.0 Tg CH_4 yr^{-1}). Other developing regions including Central Asia, Northern South America, Southern Africa, Central America, Middle East, Southeast Asia, Southwest South America, and Equatorial Africa had emissions in the range of 2.7–6.7 Tg CH_4 yr^{-1}. Large emissions were also found in developed regions including the United States (8.3 Tg CH_4 yr^{-1}) and Western Europe (7.2 Tg CH_4 yr^{-1}) in the recent decade, while emissions in Canada, Russia, Eastern Europe, Oceania, and Korean Japan were relatively low, in the range of 0.8–2.3 Tg CH_4 yr^{-1} (Figure 3). At the country level, the top 10 emitters were India (24.0 Tg CH_4 yr^{-1}), Brazil, China, the United States, Pakistan (7.4 Tg CH_4 yr^{-1}), Argentina (2.8 Tg CH_4 yr^{-1}), Ethiopia (2.4 Tg CH_4 yr^{-1}), Sudan (2.2 Tg CH_4 yr^{-1}), Mexico (2.1 Tg CH_4 yr^{-1}), and Bangladesh (1.8 Tg CH_4 yr^{-1}) (Figure 4b). There were 18% and 82% of the global emissions in recent decade come from developed and developing regions, respectively. Developing regions contributed 91% of the global increased CH_4 emissions from livestock between the 1890s and 1990s, while developed regions contributed the remaining 9% (Figure 3).

Over the past 130 years, South Asia had the largest increase (26.6 Tg CH_4 yr^{-1}) in livestock CH_4 emissions, accounting for 29% of the global total increased emissions from the 1890s to 2010s,

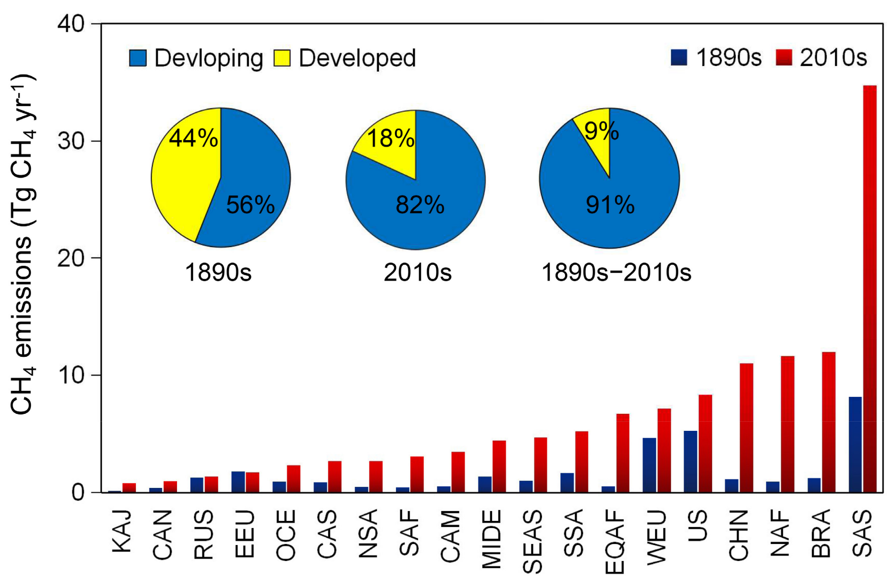


FIGURE 3 Regional CH_4 emissions from livestock in the decades of the 1890s and 2010s, and for the period 1890s–2010s. The illustrations show the share of developing and developed regions in total global CH_4 emissions, and also the contributions from developing and developed regions to the global increased emissions between the 1890s and 2010s. [Colour figure can be viewed at wileyonlinelibrary.com]

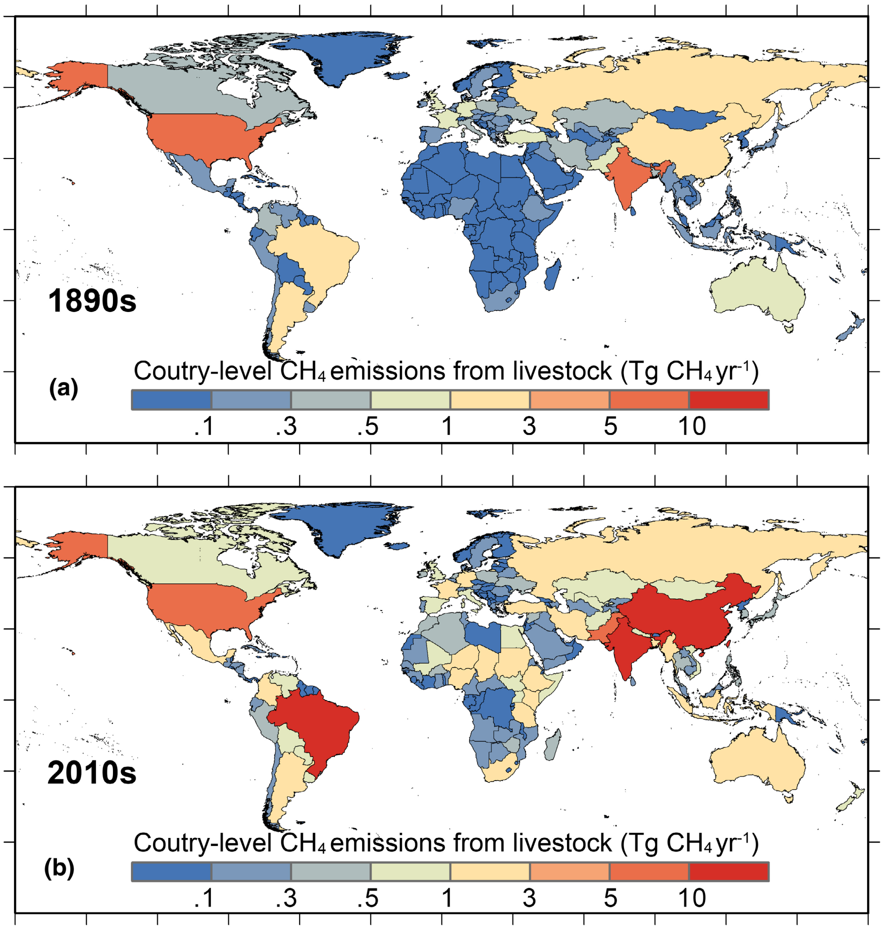


FIGURE 4 Country-level CH_4 emissions from livestock in the decades of (a) the 1890s and (b) the 2010s. [Colour figure can be viewed at wileyonlinelibrary.com]

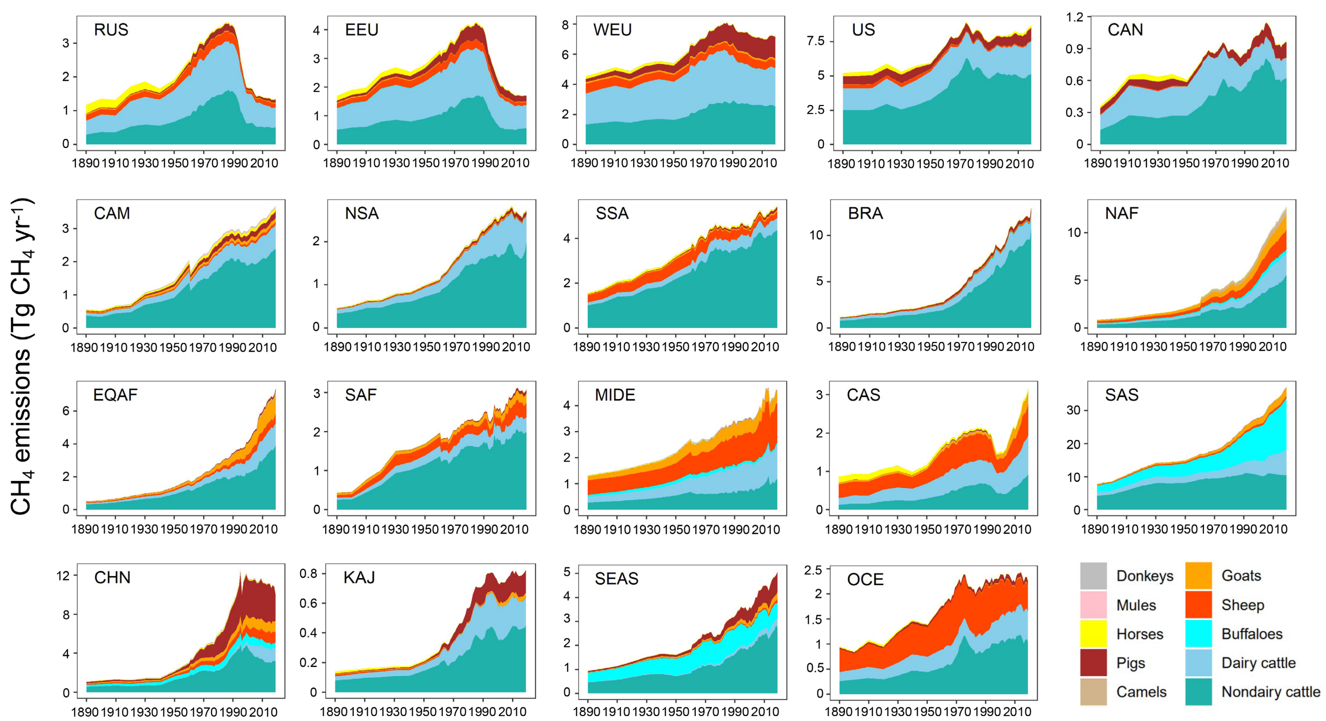


FIGURE 5 Temporal changes in regional CH_4 emissions from livestock during 1890–2019. [Colour figure can be viewed at wileyonlinelibrary.com]

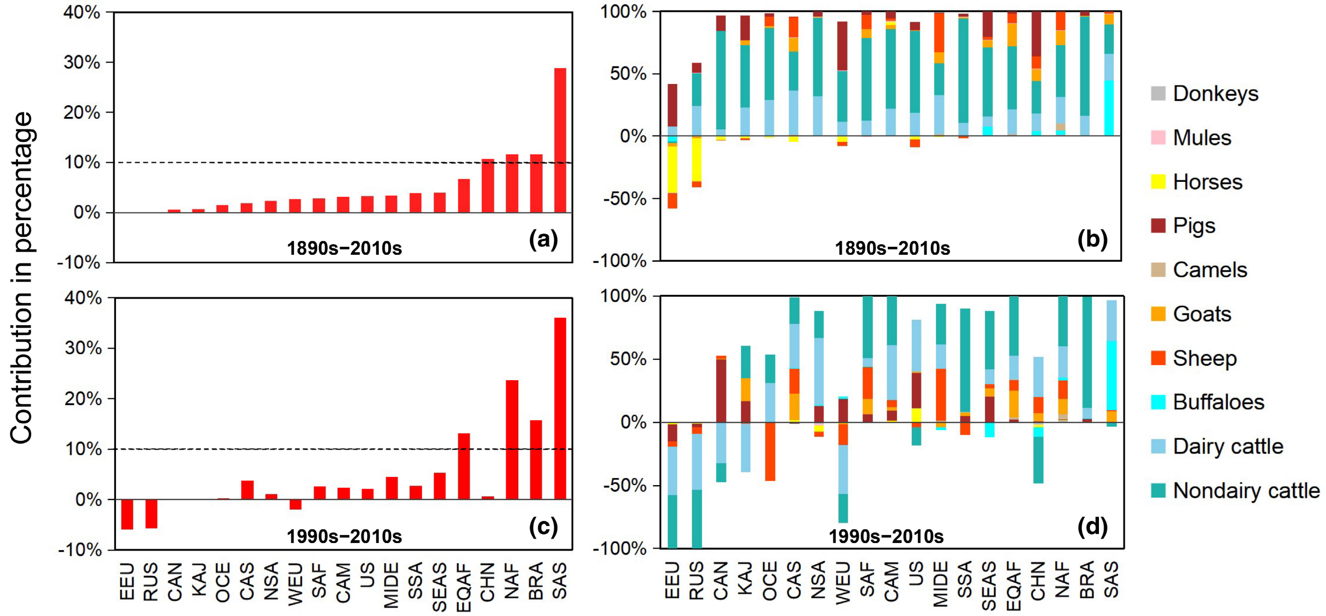


FIGURE 6 Contributions of different regions to the increased global livestock CH_4 emissions in the periods between the (a) 1890s and 2010s, and between the (c)1990s and 2010s, and contributions of different livestock categories to the changes in regional CH_4 emissions between the (b) 1890s and 2010s, and between the (d) 1990s and 2010s. [Colour figure can be viewed at wileyonlinelibrary.com]

followed by Brazil (12%), Northern Africa (12%), and China (11%) (Figures 5, 6a). CH_4 emissions in South Asia, Brazil, and Northern Africa all underwent continuous growth but were driven by different animals. For example, the growth in South Asia between the 1890s and 2010s was primarily attributed to buffaloes (45%), nondairy cattle (23%), and dairy cattle (21%). The increased Brazil emissions were mostly (79%) driven by nondairy cattle in the past 130 years (Figure 6b). In China, emissions first increased driven by dairy and nondairy cattle and pigs, but declined after the late 1990s due to emissions reductions from nondairy cattle and buffaloes. Equatorial Africa contributed 7% of the global total increased CH_4 emissions in the past 130 years. And the fast-growing emissions in this region were primarily driven by dairy and nondairy cattle, goats, and sheep (Figures 5, 6). Other developing regions, such as Southeast Asia, Southwest South America, Central America, Middle East, Southern Africa, Northern South America, and Central Asia, underwent rapid growths in CH_4 emissions in the past 130 years (Figure 5) but contributed less (2%–4%) to the total global growth (Figure 6a) due to the lower magnitude of emissions. The rising emissions in the seven regions were primarily driven by nondairy and dairy cattle, while sheep and goats played an import role in Middle East and Central Asia. For example, in Middle East, sheep contributed 32% and 47% of the increased emissions, respectively, for the periods between 2010s and 1890s and between 2010s and 1990s (Figures 6b,d). In the past 130 years, emissions in the United States first increased, then dropped over the decades of 1970s and 1980s, and then increased slightly. Trends in the United States emissions were mainly associated with changes in nondairy cattle, dairy cattle, and pigs given other animals producing less amount of CH_4 in this region (Figure 5). The emissions in Western Europe underwent two main phases. First, emissions increased by 63% between the 1890s and 1990s, mostly driven by nondairy cattle and pigs, and second, emissions declined by 6% from the 1990s to 2010s as a result of reducing emissions from bovine animals and sheep (Figures 5, 6b,d). In Oceania, CH_4 emissions first increased significantly and slowed down due to the decline in sheep emissions in recent decades (Figures 5, 6d). Eastern Europe and Russia had similar trends in terms of the livestock CH_4 emissions. Emissions in the two regions grew first and fell drastically after 1990 due to the collapse of the former Soviet Union, resulting in emissions in 2019 nearly the same as those 130 years ago (Figure 5). Korean Japan also underwent a slowdown in CH_4 emissions after 1990, which is primarily attributed to decreasing emissions from dairy cattle (Figures 5, 6d). In Canada, the emissions showed an overall increasing trend in the past 130 years but a sharp decline in the 2000s caused by dairy and nondairy cattle (Figure 5).

3.3 | Spatial patterns of livestock CH_4 emissions over time

The spatial patterns of livestock CH_4 emissions show major shifts over the global land surface from the 1890s to 2010s (Figure 7). In the 1890s, the hotspots of CH_4 emissions were mainly in Europe, South Asia, and the United States, with emission intensity (CH_4 emissions per unit area) of 10–30 kg CH_4 ha^{-1} yr^{-1}. Emission intensities in other areas were mostly lower than 3 kg CH_4 ha^{-1} yr^{-1} (Figure 7a). In the 2010s, the hotspots of CH_4 emissions were distributed mostly in South Asia, Western Europe, central and eastern United States, Brazil, tropical Africa, northern Middle East, eastern China, and southeastern Oceania. Of all regions, South Asia had the

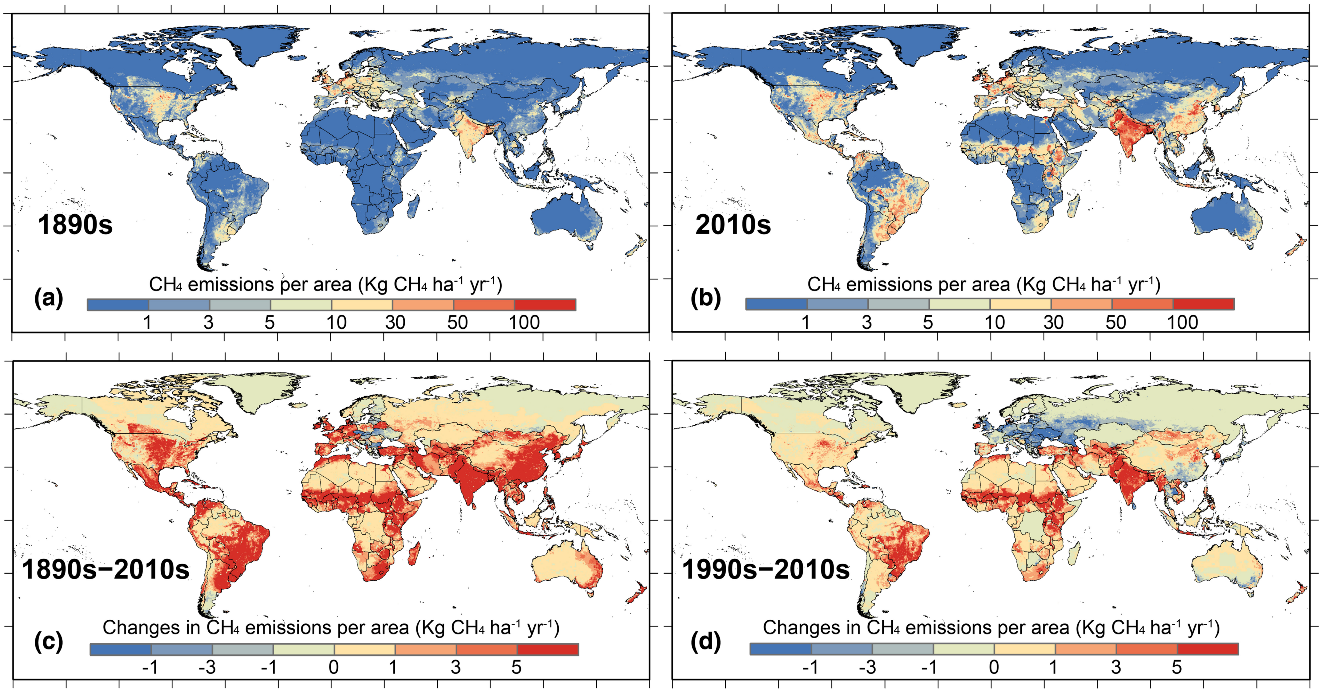


FIGURE 7 Spatial patterns of CH_4 emissions from global livestock in the (a) 1890s and (b) 2010s, and changes between the (c) 1890s and 2010s, and between the (d) 1990s and 2010s. [Colour figure can be viewed at wileyonlinelibrary.com]

largest emission intensity in the recent decade, with values generally higher than 50 kg CH_4 ha^{-1} yr^{-1}. Whereas the areas in high latitudes or high altitudes had much lower emission intensities, with values mostly less than 1 kg CH_4 ha^{-1} yr^{-1} (Figure 7b). Compared to the 1890s, CH_4 emission intensities in the 2010s increased significantly in most parts of the world except some areas in Eastern Europe. The largest growth in CH_4 emission intensity was found in South Asia, eastern China, tropical Africa and parts of Latin America with values generally higher than 5 kg CH_4 ha^{-1} yr^{-1} (Figure 7c). However, compared to the 1990s, emission intensities in the 2010s had decreased in most of developed regions and also some areas in China. Europe and eastern Russia had the largest decreases in CH_4 emission intensities in the past three decades. By contrast, South Asia, tropical Africa, and Brazil have become the regions with largest increases in CH_4 emissions intensity since the 1990s (Figure 7d).

4 | DISCUSSION

4.1 | Spatiotemporal variations in livestock CH_4 emissions

Our estimates show that global CH_4 emissions from livestock were 131.7 [109.6–153.7] Tg CH_4 yr^{-1} in 2019 (Figure 2), accounting for 34% of the total global anthropogenic CH_4 emissions (392 Tg CH_4 yr^{-1}) in the same period (Olivier & Peters, 2020). From 1890 to 2019, CH_4 emissions from global livestock first increased slowly and then accelerated after 1950 (Figure 2). The temporal changes in CH_4 emissions from livestock coincide with the development of the world economy and the transformation of agriculture in many parts of the world, from more traditional, extensive systems to more intensive, modern productive systems. In the past 130 years, the global economy was suppressed by two World Wars and the Great Depression but by mid-1940s the economy was rapidly developing (IMF, 2000). The booming economy and population growth created a large demand for livestock products (Herrero et al., 2013) resulting in the rapid growth of livestock numbers and CH_4 emissions since 1950 (Figure 2; Figure S2). Correlation analyses show that there are strong positive relationships between the global livestock emissions and human population as well as GDP per capita ($p < 0.01$), underlying well-recognized links between increases in human population and national income levels and livestock production, which in turn drives CH_4 emissions (Figure 8). However, while emissions are highly positively correlated with population and income at the global scale, there are some inconsistencies by region, as negative correlations were found in Europe, Russia, and the United States. This could be related to factors including policy, diet shifts, livestock productivity improvement, and international trade (see below for further discussions). For different livestock categories, bovine animals including dairy and nondairy cattle and buffaloes contributed most (79%) of the global increased CH_4 emissions over the study period. This is due to the large and rising herd and emission factors of bovine animals. For example, the numbers and average enteric emission factors of global dairy cattle have increased by ~210% and ~20%, respectively, from the 1890s to the 2010s (Figure 9; Figure S2). The small ruminants and pigs also made a significant contribution (20%) to the world-total increase in CH_4 emissions, resulting from the growth of the animal numbers and emission factors (Figure 9; Figure S2).

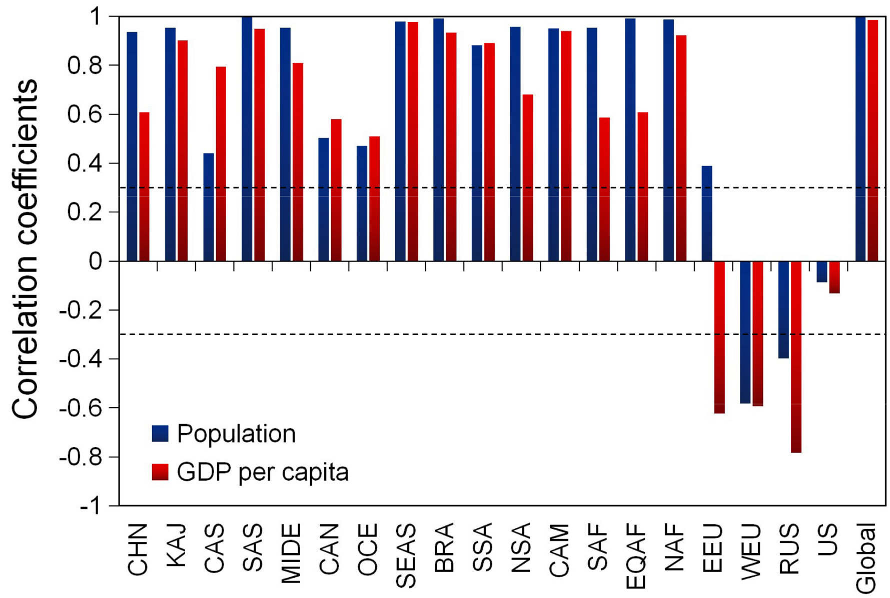


FIGURE 8 Correlations between CH_4 emissions from livestock and population and GDP per capita. The relationship was constructed based on data over the period 1970–2019. Population data were collected from the UN (2019), and GDP per capita data (in 2015 USD) were collected from FAOSTAT (FAO, 2021b). Dashed lines indicate a significant level of 0.01. [Colour figure can be viewed at wileyonlinelibrary.com]

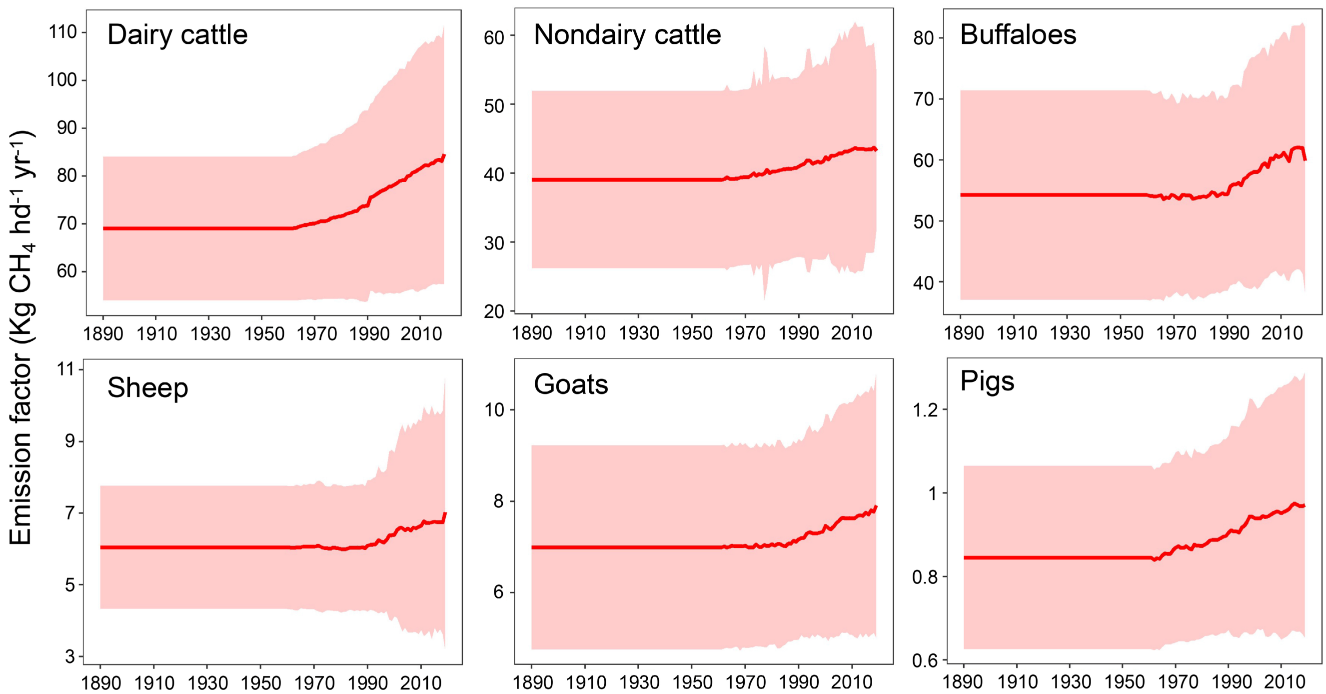


FIGURE 9 Changes in emission factor of enteric fermentation for livestock during 1890–2019. The shaded area shows the standard deviation of the estimates. [Colour figure can be viewed at wileyonlinelibrary.com]

However, there was a significant decrease in CH_4 emissions from horses, due to the shrinking populations (Figure S2).

Regionally, our analysis shows that developing regions contributed the majority (91%) of the global increased CH_4 emissions from livestock between the 1890s and 2010s (Figure 3). The large contribution from developing regions has been also found in previous estimates (e.g., Caro, Davis, et al., 2014; Chang et al., 2019; FAO, 2021b; Tubiello et al., 2013) and is related to several factors.

First, developing regions experienced much higher population growth than developed countries. For example, African population increased by 3.6 times from the 1950s to 2010s, by contrast, population in Europe increased by only ~30% over the same period (UN, 2019). The soaring population in developing regions, alongside increases in income, created a higher demand for consumption of livestock products and thus more emissions (Herrero et al., 2013; Patra, 2014; Thornton, 2010).

Second, per-capita consumption of animal products in developing countries grew faster than that in developed countries where the consumption level is already high (Milford et al., 2019). For instance, the consumption of animal protein per capita per day in China increased by eight times (4.2 g to 37.2 g) from 1961 to 2011, while that in Spain increased by the much smaller quantity of ~130% (28.1 g to

65.8 g) (Sans & Combris, 2015). Per-capita meat consumption per year in Latin America increased by ~80% (~40 kg to ~70 kg) from 1990 to 2010, but that in western countries remained stable at ~90 kg over the same period (Milford et al., 2019). Increased consumption of animal products can lead to rapid growths in livestock populations and CH_4 emissions (FAO, 2018; Godfray et al., 2018; Herrero et al., 2016; Thornton, 2010).

Third, compared with developed countries, more people in developing countries rely on animal husbandry for livelihoods. It is estimated that about a quarter of the global poor are livestock keepers, most of whom are living in developing regions (Perry, 2002; Thornton et al., 2003). In order to gain more profit, pastoralists in these regions continue to expand their livestock herds (Herrero et al., 2008; Perry, 2002), which can result in more emissions in case of lacking mitigation efforts (Descheemaeker et al., 2016). The pursuit of economic benefits may also drive changes in proportion of livestock holdings. For example, in India, milk yield of buffalo (5.92 kg head^{-1} day^{-1}) is 67% higher than that of cattle (3.54 kg head^{-1} day^{-1}), and buffalo milk is more expensive due to higher fat content, thus dairy farmers are willing to raise more buffaloes to earn more profits (Kumar et al., 2019). This has resulted in higher CH_4 emissions from buffaloes in recent decades in South Asia (Figures 5, 6). In drought-prone Africa, herders increasingly rely on goats which are cheaper to acquire and reproduce (Peacock, 2005). For instance, goat populations in Sudan has increased by over 5 times from the 1960s to the 2010s (FAO, 2021b). This helps to explain the upward trend in goats CH_4 emissions in Africa (Figures 5, 6).

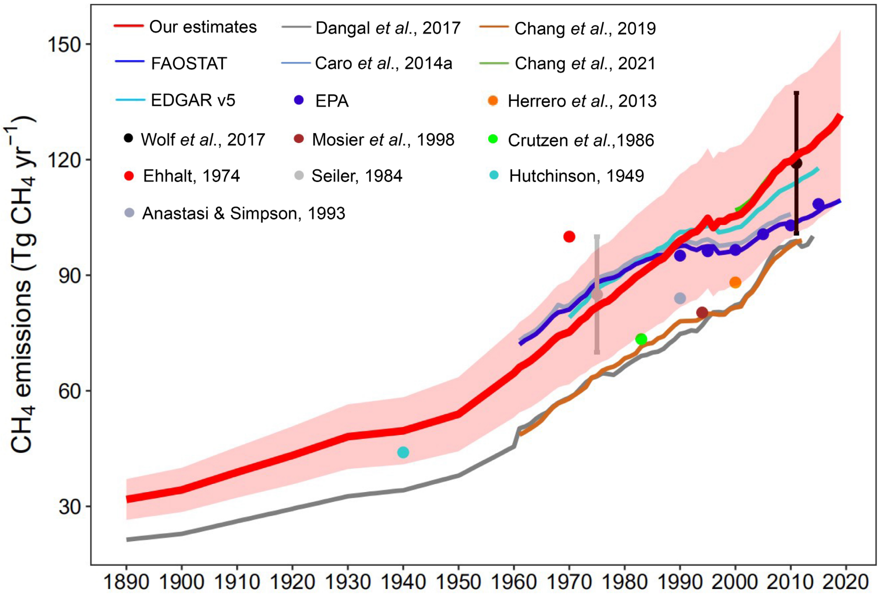
From 1890 to 2019, CH_4 emissions underwent a continuous growth in most of developing countries, with an exception of a downward shift since the late 1990s in China (Figure 5). The reduction in China's emissions was primarily due to trends in nondairy cattle (Figure 6d). In order to meet the demand for beef consumption, the cull rate of beef cattle has increased significantly since the mid-1990s, resulting in a decrease in nondairy cattle population and thus CH_4 emissions (Li et al., 2018; Zhang, Tian, et al., 2021). By contrast, the declining or slowdown in emissions is common in developed regions, mainly due to significant changes in policy and regulation concerning agriculture that were implemented towards the end of the 1980s, as well as fundamental changes in Eastern Europe (Chang et al., 2019). For example, the collapse of the Soviet Union in 1991 led to a drop in livestock production and thus CH_4 emissions in Russia and Eastern Europe. In 1992, European Union changed the agriculture policies to subsidize farmers who retreat land from production, thereby reducing livestock numbers in the following years. Starting in 1984, the EU's common agricultural policy (CAP) have introduced milk quotas to deal with overproduction of milk and milk products, leading to a reduction in cow herds in the following years (CAP, 2021). The downward CH_4 emissions were also related to economic conditions and diet shifts. For instance, the Oil Crisis in 1973 had large negative impacts on the economy and affected beef consumption in subsequent years (IMF, 2000). In 1977, the US Senate Select Committee published the *Dietary Goals for the United States*, encouraging people to reduce fat and cholesterol intake, thereby reducing beef consumption and cattle populations (Davis & Lin, 2005; Kritchevsky, 1998).

In recent decades, people in developed regions have increasingly preferred to eat chicken and pork instead of beef and lamb (Kanerva, 2013; OECD, 2021; Whitnall & Pitts, 2019). That choice resulted in the rapid growth in production of chicken and pig meat but low growths or even declines in beef and mutton (Figure S5). For instance, production of chicken and pig meat in the United States increased by approximately 500% and 100% from the 1960s to 2010s, respectively, while bovine meat production increased by only 34% over the same period, and sheep and goat meat decreased by 74%. This changes cause a decline in CH_4 emissions from livestock, because emissions associated with production of poultry and pork are much lower than that of beef and lamb (Caro, Davis, et al., 2014; Chang et al., 2021). The declining emissions in developed regions were also associated with the improvement in livestock productivity. For example, the dairy cattle populations in Western Europe decreased by 24% from the 1990s to 2010s, but the milk production increased by 6% over the same period as a result of growing cow milk yield (Figure S6). Improving livestock productivity can produce more with lower emissions (Chang et al., 2021). Another incentive for lower emissions in some developed countries may be international trade. A study from Caro, Lopresti, et al. (2014) showed that there were over 5 million tons of CO_2-eq embodied in meat import to Russia in 2010, mostly from Brazil and Argentina. Based on data from FAOSTAT, cattle imports into Russia has increased by ~120% from the 1990s to 2010s (FAO, 2021b). International trade can reduce livestock sourced emissions in importer counties but enhance the emissions in exporters. The factors above can help explain why emissions are negatively correlated with population and national income in some developed regions (Figure 8).

4.2 | Comparison with previous estimates

We compared our results with 15 previous estimates including FAOSTAT (FAO, 2021b; Tubiello et al., 2013), EDGAR v5 (Crippa et al., 2020), EPA (2012), Dangal et al. (2017), Chang et al. (2019), Caro, Davis, et al. (2014), Herrero et al. (2013), Wolf et al. (2017), Chang et al. (2021) Crutzen et al. (1986), Hutchinson (1949), Ehhalt (1974), Seiler (1984), Mosier et al. (1998), and Anastasi and Simpson (1993) (Figure 10, Table 1). Compared with FAOSTAT, Caro, Davis, et al. (2014) and EPA, our study shows a higher growth trend in CH_4 emissions. Our estimates are ~8% lower in 1970 than the estimates from FAOSTAT as well as Caro, Davis, et al. (2014) but are ~20% higher in 2019 than FAOSTAT estimates. The discrepancies are mainly associated with how the different estimates were calculated. In order to replicate the way in which most developing countries report GHG data to the climate convention, FAO and EPA data efforts are built by design to using Tier 1 methods, which assumed the emission factors are time-invariant. Caro, Davis, et al. (2014) is also based on the IPCC Tier 1 methods. However, livestock productivity has increased over the recent decades (Thornton, 2010). For

FIGURE 10 Estimates of CH_4 emissions from global livestock during 1890–2019 and comparisons with those reported in other inventories. The shaded area shows the 95% confidence interval of our estimates. [Colour figure can be viewed at wileyonlinelibrary.com]



example, according to FAO estimates, the average milk yield of global dairy cows has doubled from the 1960s to 2010s (Figure S3). The rising livestock productivity will lead to upwards in emission factors (Figure 9) and thus CH_4 emissions, as animals with higher productivity require more energy (IPCC, 2019). Using the Tier 2 methods, we estimated CH_4 emissions based on dynamic emission factors which incorporate the trends in livestock productivity. Thus our study found higher growths of CH_4 emissions as compared to the Tier 1 estimates. Unlike the FAOSTAT, EPA and Caro, Davis, et al. (2014), EDGAR partially considered the changes in livestock productivity by incorporating the trends in milk yield and carcass weight of cattle (Crippa et al., 2020; Janssens-Maenhout et al., 2019). Therefore, EDGAR suggested a higher growth of CH_4 emissions, in closer agreement with our estimates. Our results are close to estimates from Chang et al. (2021), as both our study and Chang et al. (2021) incorporated the changes in livestock productivity by using the Tier 2 methods from IPCC (2019) guidelines.

For the single year of 2011, our estimate of emissions is 121.0 [100.9–141.1] Tg CH_4 yr^{-1}, which is close to the estimate (119.1 [100.9–137.3] Tg CH_4 yr^{-1}) from Wolf et al. (2017). By considering the recent changes in body weight, milk yield, feed conditions, and manure management, Wolf et al. (2017) revised the emission factors for cattle and pigs by following the Tier 2 method or by collecting updated regional information. Therefore, their estimated CH_4 emissions from livestock are higher than the IPCC (2006) Tier 1 estimates but close to our estimates. For the livestock CH_4 emissions in 2000, our result is 20% higher than that from Herrero et al. (2013). This could be due to the methods given that Herrero et al. (2013) used the IPCC (2006) Tier 3 approach to estimate the enteric CH_4 emissions from global ruminants. Our results are 5–14% higher than estimates from Crutzen et al. (1986), Anastasi and Simpson (1993), and Mosier et al. (1998) for the same subsets of emissions (Table 1). Based on feed energy utilization, Crutzen et al. (1986) derived the CH_4 production rates (i.e., emission factors) of animals and then estimated the CH_4 emissions from global livestock. The emission factors from Crutzen et al. (1986) were also used by Anastasi and Simpson (1993) and Mosier et al. (1998) in their estimates. However, the values of these emission factors could be on the low side for some animals. For example, Crutzen et al. (1986) estimated the emission factors of global cattle (without distinction between dairy and nondairy cattle) as 35–55 kg CH_4 yr^{-1} $head^{-1}$. But the emission factors of global dairy cattle provided by IPCC (2019) are in the range of 73–138 kg CH_4 yr^{-1} $head^{-1}$, and those in our estimates are ~70–85 kg CH_4 yr^{-1} $head^{-1}$ (Figure 9). Our result is generally consistent with the estimate from Seiler (1984) but 10–40% lower than those from Hutchinson (1949) and Ehhalt (1974) for the same subsets of emissions. Hutchinson (1949) and Ehhalt (1974) estimated livestock CH_4 emissions by multiplying the global livestock numbers by the emission rates of different animals, while emission rates were derived by measuring animal emissions in the United States. This could lead to an overestimation of global emissions because of the higher emission rates of livestock in developed regions (IPCC, 2019).

Our study found larger magnitude of CH_4 emissions from livestock as compared with the Tier 2 estimates from Dangal et al. (2017) and Chang et al. (2019). For example, our estimates in the 2000s are ~25% higher than that from Dangal et al. (2017). This is mainly due to the estimation boundary (i.e., the emission sources and livestock categories which are included in estimates). As we estimated CH_4 emissions associated with enteric fermentation and manure management from 10 categories of livestock including ruminants and nonruminants, while Dangal et al. (2017) only estimated CH_4 emissions from four ruminants (dairy cattle, nondairy cattle, sheep, and goats) and Chang et al. (2019) only considered the enteric emissions but not manure management emissions. Even for the same subsets of emissions, there are still some differences between our estimates and those from Dangal et al. (2017) and Chang et al. (2019). For example, our estimate for year 2000 is close to the result of Dangal et al. (2017) but 12% higher than that of Chang et al. (2019), and our estimate for year 1890 is 23% higher than that of Dangal et al. (2017) (Table 1). Those discrepancies are related to the differences in

TABLE 1 Comparison of CH_4 emissions from global livestock between our estimates and previous estimates

Year	Our estimates[a] (Tg CH_4 yr^{-1})	Previous estimates (Tg CH_4 yr^{-1})	Methods[b]	References
2019	131.7 [109.6–153.7]	109.5	IPCC 2006 Tier 1	FAOSTAT
2011	121.0 [100.9–141.1]	119.1 [100.9–137.3]	Revised IPCC 2006 Tier 1	Wolf et al., 2017
2000	105.3 [87.2–123.4]	96.5	IPCC 2006 Tier 1	FAOSTAT
		98.2	IPCC 2006 Tier 1	Caro, Davis, et al., 2014
		102.3	Hybrid IPCC 2006 Tier 1	EGDGAR
		96.6	IPCC Tier 1	EPA
		106.8	Mixed IPCC 2019 Tiers	Chang et al., 2021
		88.1	IPCC 2006 Tier 3	Herrero et al., 2013
	83.5 [69.2–97.9]	82.2	IPCC 2006 Tier 2	Dangal et al., 2017
	91.4 [75.7–107.1]	81.6	IPCC 2006 Tier 2	Chang et al., 2019
1994	102.9 [85.0–120.8]	97.3	IPCC 2006 Tier 1	FAOSTAT
	91.2 [75.4–107.1]	80.3	Raw IPCC Tier 1	Mosier et al., 1998
1990	99.0 [81.7–116.2]	97.6	IPCC 2006 Tier 1	FAOSTAT
		99.2	IPCC 2006 Tier 1	Caro, Davis, et al., 2014
		101.2	Hybrid IPCC 2006 Tier 1	EGDGAR
		95.1	IPCC Tier 1	EPA
	79.9 [66.0–93.9]	74.8	IPCC 2019 Tier 2	Dangal et al., 2017
	85.6 [70.6–100.5]	78.0	IPCC 2006 Tier 2	Chang et al., 2019
	88.0 [72.6–103.3]	84	Raw IPCC Tier 1	Anastasi & Simpson, 1993
1983	90.5 [74.4–106.6]	93.4	IPCC 2006 Tier 1	FAOSTAT
	80.2 [65.9–94.5]	73.4	Raw IPCC Tier 2	Crutzen et al., 1986
1975	81.7 [66.8–96.7]	88	IPCC 2006 Tier 1	FAOSTAT
	73.3 [59.9–86.7]	70–100	Raw IPCC Tier 1	Seiler, 1984
1970	75.2 [61.6–88.8]	81.1	IPCC 2006 Tier 1	FAOSTAT
		82.2	IPCC 2006 Tier 1	Caro, Davis, et al., 2014
		79	Hybrid IPCC 2006 Tier 1	EGDGAR
	60.1 [49.2–70.9]	100	Raw IPCC Tier 1	Ehhalt, 1974
1940	49.6 [40.1–58.3]			
	39.7 [32.7–46.7]	44.7	Raw IPCC Tier 1	Hutchinson, 1949
1890	31.8 [26.5–37.1]			
	26.2 [21.9–30.6]	21.3	IPCC 2006 Tier 2	Dangal et al., 2017

[a] Values of our estimates are shown as mean [minimum–maximum of 95% confidence interval]. Considering there are significant differences in subsets of emissions between our study and Dangal et al. (2017), Chang et al. (2019), Crutzen et al. (1986), Hutchinson (1949), Ehhalt (1974), Seiler (1984), Mosier et al. (1998), and Anastasi and Simpson (1993), we also provided values for the same subset of emissions as in their estimates to make a direct comparison.

[b]Hybrid IPCC 2006 Tier 1 adopted by EDGAR refers to the methods which have incorporated the trends in milk yield and carcass weight of cattle; Mixed IPCC 2019 Tiers used in Chang et al. (2021) refers to the mixed Tier 1 and Tier 2 methods from the IPCC (2019) guidelines; Wolf et al. (2017) revised the emission factors from IPCC (2006) guidelines for cattle and swine by considering the changes in body weight, milk yield, feed conditions, and manure management, thus the method used by Wolf et al. (2017) was called Revised IPCC 2006 Tiers; In the early era, Crutzen et al. (1986) estimated the ruminant CH_4 emissions based on energy utilization in animals, this approach is the prototype of the IPCC Tier 2 method, thus we called method adopted by Crutzen et al. (1986) the Raw IPCC Tier 2; Hutchinson (1949), Ehhalt (1974), Seiler (1984), Mosier et al. (1998), and Anastasi and Simpson (1993) estimated emissions by multiplying CH_4 release rates per animal (i.e., emission factors) by the estimated livestock populations, thus the methods they adopted were called the Raw IPCC Tier 1.

guidelines used in the different studies. We followed the IPCC (2019) guidelines while Dangal et al. (2017) and Chang et al. (2019) followed the IPCC (2006) guidelines. The use of different feed digestibility values can also cause different results. We and Dangal et al. (2017) did not distinguish feed types of the global livestock sector, but used the regional feed digestibility defaults (ranging from 50.7% to 77%) from Opio et al., (2013). However, Chang et al. (2019) estimated the quantity of concentrate feed and assigned a higher digestibility (80%) to it, which could lead to lower emissions. Inconsistencies in activity data could be another reason. Livestock numbers used in

Chang et al. (2019) were entirely based on country-level statistics from FAOSTAT (FAO, 2021b), while we used the livestock population data from the NBSC (2021) when estimating the emissions in China. Dangal et al. (2017) used more sub-national data in the United States, Canada, Australia, China, Brazil, and Mongolia.

It is noted that although there are varying degrees of differences in magnitude of CH_4 emissions between our results and estimates from Dangal et al. (2017) and Chang et al. (2019), the trends are similar. For example, the growth rate of CH_4 emissions during 1990–2010 in our study is 1.0 Tg CH_4 yr^{-2}, while those for Dangal et al. (2017) and Chang et al. (2019) are 1.3 Tg CH_4 yr^{-2} and 1.0 Tg CH_4 yr^{-2}, respectively. In contrast, FAOSTAT estimated that the growth rate over the same period is only 0.3 Tg CH_4 yr^{-2}.

4.3 | Implications for CH_4 mitigation in livestock sector

CH_4 is considered a key target for short-term climate mitigation because of it short atmospheric lifetime (~9 year) (Saunois et al., 2016). As a major CH_4 source, the livestock sector can play an important role in reducing CH_4 emissions (Herrero et al., 2016; Kumari et al., 2020). Our results, showing that global CH_4 emissions from livestock have continued to increase in the past 130 years and accelerated in recent decades (Figure 2), illustrate current challenges but also a continuous opportunity for CH_4 mitigation.

Our estimates show that the majority (~75%) of global livestock emissions in the most recent decade (2010s) originated in South Asia, Brazil, North Africa, China, the United States, Western Europe, and Equatorial Africa (Figures 3, 4), indicating large mitigation opportunities exiting in these regions/countries (FAO, 2021b; Hristov et al., 2013). The regional emissions showed significant differences in temporal trends (Figure 5). Rapid and continuous growth over the 130 years were mostly found in the developing world. Four regions: South Asia, Brazil, North Africa, and Equatorial Africa contributed nearly 90% of the total growth in global CH_4 emissions between the 1990s and 2010s (Figure 6c). A recent study using satellite (GOSAT) based column concentrations found South Asia, tropical Africa, and Brazil have become the primary source of the growth in global anthropogenic CH_4 emissions from 2010 to 2018, with livestock being the main driver (Zhang, Jacob, et al., 2021). This finding suggests that those developing regions can play a key role in curbing the trend of the rising global CH_4 emissions. Driven by increasing demand of animal products associated with growing population, income and preference for meat, livestock populations in developing regions are expected to increase in next decades (Thornton, 2010). This will bring greater challenges to future global CH_4 mitigation. The contributions of different animals to the growth in CH_4 emissions (Figures 6b,d) could help us to identify the livestock species that should be first targeted in future mitigation efforts. For example, buffaloes and dairy cattle are primary targets in South Asia as they contributed over 90% of the growth in South Asian CH_4 emissions in last three decades. In Africa, both cattle and small ruminants are key targets when developing emission reduction plans. Given there are large spatial heterogeneity in the emissions in some countries, the gridded emission maps can help identify sub-national hot spots of emissions and help design more efficient, spatially explicit mitigation efforts (Figure 7). The gridded maps can reveal to a certain extent the spatial shifts in CH_4 emissions within countries, and thus help to formulate future mitigation strategies on a sub-national scale. For example, in China, although the total emissions have fallen since the late 1990s (Figure 5), emissions in the north have increased in the last three decades (Figure 7d), indicating that future mitigation efforts could pay more attention to the north (Xu et al., 2019).

Varies mitigation options exist in the livestock sector (Gerber et al., 2013; Herrero et al., 2016; Hristov et al., 2013; Lassen & Difford, 2020; Patra, 2012). Of which, improving livestock productivity is a key component mitigation option especially in the developing regions (Chang et al., 2021; Herrero et al., 2016), as long as the associated improvements in emission intensities can be coupled with a strategy that also focused on reducing total emissions (Tubiello, 2019). Under business as usual socio-economic scenarios, Chang et al. (2021) predicts that developing regions will contribute most of the global livestock CH_4 reduction by 2050 related to productivity improvements. This is due to the lower livestock productivity and thus the higher CH_4 emissions per unit of animal products. For example, in the 2010s, CH_4 emission per unit milk production in developing regions is about three times of that in developed regions (Figure S4), implying that CH_4 emissions from global dairy cattle can be reduced by ~50% if the milk productivity in developing countries can catch up with that in developed countries. Other strategies to improve livestock productivity and reduce emissions include improving feed quality/efficiency, intensive management, adding feed additives, genetic selection, etc. (Gerber et al., 2013; Herrero et al., 2016; Lassen & Difford, 2020; Patra, 2012). The implementation of strategies need take into account the cost and applicability. For example, improving feed quality may result in more land planted with high-energy feed crops, which could limit land needed for food production (Gill et al., 2010), especially in regions with increasing human food demand (e.g., Africa). Reasonable manure management can also promote emission reduction. A study showed that combination of anaerobic digestion and composting can reduce total CH_4 emissions from livestock by up to 15% in China (Xu et al., 2019). Based on data from four European countries (i.e., Sweden, Denmark, France, and Italy), Sommer et al. (2009) found that CH_4 emissions from pig and cattle slurry can be reduced by over ~50% via solids and liquid separation and incineration of the solids. Given the large and rapid growing manure emissions in regions like Europe and Asia (Table S4), improving manure management strategies can play a key role in reducing CH_4 emissions from global livestock, while recognizing that the important emission process that needs to be decisively reduced is enteric fermentation.

4.4 | Uncertainty sources

In this study, we followed the IPCC (2019) guidelines to estimate global CH_4 emissions from a total of 10 categories of livestock. The

Tier 2 method was used for major emitters including dairy cattle, nondairy cattle, buffaloes, sheep, and goats, and the trends of body weight were considered in the estimation of pig emissions. These efforts could help reduce the uncertainty of estimation of CH_4 emissions from livestock, as more sophisticated information on livestock production was incorporated and new revised parameters were used (Amon et al., 2021; IPCC, 2019). However, there are still some uncertain sources in this study. First, we derive dynamic emission factors by incorporating the changes in livestock productivity (e.g., body weight, milk yield), but changes in feed digestibility, feeding regimes, and manure management systems were not included due to the lack of long-term records of that information worldwide. And also the spatial resolutions of these data were relatively low. Second, we distributed country-level livestock numbers and/or CH_4 emissions to grid level based on the spatial patterns of livestock provided by Gilbert et al. (2018) for the year 2010, while the animal distribution within countries might change over the study period. Third, the HYDE data prior to 1961 may have large uncertainties in animal numbers (Mitchell, 1993, 1998a, 1998b), and also, other animals, such as poultry, were not covered in this study. These could create additional uncertainty in our estimates.

5 | CONCLUSION

In this study, we estimated the global and regional CH_4 emissions from livestock for the period 1890 to 2019, primarily based on the Tier 2 method from the IPCC (2019). We show that CH_4 emissions from global livestock increased from 31.8 [26.5–37.1] Tg CH_4 in 1890 to 131.7 [109.6–153.7] Tg CH_4 in 2019, an increase of four times in the last 130 years. Nondairy cattle had the largest contribution to the emissions from global livestock in the past 130 years, followed by dairy cattle, buffaloes, sheep, pigs, goats, and horses. Compared with previous Tier 1 estimates, our results suggest a higher growth rate of the CH_4 emissions. And our estimate is ~20% higher in 2019 than that from FAOSTAT which has been adopted by the IPCC AR6 WGIII Report (IPCC, 2022). Regionally, Europe, Russia, the United States, Oceania, and China have undergone a slowdown or decline in the emissions since the 1990s or earlier. While the emissions have continued to increase or even accelerate in most developing regions. South Asia, tropical Africa, and Brazil have dominated the growth in global CH_4 emissions from livestock since the 1990s. Changes in the livestock CH_4 emissions are primarily driven by population and national income and are also associated with the policy, diet shifts, livestock productivity improvement, and international trade.

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CONFLICT OF INTEREST

All authors have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the results of this study are available in Dryad: https://doi.org/10.5061/dryad.vt4b8gtvb

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SUPPORTING INFORMATION

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