The key role of production efficiency changes in livestock methane emission mitigation

Jinfeng CHANG[1], Shushi Peng[2], Yi Yin[3], Philippe Ciais[4], Petr Havlik[5], and Mario Herrero[6]

[1]Zhejiang University
[2]Peking University
[3]California Institute of Technology
[4]Université Paris-Saclay
[5]International Institute for Applied Systems Analysis
[6]Commonwealth Scientific and Industrial Research Organization

November 22, 2022

Abstract

The livestock sector is the largest source of anthropogenic methane emissions, and is projected to increase in the future with increased demand for livestock products. Here, we compare livestock methane emissions and emission intensities, defined by the amount of methane emitted per unit of animal proteins, estimated by different methodologies, and identify mitigation potentials in different regions of the world based on possible future projections. We show that emission intensity decreased for most livestock categories globally during 2000-2018, due to an increasing protein-production efficiency, and the IPCC Tier 2 method should be used for capturing the temporal changes in the emission intensities. We further show that efforts on the demand-side to promote balanced, healthy and environmentally-sustainable diets in most countries will not be sufficient to mitigate livestock methane emissions without parallel efforts to improve production efficiency. The latter efforts have much greater mitigating effects than demand-side efforts, and hence should be prioritized in a few developing countries that contribute most of the mitigation potential.

The key role of production efficiency changes in livestock methane emission mitigation

Jinfeng Chang[1,2], Shushi Peng[3], Yi Yin[4], Philippe Ciais[5], Petr Havlik[2], Mario Herrero[6]

[1] College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, 310058, China

[2] International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria

[3] Sino-French Institute for Earth System Science, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

[4] Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, 91125, USA

[5] Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

[6] Commonwealth Scientific and Industrial Research Organization, St Lucia, QLD 4067, Australia

Corresponding author: Jinfeng Chang (changjf@zju.edu.cn)

Key Points:

- Emission intensity decreased for most livestock categories globally during 2000-2018, with an increasing protein-production efficiency
- The continuation of the past decreases in emission intensity provides a large potential to mitigate livestock emissions
- Improving production efficiency has a much greater mitigating effect than demand-side efforts, and should be prioritized in a few countries

Abstract

The livestock sector is the largest source of anthropogenic methane emissions, and is projected to increase in the future with increased demand for livestock products. Here, we compare livestock methane emissions and emission intensities, defined by the amount of methane emitted per unit of animal proteins, estimated by different methodologies, and identify mitigation potentials in different regions of the world based on possible future projections. We show that emission intensity decreased for most livestock categories globally during 2000-2018, due to an increasing protein-production efficiency, and the IPCC Tier 2 method should be used for capturing the temporal changes in the emission intensities. We further show that efforts on the demand-side to promote balanced, healthy and environmentally-sustainable diets in most countries will not be sufficient to mitigate livestock methane emissions without parallel efforts to improve production efficiency. The latter efforts have much greater mitigating effects than demand-side efforts, and hence should be prioritized in a few developing countries that contribute most of the mitigation potential.

Plain Language Summary

Livestock production represents a third of the global anthropogenic methane emissions nowadays, and the emissions are expected to keep increasing in the future. Using three sets of methodologies and emission factors from two versions of IPCC guidelines (the 2006 and the 2019 refinement), we re-assess global livestock methane emissions over the past two decades and project the emissions till 2050. We find a decreasing trend of methane emission intensity per kg protein produced during the past two decades. We show that promoting balanced, healthy and environmentally sustainable diets in most countries can mitigate future livestock methane emissions, but a larger mitigation potential is projected if the past trend in decreasing emission intensity (i.e., increasing production efficiency) can be continued. We further identify major countries that have the largest mitigation potential through increasing production efficiency.

1 Introduction

Methane is the second-largest anthropogenic driver of current global radiative forcing after CO_2 (Myhre et al., 2013) and all representative concentration pathways (RCPs; (Collins et al., 2013)) show it maintaining this ranking in the future, thus becoming of critical importance in mitigation strategies for attaining low-warming targets. The largest anthropogenic methane source is livestock production, with the main components being the enteric fermentation of ruminants and manure management. Currently, livestock production represents a third of the global anthropogenic methane emissions, comparable to the magnitude of fossil fuels methane emissions (Saunois et al., 2020).

Livestock emissions reported by countries to the UNFCCC are based on common methodologies provided by the IPCC Guidelines (IPCC, 1997, 2000, 2003, 2006, 2019). These guidelines give the possibility to make inventories with various levels of detail, depending on country capability, from the simplest Tier 1 to the most detailed Tier 3, and are periodically updated to reflect the latest expert knowledge on methodologies and emission factors. In parallel, global inventories have been developed to quantify livestock methane emissions for the past few decades (Chang et al., 2019; Crippa et al., 2020; Dangal et al., 2017; EPA, 2012; FAOSTAT, 2020; Janssens-Maenhout et al., 2019; Wolf et al., 2017) or for some specific years (Gerber, Steinfeld, et al., 2013; Herrero et al., 2013). These datasets cover either all livestock types (Crippa et al., 2020; EPA, 2012; FAOSTAT, 2020; Janssens-Maenhout et al., 2019; Wolf et al., 2017) or major categories (Chang et al., 2019; Dangal et al., 2017; Gerber, Steinfeld, et al., 2013; Herrero et al., 2013). Livestock methane emission estimates from inventories differ substantially depending on the choice of the methodological tier, emission factors, and livestock activity data (e.g. from globally available FAOSTAT statistics or from national/regional information). For example, estimates of emissions from enteric fermentation of ruminants in 2000, obtained from different inventories (Chang et al., 2019), range from 60.9 to 86.3 Tg CH_4 yr^{-1}.

The spread between inventory estimates of livestock emissions arises from uncertainties in the intensity of emission per head of livestock, or per unit of production, such as per amount of protein. The IPCC Guidelines (*2019 IPCC Refinement (IPCC, 2019)*) recently updated their Tier 1 methodology for manure management emissions and revised many emission factors for livestock emissions. This major revision impacts global estimated emissions and their intensities. To our knowledge, no study has compared emission intensities derived from different methods at the global scale, although (Gerber, Steinfeld, et al., 2013) produced an assessment of these quantities for a single year (2005) using the Global Livestock Environmental Accounting model (GLEAM).

According to (FAOSTAT, 2020), livestock methane emissions increased by 51.4% between 1961 and 2018, following the increase in ruminant numbers and manure excretion from various livestock categories. This increasing trend will probably continue in the future, given the projected rising demand for livestock products (FAO, 2018). In developing countries, in particular, large increases in livestock production are projected, driven by the increase in per capita income and/or population. The uncertainty in emission intensities induced by the choice of method affects the future projections of livestock methane emissions, and thus climate projections.

In this study, we constructed two new estimates of global livestock methane emissions at a spatial resolution of 5 arc-min for the period 2000-2018, using both a combined Tier 1 and Tier 2 method (hereafter, 2019 Mixed Tiers, MT method) and a Tier 1 method (hereafter, 2019 T1 method) based on the latest IPCC Guidelines *(IPCC, 2019)* Vol. 4, Chapter 10 (Table S1). Further, we derived new estimates of emission intensities, expressed as emissions per kg of protein in products including milk and meat from cattle, buffaloes, goats and sheep, meat from swine, and meat and eggs from poultry, by combining our emission estimates with FAOSTAT production statistics (FAOSTAT, 2020). Finally, we investigated how our update to emission calculations using the latest IPCC Guidelines affects future projections from this sector by the year 2050 for three global socio-economic scenarios (FAO, 2018) and contrasted pathways of livestock production efficiency changes. To facilitate the usage of these new methods for assessing livestock methane emissions, we have provided a full package of R code on Zenodo for producing these two new estimates and associated projections.

2 Materials and Methods

2.1 Estimating livestock CH_4 emissions using mixed IPCC Tier 1 and Tier 2 methods from 2019 Refinement (the 2019 MT method)

The first set of livestock CH_4 emissions was estimated using a mixture of IPCC Tier 1 and Tier 2 methods from the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2019) Vol. 4, Chapter 10. Enteric fermentation CH_4 emissions from dairy cows, meat and other non-dairy cattle, buffaloes, sheep, and goats were estimated using the IPCC Tier 2 method ((IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.21) based on the gross energy intake of livestock (*GE*) and a conversion factor Y_m calculated from regional digestibility of feed (*DE*). For enteric fermentation emissions of other livestock, an adjusted IPCC Tier 1 method ((IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.19), accounting for changes in liveweight, was used to estimate CH_4 emissions from enteric fermentation. Text S1 presents a detailed description of the methods used for estimating enteric fermentation emissions.

Livestock CH_4 emissions from manure management, for all livestock categories, were estimated using an updated IPCC Tier 2 method ((IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.23), which is based on the volatile solids excreted by livestock (*VS*), maximum methane production capacity for manure produced by livestock (B_0), methane conversion factors for each manure management system and each climate region (*MCF*), and the fraction of livestock manure handled using each animal waste management system in each region (*AWMS*). The estimation was made at grid cell level through: 1) distributing country level *VS* into grid cells following the livestock distributions in the GLW3 dataset (see section 2.4), and 2) using *MCF* depending on manure management system and IPCC climate zones. Text S2 presents a detailed description of the methods used for estimating manure management emissions.

2.2 Estimating livestock CH_4 emissions using IPCC Tier 1 methods from the 2019 Refinement (the 2019 T1 method)

Another set of livestock CH_4 emissions was estimated using the IPCC Tier 1 method updated by the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2019) Vol. 4, Chapter 10. For emissions from enteric fermentation, we used the IPCC Tier 1 method ((IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.19) with the total number of livestock population associated with specific CH_4 emission factors for each category of livestock. The total number of livestock population was derived from statistics of stock and producing animals (dairy cows) from FAOSTAT (FAOSTAT, 2020) ("Live Animals" and "Livestock Primary" domains). For dairy cows, meat and other non-dairy cattle and buffaloes, regional CH_4 Tier 1 emission factors from Table 10.11 of (IPCC, 2019) Vol. 4, Chapter 10 were used. For other livestock categories, emission factors from Table 10.10 of (IPCC, 2019) Vol. 4, Chapter 10 were used, and factors for high and low productivity systems were applied for developed, and developing countries respectively.

For emissions from manure management, we used methane emission factors per unit of volatile solid (*VS)* excreted by livestock category, multiplying by the corresponding *VS* excretions. *VS* excretion for each livestock category and productivity system were calculated following Eqn 10.22A of (IPCC, 2019) Vol. 4, Chapter 10. The regional VS excretion rate for each productivity system was obtained from Table 10.13A of (IPCC, 2019) Vol. 4, Chapter 10, and the typical animal mass for each region and productivity system was obtained from Table 10A.5 of (IPCC, 2019) Vol. 4, Chapter 10. We assumed North America, Europe and Oceania to have only high productivity systems, while the regional shares between high ($S_{high,r}$) and low productivity systems ($S_{low,r}$) for Latin America, Africa, Middle East, Asia and India sub-continents were derived according to the regional mean live weights ($Weight_{mean,r}$), and live weights for high ($Weight_{high,r}$) and low productivity systems ($Weight_{low,r}$):

$$S_{high,r} = \frac{Weight_{mean,r} - Weight_{low,r}}{Weight_{high,r} - Weight_{low,r}} \quad (1)$$

where $Weight_{mean,r}$, $Weight_{high,r}$ and $Weight_{low,r}$ were derived from Table 10A.5 of (IPCC, 2019) Vol. 4, Chapter 10. The regional shares between high ($S_{high,r}$) and low productivity systems ($S_{low,r}$) could only be derived for cattle, buffalo, swine and poultry given data availability in Table 10A.5 of (IPCC, 2019) Vol. 4, Chapter 10. For other livestock categories, values representative of high and low productivity systems were applied for developed, and developing countries respectively. The methane emission factors per unit of *VS* by livestock category were derived from Table 10.14 of (IPCC, 2019) Vol. 4, Chapter 10, depending on the climate zone, manure management system and production system. Therefore, we first distributed country-level *VS* into grid cells following the livestock distributions in the GLW3 dataset (see Methods section 2.4), then applied the fraction of livestock manure handled using each animal waste management system in each region (*AWMS*), and calculated the CH_4 emissions using the methane emission factors. The procedure is similar to the IPCC Tier 2 method described above but with: 1) Tier 1 based VS calculation, and 2) default Tier 1 emission factors instead of B_0 and *MCF.*

The *2019 IPCC Refinement (IPCC, 2019)* also introduced new Tier 1a emission factors for enteric fermentation to account for increases in production levels by livestock raised in countries that apply a Tier 1 methodology for estimating enteric CH_4 emissions. For comparison, we additionally estimated another set of CH_4 emissions from enteric fermentation using the Tier 1a method (the 2019 T1a method). For dairy cows, meat and other non-dairy cattle and swine in Latin America, Africa, Middle East, Asia and India sub-continents, regional CH_4 Tier 1a emission factors from Table 10.10 and Table 10.11 of (IPCC, 2019) Vol. 4, Chapter 10 and the regional shares between high ($S_{high,r}$) and low productivity systems ($S_{low,r}$) calculated by Eqn (1) above were used. Due to the limited regional information on the production systems and on their time variation from the IPCC guideline, emissions from other livestock categories are the same as those of the 2019 T1 method, and the shares between high and low productivity systems are time-invariant in our estimate.

2.3 Uncertainty estimates

For estimates of enteric fermentation CH_4 emission from dairy cows, meat and other non-dairy cattle, buffaloes, sheep, and goats using the 2019 MT method, we assessed uncertainties due to the conversion factor Y_m. Following Table 10.12 and 10.13 of (IPCC, 2019) Vol. 4, Chapter 10, a standard deviation of 20% was applied for dairy cows, meat and other non-dairy cattle and buffaloes, while a standard deviation of 13.4% for sheep and 18.2% for goats were applied. Table 10.10 of IPCC, 2006 Vol. 4, Chapter 10 gives an uncertainty of ± 30-50% for the Tier 1 emission factors (validated also by (IPCC, 2019) Vol. 4, Chapter 10), which is defined as 1.96 times of the standard deviation of the mean. For uncertainty estimates of enteric fermentation CH_4 emission from other livestock using the 2019 MT method, and from all livestock using the 2019 T1 method, we applied a median standard deviation of 40%/1.96=20.4% (using 40% as a median of ± 30-50%). For all uncertainty estimates of manure management CH_4 emission using the 2019 MT and 2019 T1 methods, we applied a standard deviation of 30%/1.96=15.3%, as an uncertainty of ± 30% was given for methane conversion factors (*MCF*) used in the 2019 MT method (Table 10.17 of (IPCC, 2019) Vol. 4, Chapter 10), and also for emission factor used in the 2019 T1 method (Table 10.14 and 10.15 of (IPCC, 2019) Vol. 4, Chapter 10). Uncertainties were derived from Monte Carlo ensembles (n = 1000) from the range of uncertainties reported for the above parameters and / or emission factors used in the calculations. In the Monte Carlo ensembles, we assumed independent uncertainties for each livestock category, and for methane emissions from enteric fermentation and manure management.

2.4 Estimating gridded livestock CH_4 emissions

The Gridded Livestock of the World v3.0 dataset (hereafter referred to as GLW3; (Gilbert et al., 2018)) provides global spatial distribution data for cattle, buffaloes, horses, sheep, goats, swine, chickens and ducks in the year 2010 at a spatial resolution of 5 arc min. We estimated the gridded enteric fermentation emissions by distributing country emissions into grid cells following the GLW3 livestock distribution data (data produced from dasymetic (DA) model in (Gilbert et al., 2018) were used; Table S2). We assumed no changes in the distribution of livestock during the period 2000-2018 in the gridded products, as time-variable livestock distribution data, to our knowledge, is not available at the global scale. Gridded enteric fermentation emission in grid cell i of country j for livestock category k at year m ($F_{CH4-Enteric,i,j,k,m}$) was calculated as:

$$F_{CH4-Enteric,i,j,k,m} = F_{CH4-Enteric,j,k,m} \times \frac{D_{GLW3,i,j,k} \times A_i}{\sum_{i \in j} D_{GLW3,i,j,k} \times A_i} \quad (2)$$

where $F_{CH4-Enteric,j,k,m}$ is the total enteric fermentation emission of country j for livestock category k in year m as calculated above, $D_{GLW3,i,j,k}$ is livestock density for category k in grid cell i of country j from GLW3 (unit: head km^{-2}), and A_i is the land area of grid cell i. For livestock categories that were not represented in GLW3 (i.e., asses, camels, mules, and llamas), the spatial distribution of cattle was used.

The same method was used to distribute country-level *VS* (for both Tier 1 and Tier 2 methods), which then were used to estimate livestock CH_4 emissions from manure management at the grid cell level.

2.5 Revisiting emission intensities for livestock production and individual livestock

For economic output, we derived the methane emission intensities (including enteric fermentation and manure management emissions) per kg protein produced for category k in country j and year m ($EF_{protein,j,k,m}$; unit: kg CH_4 per kg protein) as:

$$EF_{protein,j,k,m} = \frac{F_{CH4-Enteric,j,k,m} + F_{CH4-Manure,j,k,m}}{P_{protein,j,k,m}} \quad (3)$$

where $P_{protein,j,k,m}$ is the protein produced by livestock category k in country j and year m, and is calculated as:

$$P_{protein,j,k,m} = P_{meat/milk,j,k,m} \times c_{meat/milk,k} \quad (4)$$

where $P_{meat/milk,j,k,m}$ is the meat and/or milk production (unit: kg) by livestock category k in country j and year m (production quantity from (FAOSTAT, 2020) "Livestock Primary" domain), and $c_{meat/milk,k}$ is the protein content of the meat or milk of livestock category k (unit: kg protein per kg meat/milk). Here, we used a protein content of 0.158 kg protein per kg bovine carcass weight (cattle and buffaloes), 0.141 kg protein per kg sheep carcass weight, 0.134 kg protein per kg goat carcass weight, 0.131 kg protein per kg pig carcass weight, 0.143 kg protein per kg poultry carcass weight, 0.124 kg protein per kg eggs, and 0.033 kg protein per kg milk. The protein content of meat and carcass weights were derived from Table 9.1 of the GLEAM v2.0 Documentation (FAO, 2017), and the protein content of milk was calculated as 1.9 + 0.4 * %Fat (*Milk PR%* in (IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.33) with a typical %Fat of 3.5%

(see (IPCC, 2019) Vol. 4, Chapter 10, Table 10A.1 – 10A.3). It is acknowledged that meat and other non-dairy cattle and buffaloes are used as draft animals in many developing regions, especially in Asia. Hence, for developing countries, we also calculated the methane emission intensities per kg of protein excluding emissions from draft animals. Emissions from draft animals ($F_{CH_4-draft,j,k,m}$) were calculated with the IPCC Tier 2 method ((IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.21) using the *GE* of draft animals (see Text S3 for the calculation of *GE*).

The enteric fermentation emission intensities of country *j* for livestock category *k* (here, cattle, sheep, goats, and buffaloes) in year *m* ($EF_{head-Enteric,j,k,m}$; unit: kg CH_4 per head) are calculated as:

$$EF_{head,j,k,m} = \frac{F_{CH4-Enteric,j,k,m}+F_{CH4-Manure,j,k,m}}{N_{head,j,k,m}} \quad (5)$$

where $N_{head,j,k,m}$ is the number of livestock (unit: head) for category *k* in country *j* and year m. For dairy cows, $N_{head,j,cows,m}$ is the number of producing animals obtained from the (FAOSTAT, 2020) "Livestock Primary" domain; for meat and other non-dairy cattle, $N_{head,j,other\ cattle,m}$ is the total stock (the (FAOSTAT, 2020) "Live Animals" domain) minus the number of dairy cows; for sheep, goats and buffaloes, $N_{head,j,k,m}$ is the total stock from the (FAOSTAT, 2020) "Live Animals" domain; for swine, $N_{head,j,swine,m}$ is the slaughtered number from the (FAOSTAT, 2020) "Livestock Primary" domain, given their life span is usually shorter than one year.

2.6 Projecting livestock methane emissions

Future livestock methane emissions depend on changes in livestock production (usually expressed in kg of protein) and emission intensities per livestock production (i.e., kg CH_4 per kg protein produced). Here, we projected livestock methane emissions forward until 2050, using the projected relative changes in protein production from major livestock categories under different socio-economic scenarios, and assuming different pathways of emission intensity changes. Three socio-economic scenarios: Business As Usual (BAU), Stratified Societies (SS), and Toward Sustainability (TS), and two pathways where we made contrasted assumptions about production efficiency changes: constant emission intensity and improving efficiency (i.e., decreasing emission intensity) were used. Future livestock CH_4 emissions for product *p* (milk or meat) of livestock category *k* in country *j* and year *m* under socio-economic scenario *s* and emission intensity change pathway *w* during the period 2012-2050 were calculated as:

$$F_{CH_4,j,k,m,s,w} = F_{CH_4-prod,j,k,2012} \times P_{rel,j,k,m,s} \times EF_{rel-protein,j,k,m,w} + F_{CH_4-draft,j,k,2012} \times I_{rel-draft,j,k,m,w} \quad (6)$$

where $F_{CH_4-prod,j,k,2012}$ and $F_{CH_4-draft,j,k,2012}$ are the methane emissions from livestock category k in country j and year 2012 used for production and for draft power, respectively (draft animals are meat and other non-dairy cattle and buffaloes used as draft power in developing countries only; see section 2.5 for details of the emissions of draft animals); $P_{rel,j,k,m,s}$ is the change in protein production for livestock category k in country j and year m relative to 2012 under socio-economic scenario s; $EF_{rel-protein,j,k,m,w}$ is the change in production efficiency (emission intensity per livestock production; $EF_{protein,j,k,m}$) for livestock category k in country j and year m relative to the 2012 value under emission intensity change pathway w; $I_{rel-draft,j,k,m,w}$ is the change in the number of draft animals for livestock category k in country j and year m relative to the 2012 value under production efficiency change pathway w. We used the year 2012 as the start of the projection since the FAO projections for livestock production started in 2012 (FAO, 2018). For livestock other than cattle, buffaloes, sheep, goats, pigs and poultry, we assumed dynamic emissions to have their historical values during 2012-2018 and constant emissions their values in 2018 for the period of 2019-2050.

FAO (FAO, 2018) provides country level changes in productivity (raw milk and meat) and herd size for cattle, buffaloes, sheep, goats, pigs and poultry under three socio-economic scenarios: Business As Usual (BAU), Stratified Societies (SS), and Toward Sustainability (TS). Data were provided for the year 2012, 2030, 2035, 2040, and 2050, and linear changes of both productivity (raw milk and meat) and herd size were assumed in this study. Given the fact that herd sizes for dairy cows and meat and other non-dairy cattle were not provided separately by FAO, we assumed that the relative changes in herd sizes for dairy cows and meat and other non-dairy cattle are the same as the changes in cattle. Changes in protein production for livestock category k in country j and year m relative to 2012 under socio-economic scenario s ($P_{rel,j,k,m,s}$) were then calculated as:

$$P_{rel,j,k,m,s} = \frac{\sum_p Y_{p,j,k,m,s} \times H_{j,k,m,s} \times C_{protein,p,j}}{\sum_p Y_{p,j,k,2012,s} \times H_{p,j,k,2012,s} \times C_{protein,p,j}} \quad (7)$$

where $Y_{p,j,k,m,s}$ is the productivity (unit: kg animal^{-1} yr^{-1}) for product p (milk or meat) of livestock category k in country j and year m under socio-economic scenario s; $H_{j,k,m,s}$ is the herd size (unit: head) for livestock category k in country j and year m under socio-economic scenario s; and $C_{protein,p,j}$ is the protein content (unit: kg protein (kg milk/meat^{-1}) of product p

(milk or meat) of livestock category *k* (see section 2.5). For buffaloes, sheep and goats, protein from milk and meat were summed to obtain the total protein production changes.

As outlined above, two variant pathways of production efficiency changes (i.e., methane emission intensity changes per kg protein produced) were assumed: "*constant intensity*" and "*improving efficiency*".

Under the "*constant intensity*" pathway, both $EF_{rel-protein,j,k,m,w}$ and $I_{rel-draft,j,k,m,w}$ were assumed to be 1, which means no changes in the methane emission intensities per livestock production ($EF_{protein,j,k,m}$) and no reduction in the numbers and methane emissions of draft animals in developing countries.

We found decreasing trends in emission intensity for major livestock categories during the past two decades, due to increasing production efficiency. Based on this finding, we constructed our "*improving efficiency*" pathway, assuming a continuing decrease of emission intensity. Under this pathway, the future will see 1) a continuation of the country-specific historical trends of the development of GDP per capita for countries showing decreasing emission intensity during the past two decades; and 2) constant emission intensities for countries that experienced no change or an increasing emission intensity in the past two decades. For each country, a regression between the emission intensity per kg protein over four periods (2000-2004, 2005-2009, 2010-2014, 2014-2017) and the corresponding GDP per capita was calculated to derive the country-specific trends of emission intensities from projections of GDP per capita. Note that the last period only contains four years because GDP per capita from (FAOSTAT, 2020) is only available until 2017. We calculated the regression for these periods, rather than on an annual basis, to avoid the impact of potentially strong inter-annual variation of the emission intensities due to temporary effects such as livestock epidemics or economic shocks. We calculated the emission intensity per kg protein production for livestock category *k* in country *j* and year *m* relative to 2012 $EF_{rel-protein,j,k,m,s}$ as:

$$EF_{rel-protein,j,k,m,s} = \frac{EF_{protein,j,k,m,s}}{EF_{protein,j,k,2012}} \quad (8)$$

Where $EF_{protein,j,k,2012}$ is the emission intensity per kg protein production for livestock category *k* in country *j* in 2012; and $EF_{protein,j,k,m,s}$ is the future emission intensity per kg protein for livestock category *k* in country *j* in year *m* under socio-economic scenario *s*, which is calculated as:

$$EF_{protein,j,k,m,s} = a_{j,k} \times GDPperCapita_{j,s} + b_{j,k} \quad \text{, when } a_{j,k} < 0 \quad (9)$$

where $GDPperCapita_{j,s}$ is the GDP per capita in country j in year m under socio-economic scenario s given by (FAO, 2018); $a_{j,k}$ and $b_{j,k}$ are the regression coefficients representing the trend and intercept, respectively, from the regression between the emission intensity per kg protein over four periods (2000-2004, 2005-2009, 2010-2014, 2014-2017) and the corresponding GDP per capita during the historical period. Equation (9) only applies to countries showing decreasing emission intensities during the past two decades (i.e., $a_{j,k} < 0$). For countries with no change or increasing emission intensities in the past two decades (i.e., $a_{j,k} \geq 0$), a constant emission intensity is applied. Furthermore, to avoid unrealistically low emission intensities in the future, we set a minimum emission intensity per kg protein for each livestock category k ($EF_{protein,k,min}$) as a threshold. This is derived as the 0.05-quantile of the emission intensities per kg protein from all countries with more than 100 tonnes of protein production per year for that livestock category during the most recent 5-year period (2014-2018). The thresholds varied with the different methods used (the 2019 MT, the 2019 T1, or the 2006 T1 method) and are listed in Table S3. Figure S17 provides the number of countries that reach the minimum emission intensity per kg protein for each livestock category by 2050, and the protein production of these countries under the "*improving efficiency*" pathway.

Additional sensitivity pathway of production efficiency changes (i.e., methane emission intensity changes per kg protein produced) was considered: 1) a continuation of the country-specific trend of the development of GDP per capita for countries showing decreasing emission intensity during the past two decades; and 2) a continuation of the country-specific trend of the development of GDP per capita for countries showing increasing emission intensity during the past two decades. For countries showing decreasing emission intensities, same as the "*improving efficiency*" pathway, we set a minimum emission intensity per kg protein for each livestock category k ($EF_{protein,k,min}$) as a threshold to avoid unrealistically low emission intensities. Similarly, to avoid unrealistically low emission intensities for countries showing increasing emission intensities, we set a maximum emission intensity per kg protein for each livestock category k ($EF_{protein,k,max}$) as a threshold. This is derived as the 0.95-quantile of the emission intensities per kg protein from all countries with more than 100 tonnes of protein production per year for that livestock category during the most recent 5-year period (2014-2018). The thresholds varied with the different methods used (the 2019 MT, the 2019 T1, or the 2006 T1 method) and are listed in Table S4.

3 Estimated livestock methane emissions and recent changes

The magnitude of global livestock methane emissions estimated for 2010 using our 2019 MT method (122 ± 13 Tg CH_4 yr^{-1}; Fig. 1a) is consistent with that estimated by EDGAR v4.3.2 (Janssens-Maenhout et al., 2019) (115 Tg CH_4 yr^{-1}), EDGAR v5.0 (Crippa et al., 2020) (113 Tg CH_4 yr^{-1}), and (Wolf et al., 2017) (118 ± 18 Tg CH_4 yr^{-1}). All these datasets consider trends in liveweight and/or productivity of livestock (Table S1). They are all higher than those of the most recent FAOSTAT (FAOSTAT, 2020) data (104 Tg CH_4 yr^{-1}) and the U.S. EPA dataset (EPA, 2012) (103 Tg CH_4 yr^{-1}). FAOSTAT used default 2006 T1 emission factors, while the U.S. EPA dataset (EPA, 2012) used 2006 T1 supplemented by country-reported inventory data. We found a higher estimate using the new 2019 T1 method (130 ± 14 Tg CH_4 yr^{-1}), which is explained by higher emission factors (Table S4) for both enteric fermentation and manure management, and changes in the method used for estimating manure management to reflect the latest livestock characteristics. Global estimates using the 2019 T1a method (see section 2.2) are nearly the same as that using the 2019 T1 method (< 0.2% differences; Table S2) with differences ranging from 0.01% to 3.4% in regional estimates, thus we do not discuss the emissions using the 2019 T1a method hereafter. It should be kept in mind that it is a purely academic exercise to show the effect of the different Tiers on total livestock methane emissions. As emphasized in the *2019 IPCC Refinement (IPCC, 2019)* Vol.4 Chapter 10 Section 10.3.1, "the Tier 2 method should be used if enteric fermentation is a key source category for the animal category that represents a large portion of the country's total emissions", and "the Tier 1 method is likely to be suitable for most animal species in countries where enteric fermentation is not a key source category, or where enhanced characterization data are not available".

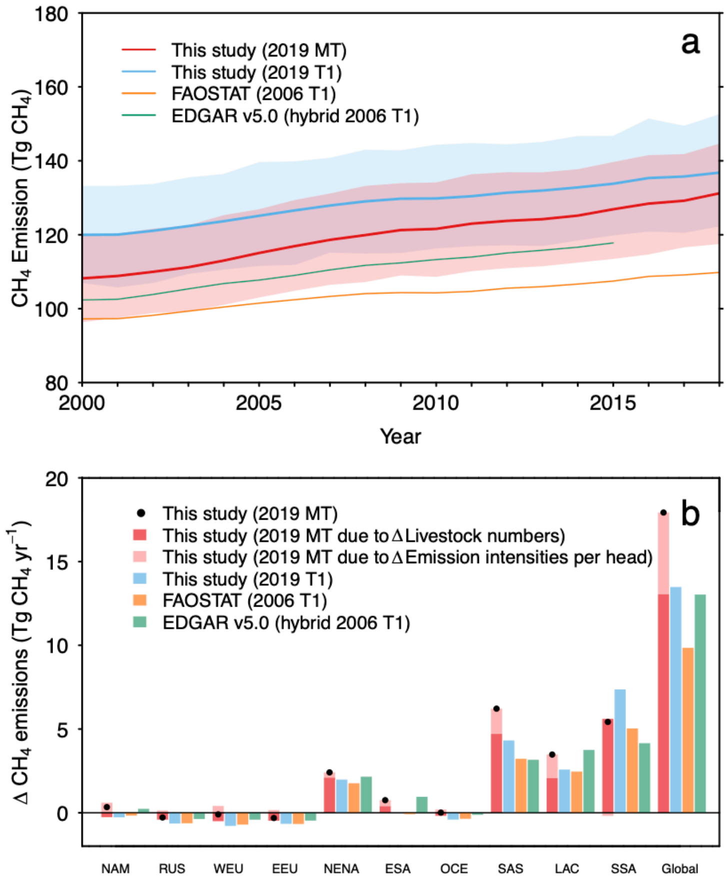


Figure 1. Global livestock methane emission changes from 2000 to 2018 (a), and global and regional changes in livestock methane emissions between the periods 2000-2004 and 2014-2018 (b). The shaded area indicates the 1-sigma standard deviation of the estimates using the 2019 MT and the 2019 T1 methods in this study. Uncertainties were derived from Monte Carlo ensembles (n = 1000) from the range of uncertainties reported for various parameters and/or emission factors used in the calculations (see Methods). In the Monte Carlo ensembles, we assume independent uncertainties for each livestock category, and for methane emissions from enteric fermentation and manure management. Contributions due to the changes in livestock numbers and to the changes in emission intensities per head are shown separately in (b). For EDGAR v5.0, the changes in (b) are between the periods 2000-2004 and 2014-2015. Regions are classified following the definition of the FAO Global Livestock Environmental Assessment Model (GLEAM): NAM, North America; RUS, Russia; WEU, western Europe; EEU, eastern Europe, NENA, Near East and North Africa; EAS, eastern Asia; OCE, Oceania; SAS, south Asia; LAC, Latin America and Caribbean; SSA, Sub-Saharan Africa.

Globally, we found that 88% to 91% of the livestock methane emissions come from enteric fermentation (Table S2), and are dominated by cattle, sheep, goats and buffaloes. The share of the total emissions attributed to different livestock categories varies between regions, while the pattern are similar between our two estimates and (FAOSTAT, 2020) (Figure S1). There are significant regional differences in livestock methane emissions between the four datasets (Figure S2), mainly due to the revised Tier 1 enteric fermentation emission factors used in the 2019 Guidelines and the Tier 2 method (the 2019 MT in Figure S2). We also established gridded livestock methane emission fields by downscaling our national totals (Figure S3), which can provide valuable high-resolution prior information for atmospheric inverse studies. These emission maps show higher livestock methane emission intensity per area of land, compared to EDGAR v5.0 (Crippa et al., 2020), in the Sahel countries, Eastern Africa, South Asia, Eastern China, and Northeast Australia, but lower values in Europe and Latin America (Figure S4a,c).

Temporal changes of livestock methane emissions in the last two decades or so (2000-2018) were quantified as the difference between the values in 2000-2004 and those in 2014-2018. We found that global emissions increased by +10 to +18 Tg CH_4 yr^{-1} between these two periods (Fig. 1b), the largest increase being found with our 2019 MT method and the lowest with FAOSTAT. The 2019 MT method accounts for changes in productivity through varying liveweight and production (see Methods), and thus allows attribution of the increase to changes in livestock numbers versus emission intensities per head. We estimated that 73% of the increase in global emissions between the two periods is explained by increasing livestock numbers, the remaining 27% due to increasing emission intensities per head in most regions (i.e., larger mean body size, and higher meat and milk production per head).

Regional analysis gives however a more nuanced picture of the role of these two drivers (Fig. 1b; Figure S5). The most noticeable increases in emissions between the two periods were found in South Asia (+3 to +6 Tg CH_4 yr^{-1}) and Sub-Saharan Africa (+4 to +7 Tg CH_4 yr^{-1}; see also Figure S6). For the 2019 MT emission estimates, 24% of the increase in South Asia during the period 2000-2018 can be attributed to changes in emission factors per head, while the entire increase in emissions in Sub-Saharan Africa is explained by rising livestock numbers. Moderate increases were found in Latin America, Near East and North Africa, and East and Southeast Asia. On the other hand, estimated emissions decreased in the developed regions between the two periods when using the Tier 1 methods, while estimates using the 2019 MT method showed slightly increased emissions in North America and almost constant emissions in other developed regions as increasing yield and liveweight were accounted for.

Dairy cows (+2 to +6 Tg CH_4 yr^{-1}) and meat and other non-dairy cattle (+2 to +4 Tg CH_4 yr^{-1}) in developing countries are the major contributors to the increase of livestock methane emissions during 2000-2018, followed by buffaloes in South Asia (+2 to +3 Tg CH_4 yr^{-1}; Figure S5). Sheep in Near East and North Africa, East and Southeast Asia, and Sub-Saharan Africa, goats in Sub-Saharan Africa, and swine in East and Southeast Asia also contributed significantly to the regional emission increases (Figure S5).

4 Revised estimates of emission intensities for livestock protein production and the recent changes

We analysed estimates of emission intensities per kg protein production for each livestock category, as derived from: i) protein production figures given by livestock production commodities statistics from (FAOSTAT, 2020) and their protein content obtained from the GLEAM model (FAO, 2017), and ii) emissions estimates using our new 2019 MT and 2019 T1 calculations, and the 2006 T1 method (i.e., data from (FAOSTAT, 2020)).

During 2014-2018, methane emission intensity per kg of protein produced, is the lowest for poultry meat and eggs (0.02-0.08 kg CH_4 per kg protein at global scale) followed by swine meat (0.3-0.5 kg CH_4 per kg protein), because of negligible enteric fermentation emissions from monogastric (Fig. 2). Ruminant meats have the highest methane emission intensity per kg of protein among major livestock products. At the global scale, we estimated intensities of 3.5-4.2 kg CH_4 per kg protein for beef cattle, 3.8-5.5 kg CH_4 per kg protein for goats and 4.1-5.0 kg CH_4 per kg protein for sheep. Higher methane emission intensities of goats and sheep meat than that of beef are mainly due to the low digestibility of feed (low-quality roughage). On the other hand, it means that goats and sheep depend less on human-edible feed and avoid food-feed competition (Mottet et al., 2017; Van Zanten et al., 2018). Cow milk production has a global average methane emission intensity of 1.0-1.2 kg CH_4 per kg protein, lower than meat production because of 1) the higher protein production efficiency of milk compared with meat and 2) a more protein-rich and digestible diet given to milking cows. Buffaloes are mostly used as draft animals in Asia with only a small fraction of them used for meat and milk production. Excluding the emissions from draft animals, the global average methane emission intensity for buffalo meat and milk, which is essentially only produced in Asia and some European countries, ranges from 2.0-3.0 kg CH_4 per kg protein. Accounting for all the above seven major protein-producing livestock, globally the weighted average emission intensity ranges from 1.0-1.3 kg CH_4 per kg protein (Fig. 2).

For ruminant products, intensity differences between regions are mainly due to differences in productivity, themselves explained by differences in diet and/or grazing intensity, with a less nutritious/digestible diet (e.g., low protein and high fiber) and/or more extensive grazing (ruminants only) leading to higher emissions. However, for swine and poultry, it is the management of manure that dominates methane emissions, and regional differences in emission intensities depend on climate (with warmer climate enhancing emissions) and the manure management system. The choice of a method to calculate emissions, affects the global and regional emission intensity per kg protein for each livestock product, with the strongest differences being for poultry (Fig. 2). The differences in intensities between regions and between livestock categories can also have different signs across the different methods (i.e., not always higher or lower intensities from one method compared to another).

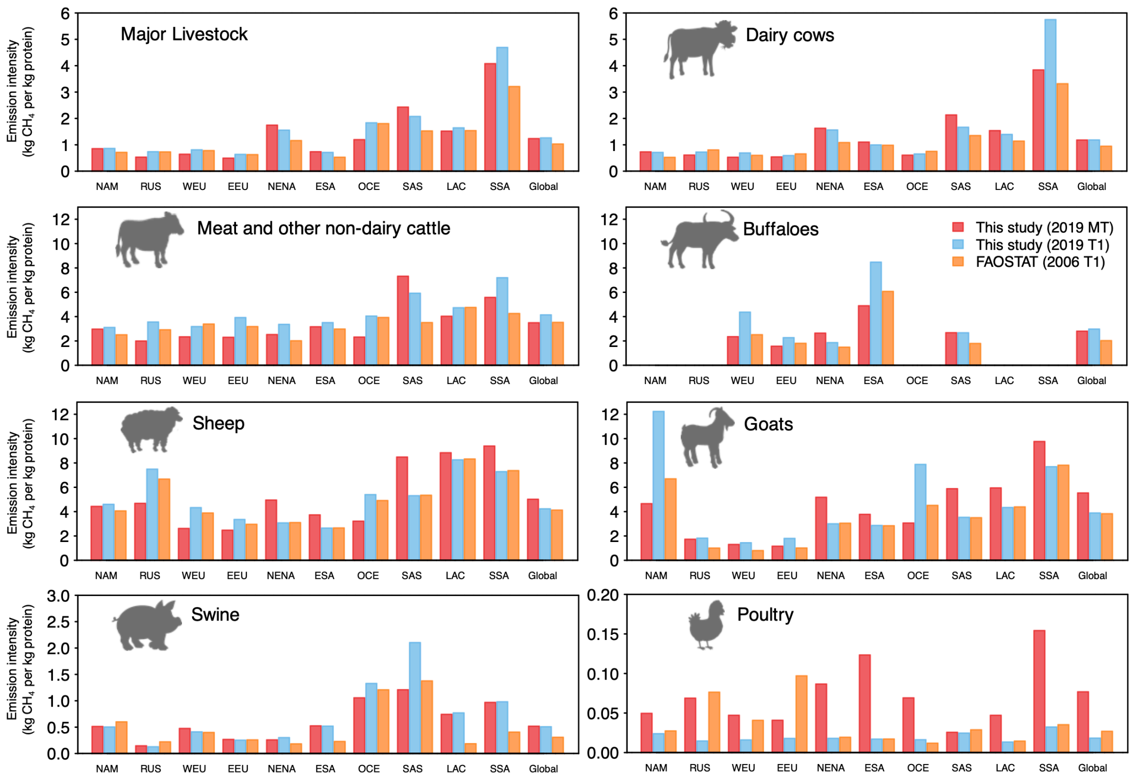


Figure 2. Livestock CH_4 emission intensities (including enteric fermentation and manure management emissions) per kg of protein produced during the period 2014-2018 for major livestock categories. Emissions from draft animals were excluded from the calculation. Regions are classified following the definition of the FAO Global Livestock Environmental Assessment Model (GLEAM): NAM, North America; RUS, Russia; WEU, western Europe;

EEU, eastern Europe, NENA, Near East and North Africa; EAS, eastern Asia; OCE, Oceania; SAS, south Asia; LAC, Latin America and Caribbean; SSA, Sub-Saharan Africa.

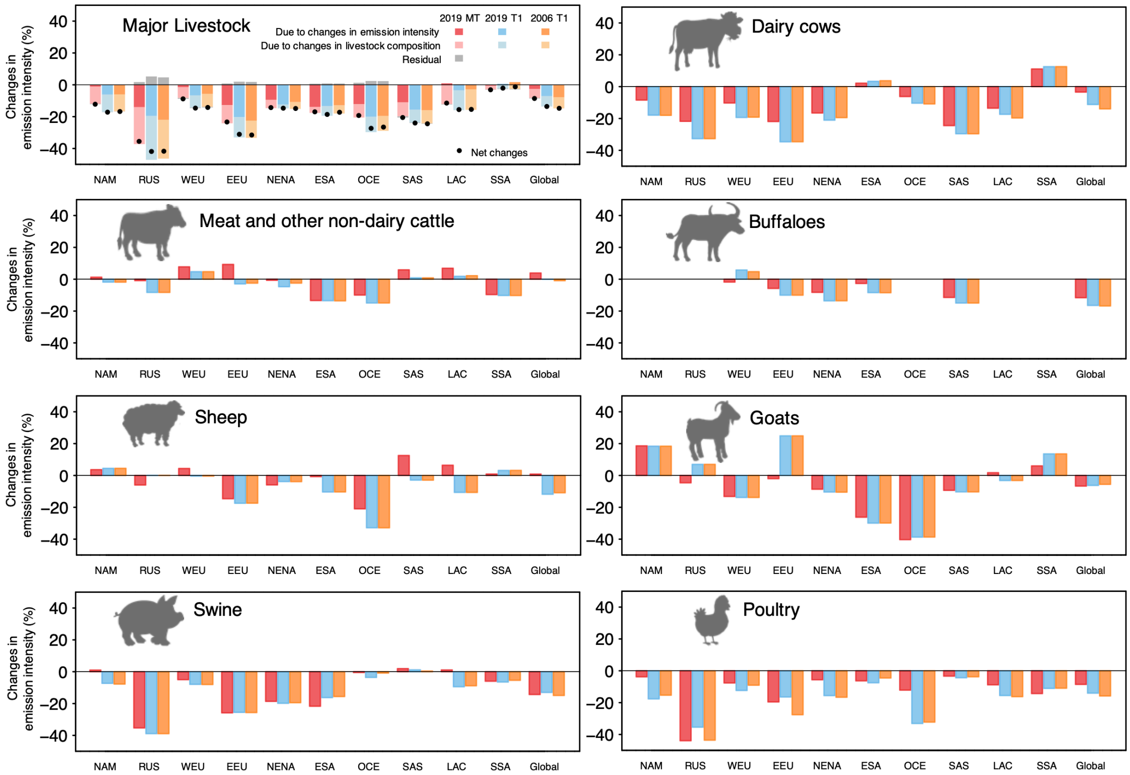


Figure 3. Relative changes in livestock CH_4 emission intensities per kg of protein produced from 2000-2004 to 2014-2018 for major livestock categories. For a livestock category, the changes between the two periods were expressed as percentage change of emission intensities during 2014-2018 compared to that during 2000-2004. For the seven major livestock categories together, the net changes in emission intensities (black points) were attributed: 1) to the changes due to the changes in emission intensity of each livestock category; 2) to the changes in the livestock composition; and 3) to the residual between the net changes and the sum of 1) and 2). Emissions from draft animals were excluded from the calculation.

During the past two decades, the emission intensity decreased for most livestock categories at the global scale (but not in all countries), indicating an increasing protein-production efficiency (Fig. 3). The emission intensity for meat and other non-dairy cattle, however, shows slight changes. Using the 2019 MT method, globally the weighted average emission intensity of the seven major protein-producing livestock categories decreased by 9% (Fig. 3). The attribution shows that 30% of the changes are due to changes in the emission per kg protein of different livestock categories, while 66% are due to changes in the mixture of livestock categories. The latter comes from the faster increase in protein from poultry with low emission intensities (+51% between 2000-2004 and 2014-2018) than that from ruminants with high emission intensities (+28% between 2000-2004 and 2014-2018; Figure S7). Using the 2006 or 2019 T1 methods, however, larger decreases in the weighted average emission intensity were estimated (around 14%), and they were mainly attributed to changes in the emission intensities per kg protein of different livestock categories (53%).

It is noteworthy that the intensity changes obtained using the 2019 MT method usually show smaller decreases or even increases in emission intensities per protein production than the estimates using the other two methods (Fig. 3). The estimates using the 2006 or 2019 T1 methods consider the fixed emissions per head of livestock, and underestimate the increasing trend of total emissions caused by the increasing yield and liveweight (Fig. 1b). Thus, with an increasing trend of protein production per head of livestock in reality, using the 2006 or 2019 T1 methods partly overestimates the decreasing trend from emission intensities per protein production. Our results highlight the key role of accounting for methane emissions due to productivity and liveweight changes (as in the 2019 MT method) in capturing the temporal changes in the emission intensities per protein production.

The changes in the weighted average emission intensity vary between regions (Fig. 3). The largest relative decrease was found in Russia, followed by Eastern Europe, South Asia and Oceania. In contrast, Sub-Saharan Africa only shows a slight decrease (3%). In North America, Western Europe, Russia, and Latin America, the decrease is mainly (>66%) due to changes in the mixture of livestock categories, with faster increases in protein from pigs and poultry with low emission intensities than in ruminants with high emission intensities. In the Near East and North Africa, Eastern and Southeast Asia, and Oceania, the decrease is mainly (>63%) due to the changes in the emission per kg protein of different livestock categories. These widespread decreases in regional emission intensities observed in the past two decades imply the potential of improving production efficiency to mitigate livestock emissions.

5 Future projections of livestock methane emissions

Combining category-specific methane emission intensities per kg protein (dairy cows, meat and other non-dairy cattle, buffaloes, sheep, goats, swine and poultry) and the FAO's projections on future livestock production (FAO, 2018), we projected future livestock methane emissions up to 2050 under different socio-economic scenarios (see Methods).

Assuming constant emission intensities, as in the period 2014-2018 (referred to as "Constant intensity" pathway), and keeping emission intensities values from the new 2019 MT method, the global livestock methane emissions were projected to increase by 51-54% from 2012 to 2050 under different socio-economic scenarios (FAO, 2018) (i.e., reach 186-191 Tg CH_4 yr^{-1} in 2050; Fig. 4a). The relative increases are similar with the 2006 T1 (46-52%) and 2019 T1 methods (51-53%; Fig. 4b-c) because of the same changes in protein production from (FAO, 2018) and constant emission intensities in this projection.

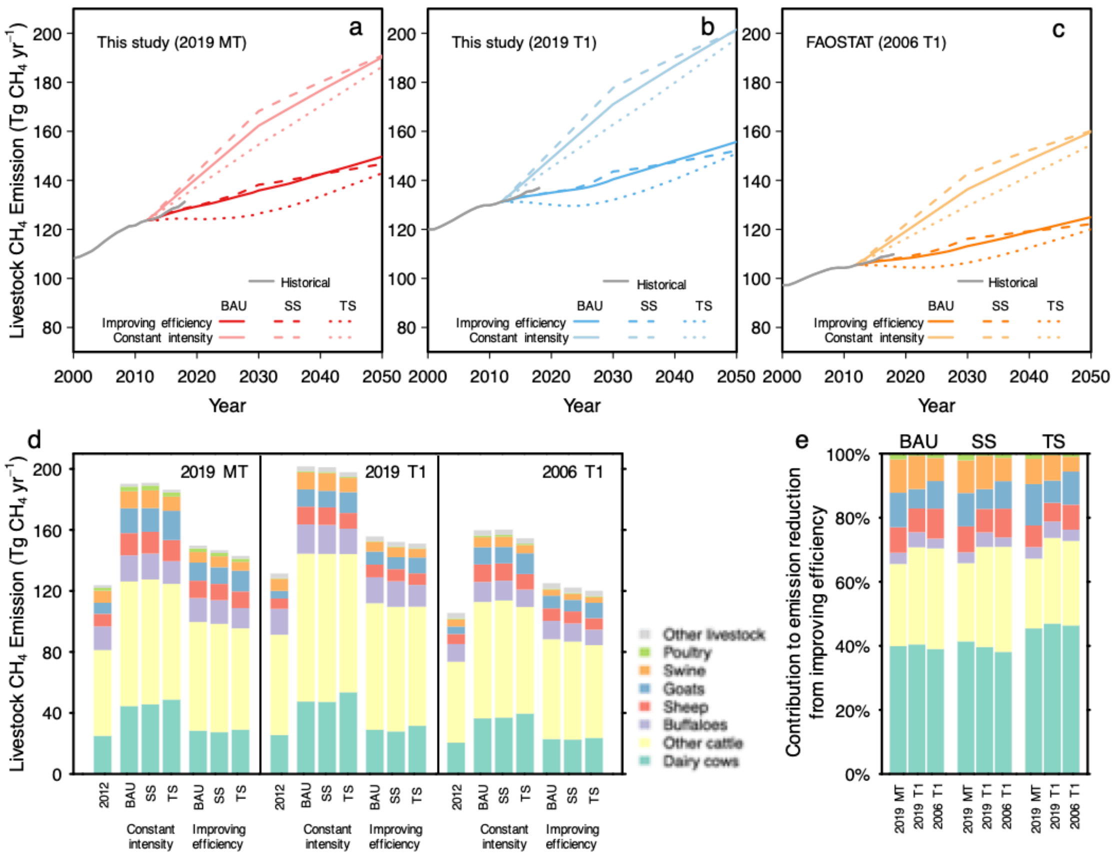


Figure 4. Projections of global livestock methane emissions under different socio-economic scenarios and emission intensity change pathways (a-c), emission contribution of each livestock category (d), and each livestock category's share of contribution to emission reduction from improving efficiency (e). Socio-economic scenarios: Business As Usual (BAU), Stratified Societies (SS), and Toward Sustainability (TS). Emission intensity

change pathways: Constant emission intensity per kg protein and improving efficiency with decreasing emission intensity per kg protein.

For the past two decades, we have shown in the previous section that methane emission intensity per kg protein for various livestock categories in each region has been observed to decrease (Fig. 3; Figure S8) following the increases in productivity. The changes in productivity could be empirically related to the development of gross domestic product (GDP) per capita. Country-specific past trends in emission intensity for major livestock categories were estimated from regressions between the emission intensity and GDP per capita (see section 2.6, and Figure S9 as examples). In the "Improving efficiency" pathway (i.e., decreasing emission intensity per kg protein), we assumed: 1) a continuation of the country-specific past trend with the development of GDP per capita for countries showing decreasing emission intensity during the past two decades; and 2) constant emission intensity for countries with no changes or increasing emission intensity in the past (Figure S8). We find that this reasonable scenario of "Improving efficiency" (e.g., Figure S10) can reduce future livestock emissions by a large amount compared to baselines where intensity is constant in the future (Fig. 4d). Global livestock methane emissions were projected to increase by only 15-21% from 2012 to 2050 using the new 2019 MT method (reach 143-150 Tg CH_4 yr^{-1} by 2050; Fig. 4a). Similar relative increases were estimated using the 2006 T1 (15-19%) and 2019 T1 methods (14-18%; Fig. 4b-c). Additional sensitivity projections were conducted with a continuation of the country-specific past trend with the development of GDP per capita allowing both increasing or decreasing emission intensity in the future (see Methods). Global livestock methane emissions were projected to increase from 2012 to 2050 by 34-35%, 30-33%, and 31-33% using the 2019 MT, the 2019 T1, and the 2006 T1 methods, respectively (Figure S11).

The higher emission intensities per kg protein from either the 2019 MT or the 2019 T1 method, compared to the 2006 T1 method, led to projections of larger livestock methane emissions in the future, for a given scenario of livestock numbers and production from (FAO, 2018). The projections using the new 2019 MT and 2019 T1 methods are 18-21% and 24-28% higher, respectively, than that given by the 2006 T1 method (Fig. 4a-c). Moving to the methodology of the *2019 IPCC Refinement(IPCC, 2019)* is important, as the differences can be substantial, particularly in regions such as Sub-Saharan Africa, Near East and North Africa, and South Asia, where large positive trends on livestock production (Figure S12) and emissions (Figure S13) are projected in the future scenarios. In the SSP database (Riahi et al., 2017) (https://tntcat.iiasa.ac.at/SspDb/), the projections for greenhouse gas emissions by Integrated Assessment Models (IAMs) were first harmonized for a base year of 2015 to the historical inventory from FAOSTAT. Our results suggest that using historical emissions from FAOSTAT as a reference in the IAMs underestimates future emissions. The updated historical emissions by the 2019 MT and 2019 T1 methods in this study could be used as references in the IAMs. We further provided alternative pathways on emission intensity per kg protein production based on country-specific past trend with the development of GDP per capita. They can be considered as supplementary scenarios of emission intensities for IAMs projections.

6 The key role of production efficiency changes in emission mitigation

Global livestock methane emissions under the Toward Sustainability (TS) scenario were projected to be lower than those under the Business As Usual (BAU) and Stratified Societies (SS) scenarios, while we found that the differences in the projections among different socio-economic scenarios are small (Fig. 4a-c). This is due to the similar global ruminant protein production (as dominant methane emitters) across the three socio-economic scenarios by 2050 (Figure S12). At the same time, the continuation of the past decreases in emission intensity provides large potential to mitigate livestock emissions (Fig. 4a-c). The estimated mitigation can be mainly contributed by the efficiency change for dairy cows (contributing 38-46% of the total reduction by 2050; Fig. 4e and Figure S14) followed by meat and other non-dairy cattle (contributing 22-33% of the total reduction by 2050). Sheep, goats, and swine also contributed a significant share of the emission reduction ranging between 5% to 13% of the total reduction by 2050.

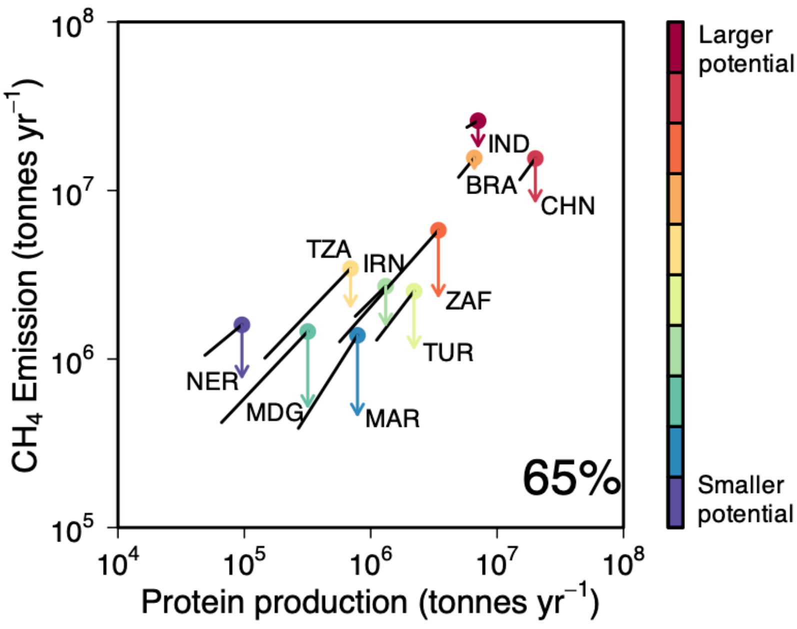


Figure 5. Projections on the increase in protein production, methane emission, and the effects of improving efficiency on reducing livestock methane emissions for all livestock under BAU scenarios, resulting from the 2019 MT method. The black lines indicate the protein production (x-axis) and methane emission (y-axis) from 2012 (start of black lines) to 2050 (dots). The arrows indicate the emission reduction potential by 2050 due to improving efficiency compared to the baseline where emission intensity is constant in the future. Results for the top ten countries/areas with the largest mitigation potential for all livestock were presented, with their ISO3 country codes (http://www.fao.org/countryprofiles/iso3list/en/) annotated near the dots or arrows. The red-yellow-violet color scheme represents the mitigation potential from large to small. The number presented in percentage indicates the contribution of these ten countries/areas in global total mitigation potential. Countries/areas were presented as ISO3 country codes.

Livestock productivity of milk and beef in most developed countries is already high nowadays (methane emission intensity is already low; Fig. 2), and there is only little room for methane reduction through productivity increase (Figure S10). On the other hand, further productivity increase requires high shares of concentrates (i.e., potential competition with human nutrition from plant-based food (Gill et al., 2010)) and encounters potential health problems in cows (see review by (Herzog et al., 2018)). In addition, the intensive livestock breeding and management have resulted in fragile systems that do not adequately handle their manure causing air and water pollution. There is a trend that some developing countries are moving from high efficiency systems towards more extensive livestock systems (such as "free range" chicken and grass-fed beef; e.g., (Cheung & McMahon, 2017)). Therefore, there is possibility that the emission intensity per kg protein in those developed countries will increase, which is opposite to our assumption of constant of decreasing emission intensity.

The potential is the largest in developing countries where the current efficiency is low (i.e., emission intensity per kg protein is high) and a large increase in livestock production is projected. For example, in our projections under the Business As Usual (BAU) scenario, 60-65% of the global reduction in livestock emissions by 2050 due to improving efficiency (compared to baselines where intensity is constant in the future) can be contributed by the top ten countries with the largest reduction potential (Fig. 5 and Figure S15-17). Most of them are developing countries in Asia, South America and Africa.

The continuation of past decreases in emission intensity, especially in developing countries, can be achieved through the transition of livestock production systems from extensive rangeland systems to mixed crop-livestock systems (Frank et al., 2018; Havlík et al., 2014) and through improving livestock management within the existing systems (Thornton & Herrero, 2010). Various factors can contribute to such a transition: for instance, better breeding, fertility and health intervention (Gill et al., 2010), better quality feed (Gill et al., 2010; Johnson & Johnson, 1995), and optimization of grazing management (e.g., forage storage to avoid losing weight in winter (Thornton & Herrero, 2010)). In addition, new technologies such as feed supplements can also reduce methane emissions from rumen (Caro et al., 2016; Gerber, Hristov, et al., 2013), while methane emissions from manure management can be mitigated through various options, such as improving housing systems, manure storage, composting, and anaerobic digestion (Gerber, Hristov, et al., 2013). However, there are adaptability issues and side-effects that must be considered when implementing these strategies. For example, breeding practices from temperate regions may not adapt well to warm conditions in Africa. A shift in productivity might involve an increase in the consumption of grain-based feed and/or high-quality fodder in the diet, but it can also be effectively achieved through better roughage quality and better grazing management. For example, in semi-arid regions where increasing crop production for feeding livestock is impossible due to water limitations (e.g., central Asia), improving grazing management to increase productivity should be prioritized as a sustainable solution rather than moving from low to industrialized systems (i.e., landless livestock systems with livestock fed by grain-based feed and/or high-quality fodder). Improving livestock production efficiency should always be in line with the natural circumstances in the respective regions. The optimal strategy should consider also other relevant sustainability goals like biodiversity, water pollution through nutrient runoff, and potential implications for livelihoods and resilience to climate change impacts.

Our results highlight the fact that 1) efforts on the demand-side to promote balanced, healthy and environmentally-sustainable diets in most counties, as assumed in the Toward Sustainability (TS) scenario (FAO, 2018), will not be sufficient for livestock methane emission mitigation without parallel efforts to improve production efficiency and decrease the emission intensity per unit protein produced; and 2) efforts to decrease emission intensity should be prioritized in a few developing countries with the largest mitigation potential.

Acknowledgments

J.C is supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA26010303). P.C acknowledges support from the CLAND Convergence Institute of the French National Research Agency (ANR).

Data Availability Statement

The data used in this study are available in the Supporting Information. The raw data are from FAO: http://www.fao.org/faostat/en/#data and http://www.fao.org/global-perspectives-studies/food-agriculture-projections-to-2050/en/. The results of this study, and the R code and the parameter files used to produce them are available at: https://doi.org/10.5281/zenodo.4663448.

Reference

Caro, D., Kebreab, E., & Mitloehner, F. M. (2016). Mitigation of enteric methane emissions from global livestock systems through nutrition strategies. *Climatic Change, 137*(3), 467-480. https://doi.org/10.1007/s10584-016-1686-1

Chang, J., Peng, S., Ciais, P., Saunois, M., Dangal, S. R. S., Herrero, M., et al. (2019). Revisiting enteric methane emissions from domestic ruminants and their δ13CCH4 source signature. *Nature communications, 10*(1), 3420. https://doi.org/10.1038/s41467-019-11066-3

Cheung, R., & McMahon, P. (2017). Back to grass: The market potential for US grassfed beef. *New York, NY: Stone Barns Center for Food and Agriculture*.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., et al. (2013). Long-term climate change: projections, commitments and irreversibility. In *Climate Change 2013-The Physical Science Basis: Contribution of Working Group I* *to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1029-1136): Cambridge University Press.

Crippa, M., Solazzo, E., Huang, G., Guizzardi, D., Koffi, E., Muntean, M., et al. (2020). High resolution temporal profiles in the Emissions Database for Global Atmospheric Research. *Scientific Data, 7*(1), 121. https://doi.org/10.1038/s41597-020-0462-2

Dangal, S. R., Tian, H., Zhang, B., Pan, S., Lu, C., & Yang, J. (2017). Methane emission from global livestock sector during 1890–2014: Magnitude, trends and spatiotemporal patterns. *Global Change Biology, 23*(10), 4147-4161.

EPA. (2012). Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030. . *United States Environment Protection Agency, Washington DC.* .

FAO. (2017). Global livestock environmental assessment model - Model Description Version 2.0 (GLEAM 2.0). *Rome.*

FAO. (2018). *The future of food and agriculture – Alternative pathways to 2050*. Retrieved from Rome:

FAOSTAT. (2020). *http://www.fao.org/faostat/en/#home (Accessed: 2020-09-22)*.

Frank, S., Beach, R., Havlík, P., Valin, H., Herrero, M., Mosnier, A., et al. (2018). Structural change as a key component for agricultural non-CO2 mitigation efforts. *Nature communications, 9*(1), 1060. https://doi.org/10.1038/s41467-018-03489-1

Gerber, P. J., Hristov, A. N., Henderson, B., Makkar, H., Oh, J., Lee, C., et al. (2013). Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. *Animal, 7*(s2), 220-234.

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., et al. (2013). *Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities*: Food and Agriculture Organization of the United Nations (FAO).

Gilbert, M., Nicolas, G., Cinardi, G., Van Boeckel, T. P., Vanwambeke, S. O., Wint, G. R. W., & Robinson, T. P. (2018). Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010. *Scientific Data, 5*, 180227. Data Descriptor. https://doi.org/10.1038/sdata.2018.227

Gill, M., Smith, P., & Wilkinson, J. (2010). Mitigating climate change: the role of domestic livestock. *Animal, 4*(3), 323-333.

Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M. C., et al. (2014). Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences, 111*(10), 3709-3714. https://www.pnas.org/content/pnas/111/10/3709.full.pdf

Herrero, M., Havlik, P., Valin, H., Notenbaert, A., Rufino, M. C., Thornton, P. K., et al. (2013). Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences of the United States of America, 110*(52), 20888-20893.

Herzog, A., Winckler, C., & Zollitsch, W. (2018). In pursuit of sustainability in dairy farming: A review of interdependent effects of animal welfare improvement and environmental impact mitigation. *Agriculture, Ecosystems & Environment, 267*, 174-187. https://www.sciencedirect.com/science/article/pii/S0167880918303128

IPCC. (1997). *Revised 1996 IPCC Guidelines for National Greenhouse Inventories. Houghton J.T., Meira Filho L.G., Lim B., Tréanton K., Mamaty I., Bonduki Y., Griggs D.J. and Callander B.A. (Eds)*. Retrieved from Paris, France:

IPCC. (2000). *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Penman J., Kruger D., Galbally I., Hiraishi T., Nyenzi B., Emmanuel S., Buendia L., Hoppaus R., Martinsen T., Meijer J., Miwa K., and Tanabe K. (Eds)*. Retrieved from Hayama, Japan:

IPCC. (2003). *Good Practice Guidance for Land Use, land- Use Change and Forestry. Penman J., Gytarsky M., Hiraishi T., Krug, T., Kruger D., Pipatti R., Buendia L., Miwa K., Ngara T., Tanabe K., and Wagner F (Eds)*. Retrieved from Hayama, Japan:

IPCC. (2006). *2006 IPCC guidelines for national greenhouse gas inventories. Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. (eds)* (Vol. 4). Hayama, Japan: Institute for Global Environmental Strategies.

IPCC. (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds)* (Vol. 4). Switzerland: IPCC.

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., et al. (2019). EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012. *Earth Syst. Sci. Data, 11*(3), 959-1002. https://www.earth-syst-sci-data.net/11/959/2019/

Johnson, K. A., & Johnson, D. E. (1995). Methane emissions from cattle. *Journal of animal science, 73*(8), 2483-2492.

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., & Gerber, P. (2017). Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security, 14*, 1-8. https://www.sciencedirect.com/science/article/pii/S2211912416300013

Myhre, G., Shindell, D., Bréon, F. M., Collins, W., Fuglestvedt, J., Huang, J., et al. (2013). Anthropogenic and natural radiative forcing. In T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Doschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 659-740). Cambridge, UK: Cambridge University Press.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change, 42*, 153-168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., et al. (2020). The Global Methane Budget 2000–2017. *Earth Syst. Sci. Data, 12*(3), 1561-1623. https://essd.copernicus.org/articles/12/1561/2020/

Thornton, P. K., & Herrero, M. (2010). Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. *Proceedings of the National Academy of Sciences, 107*(46), 19667-19672.

Van Zanten, H. H. E., Herrero, M., Van Hal, O., Röös, E., Muller, A., Garnett, T., et al. (2018). Defining a land boundary for sustainable livestock consumption. *Global Change Biology, 24*(9), 4185-4194. https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.14321

Wolf, J., Asrar, G. R., & West, T. O. (2017). Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock. *Carbon balance and management, 12*(1), 16.

AGU Advances

Supporting Information for

The key role of production efficiency changes in livestock methane emission mitigation

Jinfeng Chang[1,2*], Shushi Peng[3], Yi Yin[4], Philippe Ciais[5], Petr Havlik[2], Mario Herrero[6]

[1] College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, 310058, China

[2] International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria

[3] Sino-French Institute for Earth System Science, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

[4] Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, 91125, USA

[5] Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

[6] Commonwealth Scientific and Industrial Research Organization, St Lucia, QLD 4067, Australia

Corresponding author: Jinfeng Chang (changjf@zju.edu.cn)

Contents of this file

Text S1 to S4

Figures S1 to S17

Tables S1 to S4

Additional Supporting Information

Text S1. Estimating enteric fermentation emissions ($F_{CH4\text{-}Enteric}$) from livestock using mixed IPCC Tier 1 and Tier 2 methods (the 2019 MT method)

Text S2. Estimating manure management emissions ($F_{CH4\text{-}Manure}$) from livestock using the 2019 Tier 2 method

Text S3. Net and gross energy intake of livestock

Text S4. Typical average animal mass for population of livestock and the population

Figure S1. Each livestock category's share of total methane emissions in 2018.

Figure S2. Regional livestock methane emissions for the period 2000-2018.

Figure S3. Gridded livestock methane emission intensity per area of land for the period 2000-2018 (a and c), and the changes in emission intensity per area of land between the period 2000-2004 and the period 2014-2018 (b and d) using the 2019 MT method (a and b) and the 2019 T1 method (c and d).

Figure S4. Differences between the gridded livestock methane emission intensity per area of land for the period 2000-2015 using the 2019 MT method, the 2019 T1 method and the hybrid 2006 T1 method by EDGAR v5.0 (a and c), and differences of the changes in emission intensity per area of land between the period 2000-2004 and the period 2014-2015 (b and d).

Figure S5. Global and regional changes in methane emissions from each livestock category between the periods 2000-2004 and 2014-2018, and the contributions due to changes in livestock numbers and changes in emission factors.

Figure S6. Comparison of the changes of livestock methane emissions between the periods 2000-2004 and 2014-2018 from this study using (a) the 2019 MT method and (b) the 2019 T1 method, and values from (c) FAOSTAT and (d) EDGAR v5.0 datasets.

Figure S7. Relative changes in livestock protein production during the periods 2000-2004 and 2014-2018 for major livestock categories.

Figure S8. Changes in methane emission intensity per kg protein of each livestock category between the periods 2000-2004 and 2014-2018, resulting from the 2019 MT method, the 2019 T1 method, and the 2006 T1 method.

Figure S9. Examples of the historical trends in emission intensity for major livestock categories from the 2019 MT method in relate to the development of GDP per capita.

Figure S10. Methane emission intensity per kg protein of each livestock category during the period 2014-2018 and that projected by 2050 under different socio-economic scenarios resulting from the 2019 MT method.

Figure S11. Projections of global livestock methane emissions under different socio-economic scenarios with a continuation of country-specific past trend with the development of GDP per capita allowing both increasing or decreasing emission intensity in the future.

Figure S12. Projections of regional livestock protein production under different socio-economic scenarios.

Figure S13. Projections of regional livestock methane emissions under different socio-economic scenarios and different emission intensity change pathways, resulting from the 2019 MT method, the 2019 T1 method, and the 2006 T1 method.

Figure S14. Projections of global livestock methane emissions of each livestock category under different socio-economic scenarios and different emission intensity change pathways, resulting from the 2019 MT method, the 2019 T1 method, and the 2006 T1 method.

Figure S15. Projections on the increase in protein production, methane emission, and the effects of improving efficiency on reducing livestock methane emissions under the BAU scenarios, resulting from the 2019 MT method.

Figure S16. Projections on the increase in protein production, methane emission, and the effects of improving efficiency on reducing livestock methane emissions under the BAU scenarios, resulting from the 2019 T1 method.

Figure S17. Projections on the increase in protein production, methane emission, and the effects of improving efficiency on reducing livestock methane emissions under the BAU scenarios, resulting from the 2006 T1 method.

Figure S18. Number of countries/areas reaches the minimum emission intensity of each livestock category under different socio-economic scenarios, resulting from the 2019 MT method, the 2019 T1 method, and the 2006 T1 method.

Table S1. Comparison of global livestock methane emissions in the year 2010 and the methodologies used.

Table S2. Livestock methane emissions from each livestock category for the year 2018 and the methodologies used.

Table S3. The minimum and maximum methane emission intensities for different livestock categories ($EF_{protein,k,min}$ and $EF_{protein,k,max}$) as the thresholds.

Table S4. Comparison of enteric fermentation emission factors per head of livestock in the 2010s derived from the 2019 MT method in this study and the values for the Tier 1 method (the 2006 or 2019 T1 method).

Text S1. Estimating enteric fermentation emissions ($F_{CH4\text{-}Enteric}$) from livestock using mixed IPCC Tier 1 and Tier 2 methods (the 2019 MT method)

Enteric fermentation CH_4 emissions from dairy cows, meat and other non-dairy cattle, buffaloes, sheep and goats were estimated using Eqn (1) adapted from the IPCC Tier 2 method (IPCC, 2006 Vol. 4, Chapter 10, Eqn 10.21):

$$F_{CH4-Enteric,ruminant} = \frac{GE \times (\frac{Y_m}{100})}{55.65} \quad (1)$$

where GE is the gross energy intake of livestock (unit: MJ); Y_m is a conversion factor, representing the proportion of methane energy in the gross energy intake; the factor 55.65 (MJ Kg^{-1} CH_4) is the energy content of methane. GE was calculated using the IPCC approach (IPCC, 2019 Vol. 4, Chapter 10, Eqn 10.16), with net energy (NE; unit: MJ) and digestibility of feed (DE; unit: percent; expressed as a fraction of digestible energy in gross energy) as two key factors. NE was calculated using the IPCC approach (IPCC, 2019 Vol. 4, Chapter 10, Eqn 10.3, 10.4, 10.6, 10.7, 10.8, 10.9, 10.11, 10.12, and 10.13), and regional DE for each livestock category was derived from Table B13 of (Opio et al., 2013). We assumed that there were no changes in the regional DE from 2000 to 2018. NE includes net (metabolic) energy for maintenance, activity, growth, lactation, draft power, wool production and pregnancy. In this study, these were calculated using “Stock”, “Producing Animals/Slaughtered” and “Yield” statistics from (FAOSTAT, 2020) (“Live Animals” and “Livestock Primary” domains), parameters of herd dynamics from GLEAMv2.0 (FAO, 2017), and parameters from Table 10.4-10.7 of (IPCC, 2019) Vol. 4, Chapter 10. Text S3 presents the equations, assumptions, and data used to calculate the net and gross energy intake of livestock in detail. Methane conversion factors (Y_m) were calculated using the formula derived from (Opio et al., 2013) (their section 6.3):

$$Y_m = 9.75 - 0.05 \times DE \quad (2)$$

which was developed to better reflect the wide range of diet quality and feeding characteristics globally in life cycle assessments of greenhouse gas emissions from ruminants (Opio et al., 2013).

For enteric fermentation emissions from swine, we applied an adjusted IPCC Tier 1 method (IPCC, 2019 Vol. 4, Chapter 10, Eqn 10.19) which accounted for changes in liveweight:

$$F_{CH4-Enteric,swine} = EF_{swine,adjusted} \times N_{swine} \quad (3)$$

where N_{swine} is the number of swine stock (unit: head) from (FAOSTAT, 2020) ("Live Animals" domain); and $EF_{swine,adjusted}$ is the enteric fermentation emission factor adjusted from the changes in liveweight. We calculated $EF_{swine,adjusted}$, based on: i) the approximation that intake (and thus *GE*) scales with a three-quarters fractional exponent of liveweight (Müller et al., 2013); and ii) enteric fermentation CH_4 emissions mainly depend on *GE*, as:

$$EF_{swine,adjusted} = EF_{swine,reference} \times (\frac{Weight_{actual}}{Weight_{reference}})^{0.75} \quad (4)$$

where $EF_{swine,reference}$ is the reference emission factor for the Tier 1 method from Table 10.10 of (IPCC, 2019) Vol. 4, Chapter 10 (i.e., 1.5 and 1.0 kg CH_4 $head^{-1}$ yr^{-1} for high and low productivity systems, respectively); $Weight_{reference}$ is the reference liveweight (72 and 52 kg CH_4 $head^{-1}$ yr^{-1} for high and low productivity systems, respectively); and $Weight_{actual}$ is the actual mean liveweight of swine, which varies between countries and years. The actual mean liveweight of swine of country *j* at year *m* ($Weight_{actual,j,m}$) is calculated as:

$$Weight_{actual,j,m} = \frac{CW_{swine,j,m}}{DP_j} \times f_{scaling} \quad (5)$$

where $CW_{swine,j,m}$ is carcass weight per slaughtered head (i.e., meat yield from the (FAOSTAT, 2020) "Livestock Primary" domain) of country *j* in year *m*; the dressing percentage of country *j* (DP_j) is the proportion of liveweight that ends up as carcass derived from Table 9.2 of GLEAM v2.0 Documentation (FAO, 2017); $f_{scaling}$ is a scaling factor for mean liveweight of the population. Assuming that swine population (head) are evenly distributed from weight at birth (usually 0.8 – 1.2 kg; Table 12.4 - 12.6 of GLEAM v2.0 Documentation (FAO, 2017)) to liveweight at slaughter, the mean liveweight of the population is about half of the liveweight at slaughter (i.e., $f_{scaling} = 0.5$).

For enteric fermentation emissions from other livestock, horses, camels, mules, asses, and llamas, we also use Eqn (4) with adjustment for liveweight. Given the fact that these livestock are not mainly kept for meat, the variation in meat yield from the (FAOSTAT, 2020) "Livestock Primary" domain may not accurately reflect the changes in mean liveweight, and so, instead, we use the regional default liveweight of these livestock categories from Table 10A.5 of (IPCC, 2019) Vol. 4, Chapter 10 to adjust the regional emission factors.

Text S2. Estimating manure management emissions ($F_{CH4\text{-}Manure}$) from livestock using the 2019 Tier 2 method

(IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.23 provides the updated Tier 2 method for estimating CH_4 emissions from manure management, which is based on volatile solid excreted by livestock (*VS*), maximum methane producing capacity for manure produced by livestock (B_0), methane conversion factors for each manure management system and each climate region (*MCF*), and the fraction of livestock manure handled using each animal waste management system in each region (*AWMS*). Given the fact that MCF is climate-region dependent, we calculated CH_4 emissions from manure management at a resolution of 5 arc min ($F_{CH4-manure,i,j,k,m}$ in grid cell *i* of country *j* for livestock category *k* in year *m*) using Eqn (6) adapted from the IPCC Tier 2 method (IPCC, 2019 Vol. 4, Chapter 10, Eqn 10.23):

$$F_{CH4-manure,i,j,k,m} = VS_{i,j,k,m} \times (B_{0,j,k} \times 0.67 \times \sum_{S,i} \frac{MCF_{S,i}}{100} \times AWMS_{j,k,S}) \qquad (6)$$

where $VS_{i,j,k,m}$ (unit: kg dry matter yr^{-1}) is annual volatile solid excreted in grid cell *i* of country *j* from livestock category *k* in year *m*; $B_{0,j,k}$ (unit: m^3 CH_4 kg^{-1} of *VS* excreted) is the maximum methane producing capacity for manure produced from livestock category *k* in country *j*; 0.67 is the conversion factor from m^3 CH_4 to kg CH_4; $MCF_{S,i}$ (unit: percent) is the methane conversion factor for manure management system *S* in grid cell *i*; $AWMS_{j,k,S}$ (dimensionless) is the fraction of livestock category *k*'s manure handled using animal waste management system *S* in country *j*. We derived $B_{0,j,k}$ from Table 10.16 of (IPCC, 2019) Vol. 4, Chapter 10 for each region and each livestock category. $AWMS_{j,k,S}$ was derived from Table 10A.6 – 10A.9 of (IPCC, 2019) Vol. 4, Chapter 10 for the fractions of different manure management system in each region. $MCF_{S,i}$ was derived from Table 10.17 of (IPCC, 2019) Vol. 4, Chapter 10 for each manure management system and for each IPCC climate zone. The IPCC climate zone for each grid cell, *i,* was determined following the classification presented in Annex 10A2 of (IPCC, 2019) Vol. 4, Chapter 10. The classification is based on elevation, mean annual temperature (MAT), mean annual precipitation (MAP), and the ratio of precipitation to potential evapotranspiration. The mean elevation was obtained from the HWSD database (Fischer et al., 2008); MAT and MAP were derived from the CRU-JRA v2.0 dataset (an update of (Harris, 2019); https://catalogue.ceda.ac.uk/uuid/7f785c0e80aa4df2b39d068ce7351bbb), which is averaged over the period 2000-2018 and originally at the resolution of 0.5° × 0.5°. All the 5 arc min grid cells within the same 0.5° × 0.5° grid cell in the CRU-JRA v2.0 dataset were assumed to have the same MAT and MAP. Here, instead of calculating potential evapotranspiration to derive the ratio of precipitation to potential evapotranspiration, we used the latest aridity index (*AI*) from the CGIAR-CSI Global-Aridity and Global-PET Database (Zomer et al., 2007; Zomer et al., 2008) (version 2, accessed Feb. 2020 http://www.cgiar-csi.org) as a proxy for differentiating between moist and dry zones. The original *AI* data was at a resolution of 30 arc seconds, so an average *AI* value for each 5 arc min grid cell was calculated. Assuming no changes in the distribution of livestock during the period 2000-2018, gridded $VS_{i,j,k,m}$ was estimated by distributing the country level *VS* into grid cells following the livestock distributions given in the GLW3 dataset (Gilbert et al., 2018) (following the same methodology as presented in the Methods section "*Estimating gridded livestock CH_4 emissions*"), as:

$$VS_{i,j,k,m} = VS_{j,k,m} \times \frac{D_{GLW3,i,j,k} \times A_i}{\sum_{i \in j} D_{GLW3,i,j,k} \times A_i} \quad (7)$$

where $VS_{j,k,m}$ is the annual volatile solid excreted in country *j* from livestock category *k* in year *m*. $VS_{j,k,m}$ from dairy cows, meat and other non-dairy cattle, buffaloes, sheep and goats was calculated using Eqn (8) adapted from the IPCC Tier 2 method (IPCC, 2019 Vol. 4, Chapter 10, Eqn 10.24):

$$VS_{j,k,m} = \left[GE_{j,k,m} \times \left(1 - \frac{DE_{j,k}}{100}\right) + \left(UE \times GE_{j,k,m}\right)\right] \times \left(\frac{1-ASH}{18.45}\right) \quad (8)$$

where $GE_{j,k,m}$ is the gross energy intake of livestock category k in country j in year m, which was calculated using the IPCC approach (IPCC, 2019 Vol. 4, Chapter 10, Eqn 10.16; See Supplementary Information Note 4 for details); $DE_{j,k}$ is the *DE* for each livestock category *k* in country *j* derived from Table B13 of (Opio et al., 2013) (regional values were used for all countries in that region); UE is urinary energy expressed as fraction of GE with a typical value of 0.04 being used for ruminants as suggested by (IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.24. *ASH* is the ash content of feed, calculated as a fraction of the dry matter feed intake (*ASH* = 0.06 was used as shown in the original equation, as no country-specific values were available); the factor 18.45 (MJ kg^{-1}) is conversion factor for dietary *GE* per kg of dry matter.

$VS_{j,k,m}$ from other livestock (swine, chicken broilers, chicken layers, ducks, turkeys, asses, camels, horses, mules and llamas) was estimated using Eqn (9) adapted from the IPCC Tier 1 method (IPCC, 2019 Vol. 4, Chapter 10, Eqn 10.22A):

$$VS_{j,k,m} = VS_{rate,k} \times \frac{TAM_{pop,j,k,m}}{1000} \times 365 \times N_{pop,j,k,m} \qquad (9)$$

where $VS_{rate,j,k}$ (unit: kg VS (1000 kg animal mass)$^{-1}$ day^{-1}) is the default VS excretion rate for livestock category *k* in country *j* derived from Table 10.13A of (IPCC, 2019) Vol. 4, Chapter 10; regional values were used for all countries in that region) ; $TAM_{pop,j,k,m}$ is the typical average animal mass for population of livestock category *k* in country *j* in year *m*; $N_{pop,j,k,m}$ is the population of livestock category *k* in country *j* in year *m.* Text S4 presents in detail the method used to derive $TAM_{pop,j,k,m}$ and $N_{pop,j,k,m}$ for swine, chicken broilers, chicken layers, ducks, turkeys, asses, camels, horses, mules and llamas.

Text S3. Net and gross energy intake of livestock

Gross energy intake of livestock (*GE*) was calculated using the IPCC approach (IPCC, 2019 Vol. 4, Chapter 10, Eqn 10.16), with net energy (*NE*; unit: MJ) and digestibility of feed (*DE*; unit: percent; expressed as a fraction of digestible energy in gross energy) as the two key factors. The gross energy intake of livestock category *k* in country *j* in year *m* ($GE_{j,k,m}$) was calculated as:

$$GE_{j,k,m} = \frac{\left(\frac{NE_{maint,j,k,m}+NE_{a,j,k,m}+NE_{l,j,k,m}+NE_{work,j,k,m}+NE_{p,j,k,m}}{REM_{j,k}}\right)+\left(\frac{NE_{g,j,k,m}+NE_{wool,j,k,m}}{REG_{j,k}}\right)}{DE_{j,k}} \qquad (10)$$

where net energy (*NE*) includes net (metabolic) energy for maintenance ($NE_{maint,j,k,m}$), activity ($NE_{a,j,k,m}$), growth ($NE_{g,j,k,m}$), lactation ($NE_{l,j,k,m}$), draft power ($NE_{work,j,k,m}$), wool production ($NE_{wool,j,k,m}$) and pregnancy ($NE_{p,j,k,m}$) for livestock category *k* in country *j* in year *m*, and was calculated using the IPCC approach (IPCC, 2019 Vol. 4, Chapter 10, Eqn 10.3, 10.4, 10.6, 10.7, 10.8, 10.9, 10.11, 10.12, and 10.13); $DE_{j,k}$ is the *DE* for each livestock category *k* in country *j* derived from Table B13 of (Opio et al., 2013) (regional values were used for all countries in that region); $REM_{j,k}$ is the ratio of net energy available in the diet for maintenance to digestible energy consumed, calculated based on $DE_{j,k}$ using Equation 10.14 of (IPCC, 2019) Vol. 4, Chapter 10; $REG_{j,k}$ is the ratio of net energy available for growth in a diet to digestible energy consumed, calculated based on $DE_{j,k}$ using Eqn 10.15 of (IPCC, 2019) Vol. 4, Chapter 10. We assumed that there were no changes in the regional *DE* from 2000 to 2018.

Net energy for maintenance (NE_{maint}) is the most important component of *NE*, which determines the estimate of NE_a (for cattle and buffalo), NE_{work}, and NE_p (IPCC, 2019 Vol. 4, Chapter 10, Eqn 10.4, 10.11, and 10.13, respectively). The annual total NE_{maint} for livestock category k in country j in year m ($NE_{maint,j,k,m}$) was calculated using Eqn (11) adapted from Eqn 10.3 of (IPCC, 2019) Vol. 4, Chapter 10, as:

$$NE_{maint,j,k,m} = \sum_c Cf_{I,k} \times (Weight_{c,j,k,m})^{0.75} \times N_{c,j,k,m} \times Days_{c,j,k,m} \quad (11)$$

where $Cf_{I,k}$ (unit: MJ day^{-1} kg^{-1}) is a coefficient for livestock category k from Table 10.4 of (IPCC, 2019) Vol. 4, Chapter 10; $Weight_{c,j,k,m}$ (unit: kg) is the liveweight of livestock category k in age class c for country j in year m; $N_{c,j,k,m}$ (unit: head) is the number of livestock category k in type and class c; $Days_{c,j,k,m}$ (unit: days) is the number of days that livestock of category k in type and age class c was fed and emitted CH_4 in country j in year m. Here, type and age class c includes both type of animals (such as milking animal, replacement female, and other animals), and the age class of each type of animal (see below for detailed classification). FAO's GLEAM v2.0 Documentation (FAO, 2017) provides detailed methodology for estimating herd dynamics. However, due to the limited statistical information available in (FAOSTAT, 2020) for each country, we applied a simplified herd module here to estimate $Weight_{c,j,k,m}$, $N_{c,j,k,m}$, and $Days_{c,j,k,m}$ using parameters from the GLEAM v2.0 Documentation (FAO, 2017). Adult females producing milk (dairy cows, milking buffaloes, sheep and goats), replacement females, and other animals (mainly for meat production) were separated. The number of adult females producing milk for livestock category k in country j in year m ($N_{milking,j,k,m}$) is available from (FAOSTAT, 2020) ("Livestock Primary" domain – "Producing Animals/slaughtered"). The number of replacement females for livestock category k in country j in year m ($N_{replacement,j,k,m}$) was calculated as:

$$N_{replacement,j,k,m} = N_{milking,j,k,m} \times RRF_k \quad (12)$$

where RRF_k (unit: percent) is the percentage of replacement females for livestock category *k* derived from Table 2.4 – 2.11 of the GLEAM v2.0 Documentation (FAO, 2017). The number of other animals was calculated as:

$$N_{other,j,k,m} = N_{stocks,j,k,m} - N_{milking,j,k,m} - N_{replacement,j,k,m} \quad (13)$$

where $N_{stocks,j,k,m}$ (unit: head) is the animal stocks for livestock category *k* in country *j* in year *m* derived from (FAOSTAT, 2020) ("Live Animals" domain). We assumed that lactating animals have the liveweight of adult females (*AFkg*), as in Table 2.4 – 2.11 of the GLEAM v2.0 Documentation (FAO, 2017) (regional values for different livestock categories), and do not gain or lose weight. For replacement females, we assumed that the animals are evenly distributed from the age of 1 day and weight of birth (*Ckg*) to the age at first calving (*AFC*; unit: years) and liveweight of adult females, which means there are $\frac{1}{N_{replacement}}$ replacement females in each age class *A* (*A* = 1, 2, … $AFC \times 365$) with liveweight of $Weight = A \times \frac{AFkg-Ckg}{AFC \times 365}$ (*A* = 1, 2, … $AFC \times 365$). Given the fact that other animals ($N_{other,j,k,m}$) are mainly kept for meat, we assumed that i) they are evenly distributed from the age of 1 day and weight of birth (*Ckg*) to the age (*AS*; unit: days) and liveweight at slaughter (*Skg*), and ii) half are male and half female. This means that there are $\frac{0.5}{N_{other}}$ other male animals in each age class *A* (*A* = 1, 2, …AS_{male}) with liveweight of $Weight = A \times \frac{Skg-Ckg}{AS_{male}}$ (*A* = 1, 2, … AS_{male}), and also $\frac{0.5}{N_{other}}$ other male animals in each age class *A* (*A* = 1, 2, …AS_{female}) with liveweight of $Weight = A \times \frac{Skg-Ckg}{AS_{female}}$ (*A* = 1, 2, … AS_{female}).

The liveweight at slaughter for livestock category *k* in country *j* in year *m* ($Skg_{k,j,m}$) can be calculated as:

$$Skg_{j,k,m} = \frac{CW_{j,k,m}}{DP_{j,k}} \quad (14)$$

where $CW_{k,j,m}$ is the carcass weight for livestock category *k* in country *j* in year *m* (i.e., yield in the (FAOSTAT, 2020) "Livestock Primary" domain); and $DP_{k,j}$ is the dressing percentage for livestock category *k* in country *j* derived from Table 9.2 of the GLEAM v2.0 Documentation (FAO, 2017) (regional values were used for all countries in that region). Then the age at slaughter for livestock category k in country j in year m ($AS_{male,j,k,m}$ and $AS_{female,j,k,m}$ for slaughtered males and females, respectively; unit: days) was calculated as:

$$AS_{male,j,k,m} = \frac{Skg_{j,k,m} - Ckg_{j,k}}{DWG_{male,j,k}} \quad (15)$$

$$AS_{female,j,k,m} = \frac{Skg_{j,k,m} - Ckg_{j,k}}{DWG_{female,j,k}} \quad (16)$$

where $DWG_{male,j,k}$ and $DWG_{female,j,k}$ are daily weight gains of livestock category k in country j for males and females respectively. $DWG_{male,k,j}$ and $DWG_{female,j,k}$ were calculated as:

$$DWG_{male,j,k} = \frac{MMkg_{j,k} - Ckg_{j,k}}{AFC_{j,k} \times 365} \quad (17)$$

$$DWG_{female,j,k} = \frac{MFkg_{j,k} - Ckg_{j,k}}{AFC_{j,k} \times 365} \quad (18)$$

where $MMkg_{j,k}$ and $MFkg_{j,k}$ are the liveweight of male and female meat animals, respectively, for livestock category k in country j. Regional values for *AFkg, Ckg, MMkg, MFkg, AFC* for different livestock categories (dairy cattle, meat and other non-dairy cattle, buffaloes, sheep and goats) are all derived from Table 2.4 – 2.11 of the GLEAM v2.0 Documentation (FAO, 2017), and regional values were used for all countries in that region.

$Days_{c,j,k,m}$ in Eqn (11) indicates the number of days that livestock of category k in type and age class c was fed and emitted CH_4 in country j in year m. For milking animals and replacement females, we assumed they were fed and emitted CH_4 for the whole year ($Days_{c,j,k,m} = 365$). However, for dairy cows, $Cf_{I,cows}$ can be different during lactating periods and dry periods. Here, we assumed 10 months of lactation ($Cf_{I,cows} = 0.386\ MJ\ day^{-1} kg^{-1}$) and a 2 month dry period ($Cf_{I,cows} = 0.322\ MJ\ day^{-1} kg^{-1}$) for dairy cows ((IPCC, 2019) Vol. 4, Chapter 10, Table 10.4). For other animals, age at slaughter ($AS_{male,j,k,m}$ and $AS_{female,j,k,m}$) can be less than 1 year, especially for meat producing sheep and goats. Then, we have:

$$Days_{male,j,k,m} = \min\,(365, AS_{male,j,k,m}) \quad (19)$$

$$Days_{female,j,k,m} = \min\,(365, AS_{female,j,k,m}) \quad (20)$$

Net energy for growth (NE_g) is another important component of *NE*. NE_g only applies to replacement females and other animals, because we have assumed that lactating animals have the liveweight of adult females (*AFkg*) and do not gain or lose weight. In addition, draft animals (meat and other non-dairy cattle and buffaloes, see below) in developing countries are usually mature ones, and also do not increase in weight (i.e., they are without NE_g). Net energy for growth for livestock category k (cattle and buffalo) in country j in year m ($NE_{g,j,k,m}$) was calculated using Eqn (21) adapted from Eqn 10.6 of (IPCC, 2019) Vol. 4, Chapter 10, as:

$$NE_{g,j,k,m} = \sum_c 22.02 \times (\frac{TAM_{c,j,k,m}}{C \times MW_{c,j,k}})^{0.75} \times DWG_{c,j,k}{}^{1.097} \times N_{c,j,k,m} \quad (21)$$

where c is the animal type (replacement female, other female or other male); $TAM_{c,j,k,m}$ is the average (typical) liveweight of animals in the population in livestock category k of type c in country j in year m; $MW_{c,j,k}$ is the mature liveweight of an individual adult animal (lactating adult females (*AFkg*), mature females (*MFkg*), mature males (*MMkg*)) from Table 2.4 – 2.11 of the GLEAM v2.0 Documentation (FAO, 2017); $DWG_{c,j,k}$ is the daily weight gain for livestock category k of type c in country j in year m; and $N_{c,j,k,m}$ is the number of animals in livestock category k of type c in country j in year m. $DWG_{male,j,k}$ and $DWG_{female,j,k}$ were calculated from Eqn (17) and (18), respectively, while the daily weight gain for replacement females ($DWG_{replacement,j,k}$) was calculated as:

$$DWG_{replacement,j,k} = \frac{AFkg_{j,k} - Ckg_{j,k}}{AFC_{j,k} \times 365} \quad (22)$$

where $AFkg_{j,k}$ is the liveweight of female adult milking animals. $N_{replacement,j,k,m}$ and $N_{other,j,k,m}$ were calculated from Eqn (12) and (13). Assuming an even distribution of replacement female or other animals (meat male and female) from the age of birth to the age at first calving (for replacement female) or the age at slaughter, we can derive the average liveweight of the animals in the population as the average liveweight between weight at birth (*Ckg*) and weight of adult female animal producing milk (*AFkg*; for replacement female) or weight at slaughter (Skg). Thus, $TAM_{replacement,j,k,m}$ and $TAM_{other,j,k,m}$ were calculated as:

$$TAM_{replacement,j,k,m} = Ckg_{j,k} + \frac{AFkg_{j,k} - Ckg_{j,k}}{2} \quad (23)$$

$$TAM_{other,j,k,m} = Ckg_{j,k} + \frac{Skg_{j,k,m} - Ckg_{j,k}}{2} \quad (24)$$

For sheep and goats, net energy for growth for livestock category k in country j in year m ($NE_{g,j,k,m}$) was calculated using Eqn (25) adapted from Eqn 10.7 of (IPCC, 2019) Vol. 4, Chapter 10, as:

$$NE_{g,j,k,m} = \sum_c \frac{(BWkg_{c,j,k,m} - BW_{weaning,j,k}) \times (a + 0.5 \times b \times (BW_{weaning,j,k} + BWkg_{c,j,k,m}))}{365} \times AS_{c,j,k,m} \times N_{c,j,k,m} \qquad (25)$$

where a and b are constants as shown in Table 10.6 of (IPCC, 2019) Vol. 4, Chapter 10; $BW_{weaning,j,k}$ is the liveweight at weaning for livestock k in country j; $BWkg_{c,j,k,m}$ is liveweight at first calving (for replacement females) or at slaughter (for meat male and female); $AS_{c,j,k,m}$ is the age at first calving (for replacement females) or at slaughter (for meat male and female) for livestock category k in country j in year m; and $N_{c,j,k,m}$ is the number of animals in livestock category k of type c in country j in year m. We assumed $BW_{weaning,j,k}$ to be equal to weight at birth ($Ckg_{j,k}$), which neglected the weight gain of sheep and goats due to taking milk in the first few weeks. $AS_{male,j,k,m}$ and $AS_{female,j,k,m}$ were calculated from Eqn (15) and (16), and $AS_{replacement,j,k,m}$ is the same as AFC. $BWkg_{replacement,j,k,m}$ is the same as $AFkg_{j,k}$, while $BWkg_{other,j,k,m}$ equates to $Skg_{j,k,m}$.

The estimate of net energy for activity (NE_a; for obtaining food) for cattle and buffaloes can be calculated from NE_{maint} using Eqn 10.4 of (IPCC, 2019) Vol. 4, Chapter 10. In most regions dairy cows were stall fed and thus do not require NE_a, however, this is not the case in Latin America, Oceania, and South Asia, where dairy cows are fed on pasture/rangeland (see (IPCC, 2019) Vol. 4, Chapter 10, Table 10A.1). NE_a for sheep and goats was calculated using Eqn 10.4 of (IPCC, 2019) Vol. 4, Chapter 10 with liveweight calculated as above. NE_l was calculated using Eqn 10.8 and 10.9 of (IPCC, 2019) Vol. 4, Chapter 10, with milk production, obtained from (FAOSTAT, 2020) ("Livestock Primary" domain), as the input. Net energy for pregnancy (NE_p) was calculated from NE_{maint} using Eqn 10.13 of (IPCC, 2019) Vol. 4, Chapter 10. NE_{wool} was calculated using Eqn 10.12 of (IPCC, 2019) Vol. 4, Chapter 10 with wool production from (FAOSTAT, 2020) ("Livestock Primary" domain) as the input.

However, in many developing regions, especially in Asia, a significant fraction of meat and other non-dairy cattle and buffaloes are used as draft animals, which produce no meat unless they are too old to work. Therefore, it is important to separate meat and other non-dairy cattle and buffalo stocks that are mainly used as draft animals (N_{other_draft}) from those that are mainly used for meat production (N_{other_prod}). Assuming that: i) they are evenly distributed from the age of 1 day and weight at birth (*Ckg*) to the age (*AS*; unit: days) and liveweight at slaughter (*Skg*); and ii) half are male and half female, we calculated the number of producing animals (meat and other non-dairy cattle and buffaloes in developing countries only) as:

$$N_{other\_prod,male,j,k,m} = \frac{N_{slaughtered,j,k,m}}{2} \times \frac{AS_{male,j,k,m}}{365} \quad (26)$$

$$N_{other\_prod,female,j,k,m} = \frac{N_{slaughtered,j,k,m}}{2} \times \frac{AS_{female,j,k,m}}{365} \quad (27)$$

where $N_{other\_prod,male,j,k,m}$ and $N_{other\_prod,female,j,k,m}$ are the minimum number of animals needed to produce meat given the liveweight at slaughter (Skg) and the daily weight gains (DWG). The number of draft animals can then be calculated as:

$$N_{other\_draft,j,k,m} = N_{other,j,k,m} - N_{other\_prod,male,j,k,m} - N_{other\_prod,female,j,k,m} \quad (28)$$

Net energy for maintenance (NE_{maint}) for draft animals can be calculated using Eqn (11) above, while the weights of draft animals are the typical weights of cattle and buffalo for each region derived from Table 10A.5 of (IPCC, 2019) Vol. 4, Chapter 10. Net energy for activity (NE_a; for obtaining food) for draft cattle and buffaloes can be calculated from NE_{maint} using Eqn 10.4 of (IPCC, 2019) Vol. 4, Chapter 10. Net energy for work (NE_{work}) is only applicable to cattle and buffaloes used for draft power, and is calculated using Eqn 10.11 of (IPCC, 2019) Vol. 4, Chapter 10). For developing countries, a typical draft animal is assumed to work 40 days per year (U.S. Congress, 1991) and 10 hours per day, equating to 1.1 hours of work per day annually.

Text S4. Typical average animal mass for population of livestock and the population

Typical average animal mass for population of livestock (TAM_{pop}) and the population of livestock category (N_{pop}) were used to calculate the volatile solid excreted by livestock (*VS*) for swine, chicken broilers, chicken layers, ducks, turkeys, asses, camels, horses, mules and llamas. *VS* is critical for calculating manure management CH_4 emissions (Text S2). Regional values of TAM_{pop} for asses, camels, horses, mules and llamas were derived from Table 10A.5 of (IPCC, 2019) Vol. 4, Chapter 10. Country-level stocks for these livestock were available from (FAOSTAT, 2020) ("Live Animals" domain), and we assumed that the stocks remained the same throughout the year. For chicken layers, we assumed TAM_{pop} to be the mean of adult female liveweight at the start (*AF1kg*) and at the end of laying period (*AF2kg*). Regional *AF1kg* and *AF2kg* were derived from Table 2.20 of the GLEAM v2.0 Documentation (FAO, 2017), and regional values were used for all countries in that region. Assuming an even distribution of age and liveweight from birth to slaughter, TAM_{pop} values for swine, chicken broiler, turkeys, and ducks were calculated as half of the liveweight at slaughter:

$$TAM_{pop,j,k,m} = \frac{Skg_{j,k,m}}{2} \quad (29)$$

where $Skg_{j,k,m}$ is the liveweight at slaughter for livestock category k in country j in year m. $Skg_{j,k,m}$ was calculated using Eqn (S5) with inputs of: i) the carcass weight for livestock category k in country j in year m ($CW_{k,j,m}$; i.e., yield in the (FAOSTAT, 2020) "Livestock Primary" domain); and the dressing percentage for livestock category k in country j ($DP_{k,j}$) derived from Table 9.2 of the GLEAM v2.0 Documentation (FAO, 2017) (regional values were used for all countries in that region). N_{pop} for swine, turkeys, and ducks were country-level stocks available from (FAOSTAT, 2020) ("Live Animals" domain), and we assumed that the stocks remained the same throughout the year. For chicken layers, we assumed N_{pop} to be the number of producing animals from (FAOSTAT, 2020) ("Livestock Primary" domain). N_{pop} for chicken broilers was then calculated as the country-level stock of chickens available from (FAOSTAT, 2020) ("Live Animals" domain) minus the number of chicken layers, N_{pop}.

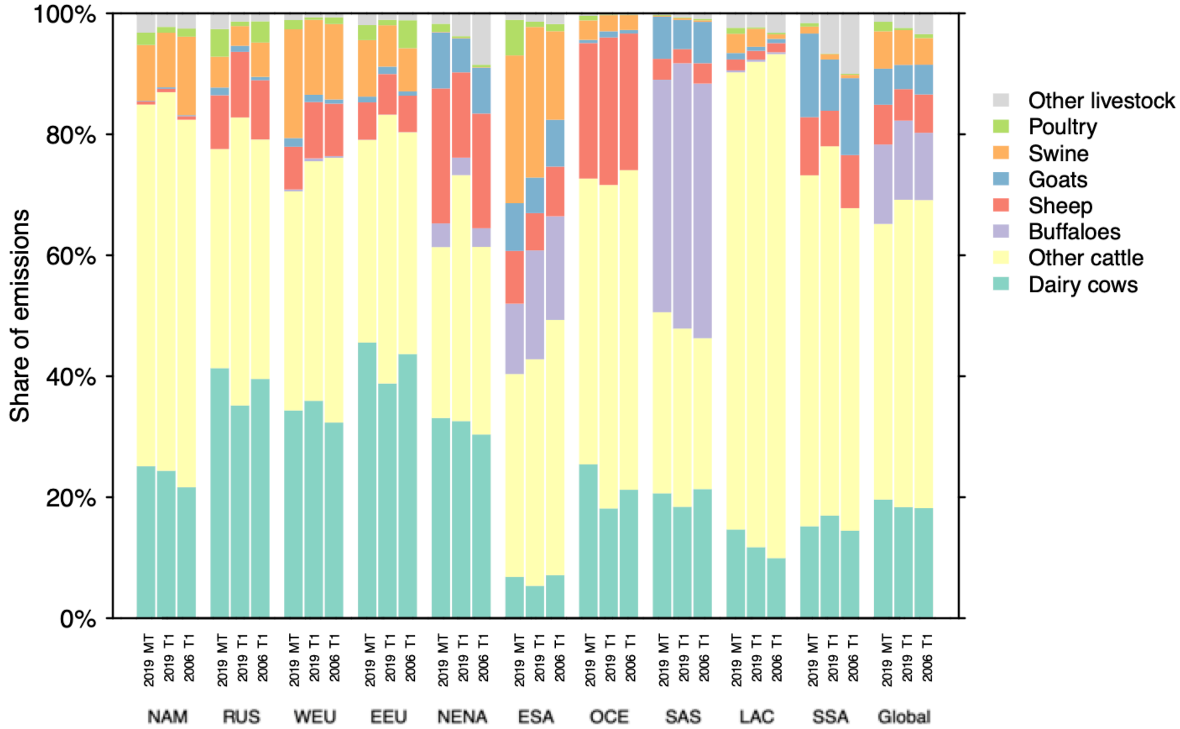


Figure S1. Each livestock category's share of total methane emissions in 2018.

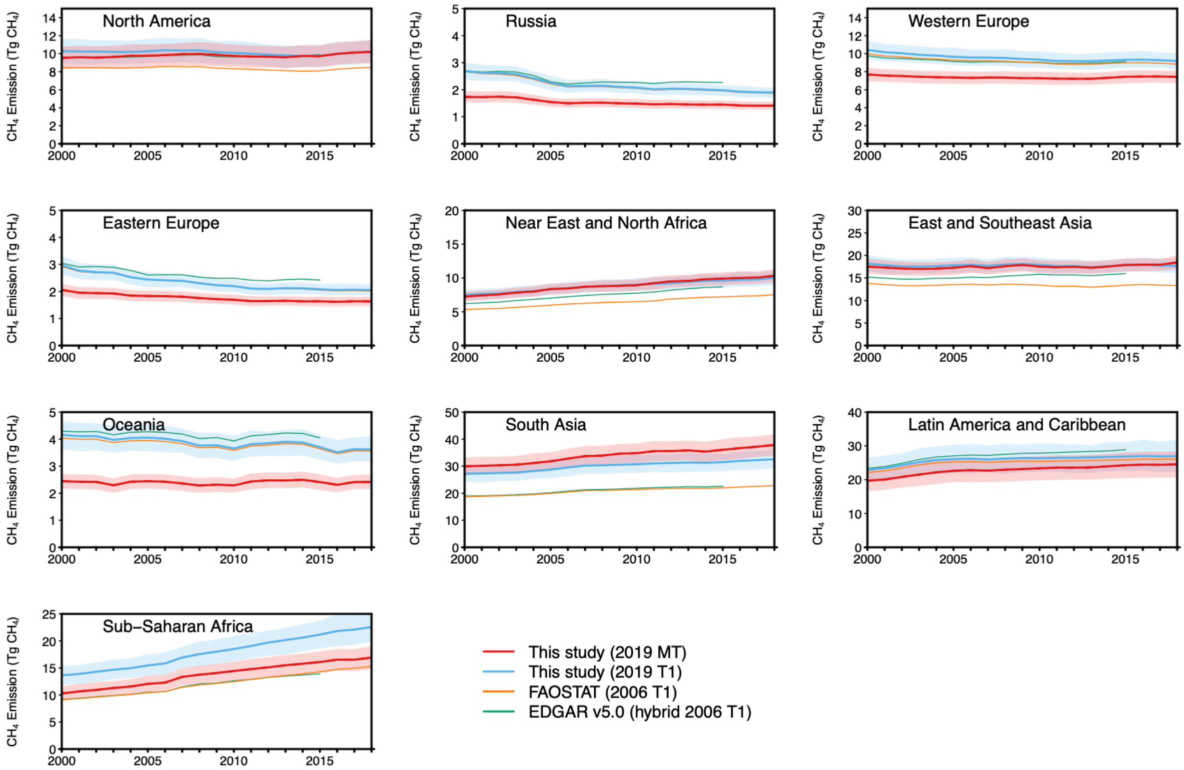


Figure S2. Regional livestock methane emissions for the period 2000-2018. Shaded areas indicate the 1-sigma standard deviation of the estimates using the 2019 MT method and the 2019 T1 method. Regions are classified following the definition of the FAO Global Livestock Environmental Assessment Model (GLEAM). Western and eastern Europe are combined as Europe.

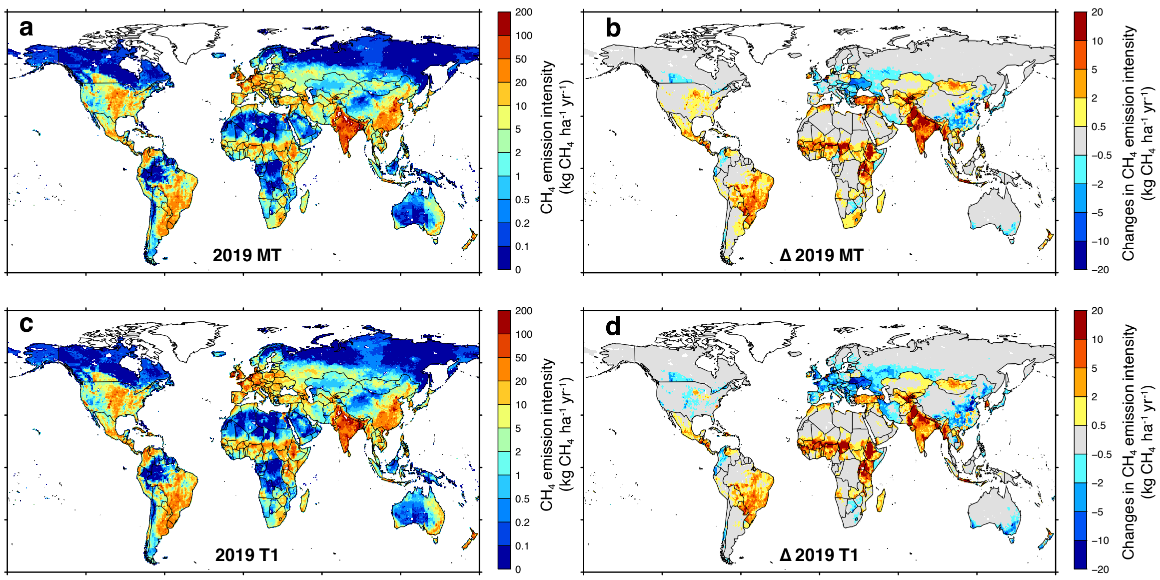


Figure S3. Gridded livestock methane emission intensity per area of land for the period 2000-2018 (a and c), and the changes in emission intensity per area of land between the period 2000-2004 and the period 2014-2018 (b and d) using the 2019 MT method (a and b) and the 2019 T1 method (c and d).

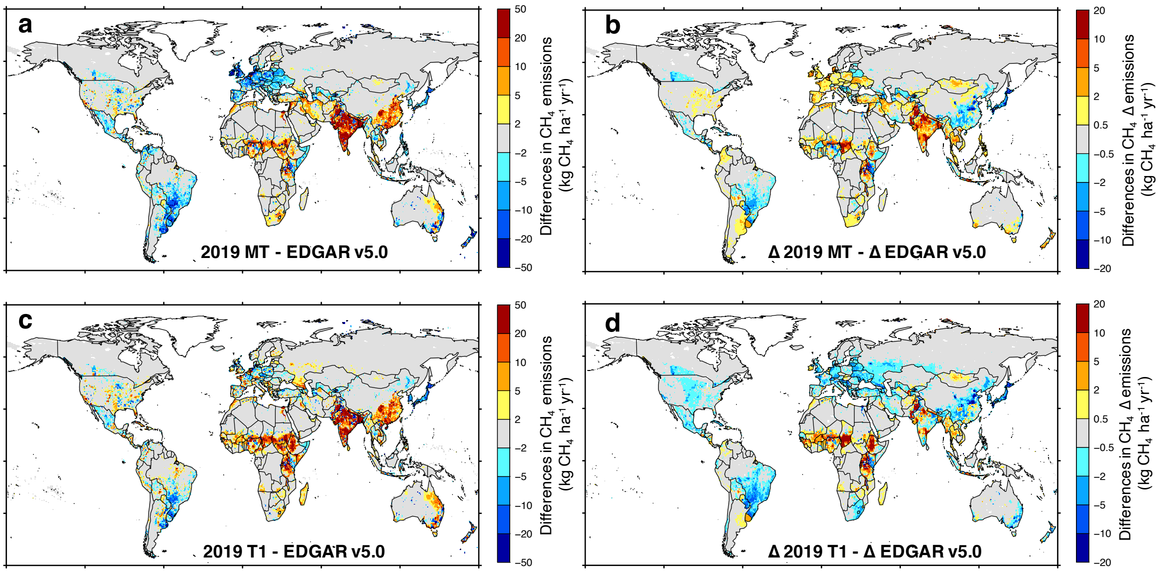


Figure S4. Differences between the gridded livestock methane emission intensity per area of land for the period 2000-2015 using the 2019 MT method, the 2019 T1 method and the hybrid 2006 T1 method by EDGAR v5.0 (a and c), and differences of the changes in emission intensity per area of land between the period 2000-2004 and the period 2014-2015 (b and d).

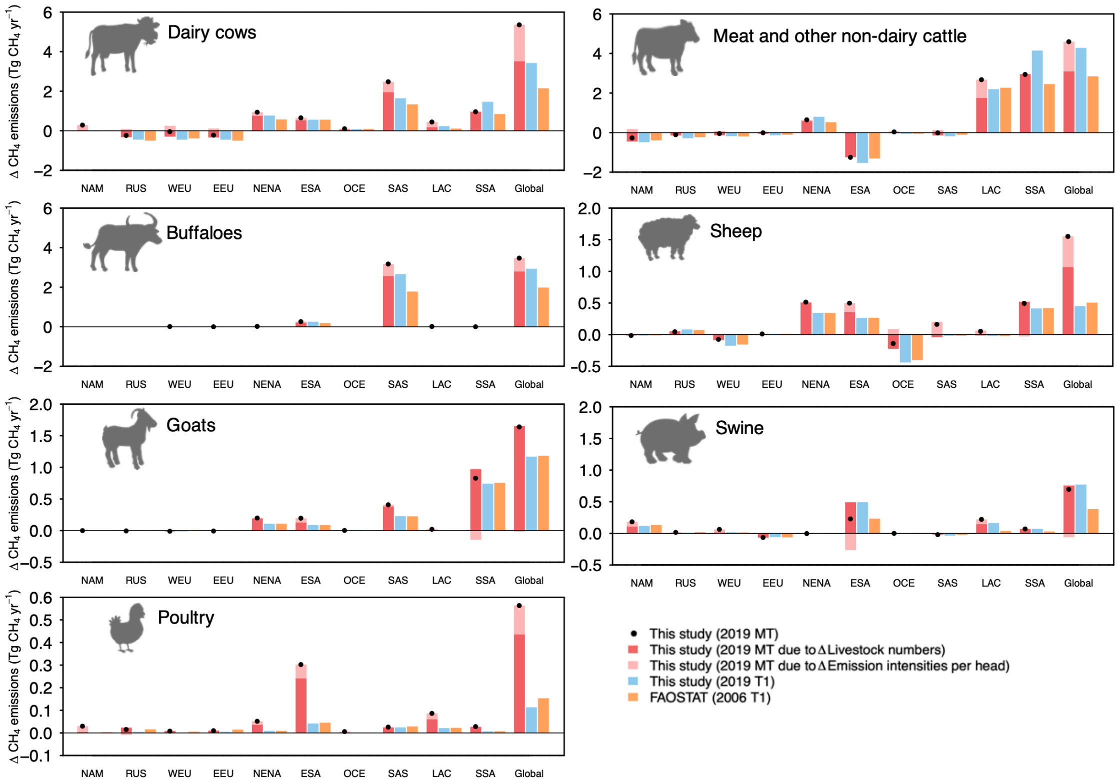


Figure S5. Global and regional changes in methane emissions from each livestock category between the periods 2000-2004 and 2014-2018, and the contributions due to changes in livestock numbers and changes in emission factors. Regions are classified following the definition of the FAO Global Livestock Environmental Assessment Model (GLEAM): NAM, North America; RUS, Russia; WEU, western Europe; EEU, eastern Europe, NENA, Near East and North Africa; EAS, eastern Asia; OCE, Oceania; SAS, south Asia; LAC, Latin America and Caribbean; SSA, Sub-Saharan Africa.

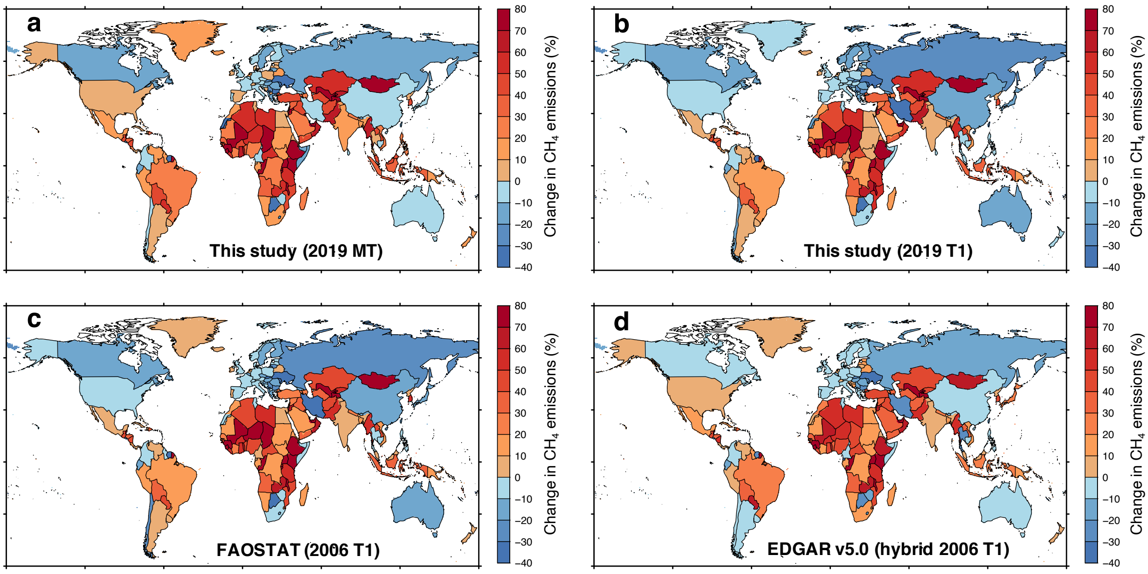
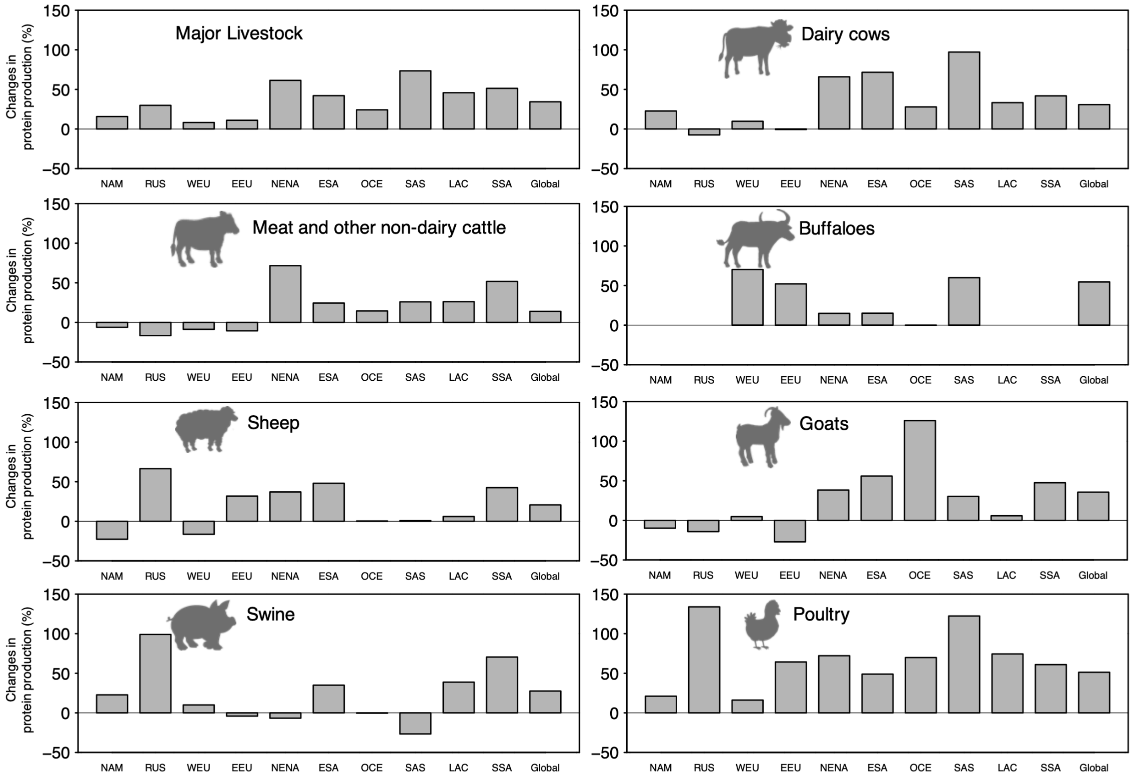


Figure S6. Comparison of the changes of livestock methane emissions between the periods 2000-2004 and 2014-2018 from this study using (a) the 2019 MT method and (b) the 2019 T1 method, and values from (c) FAOSTAT and (d) EDGAR v5.0 datasets. For the EDGAR v5.0 dataset, data for the period 2014-2015 were used as the latest period given the availability of the data.



457
458 **Figure S7. Relative changes in livestock protein production during the periods 2000-2004**
459 **and 2014-2018 for major livestock categories.**
460

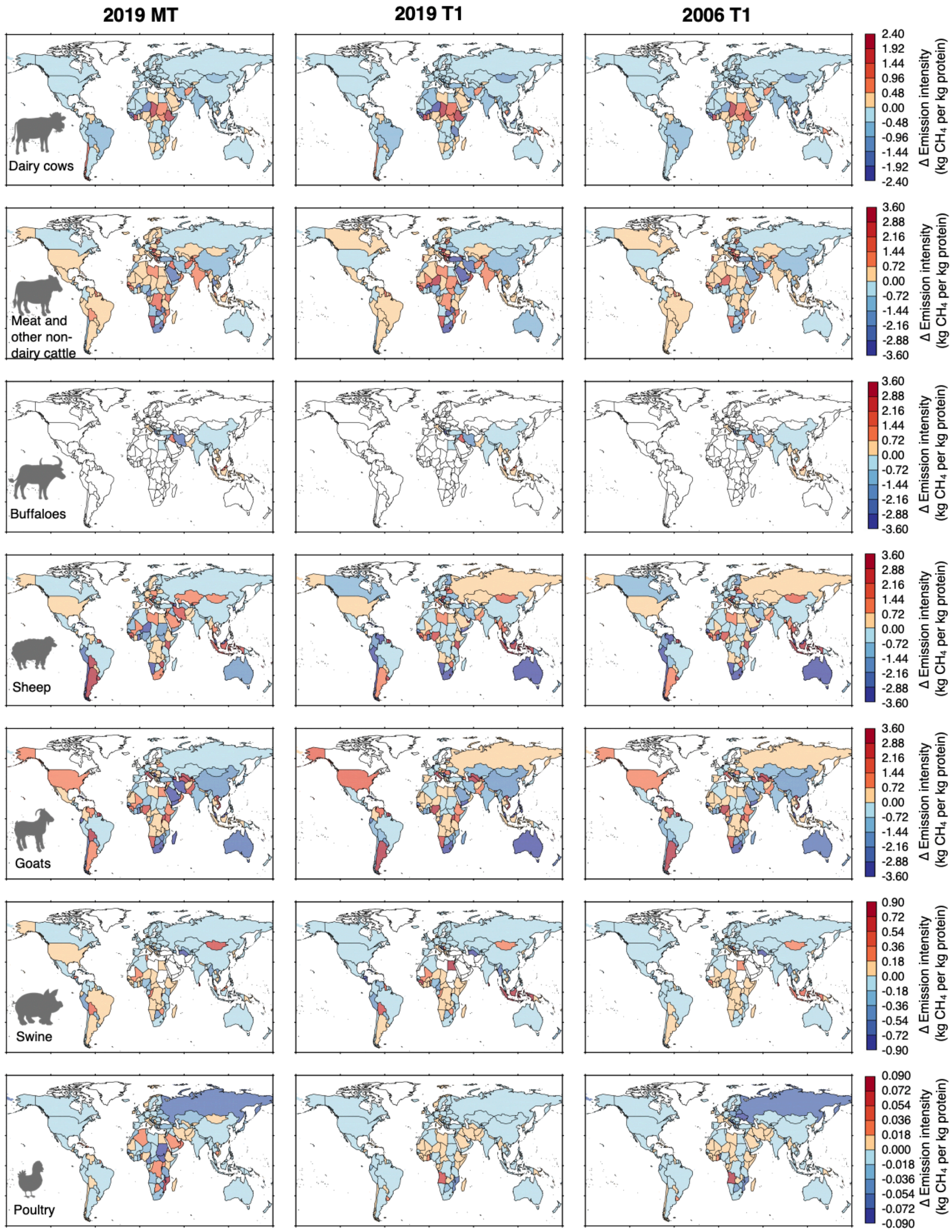
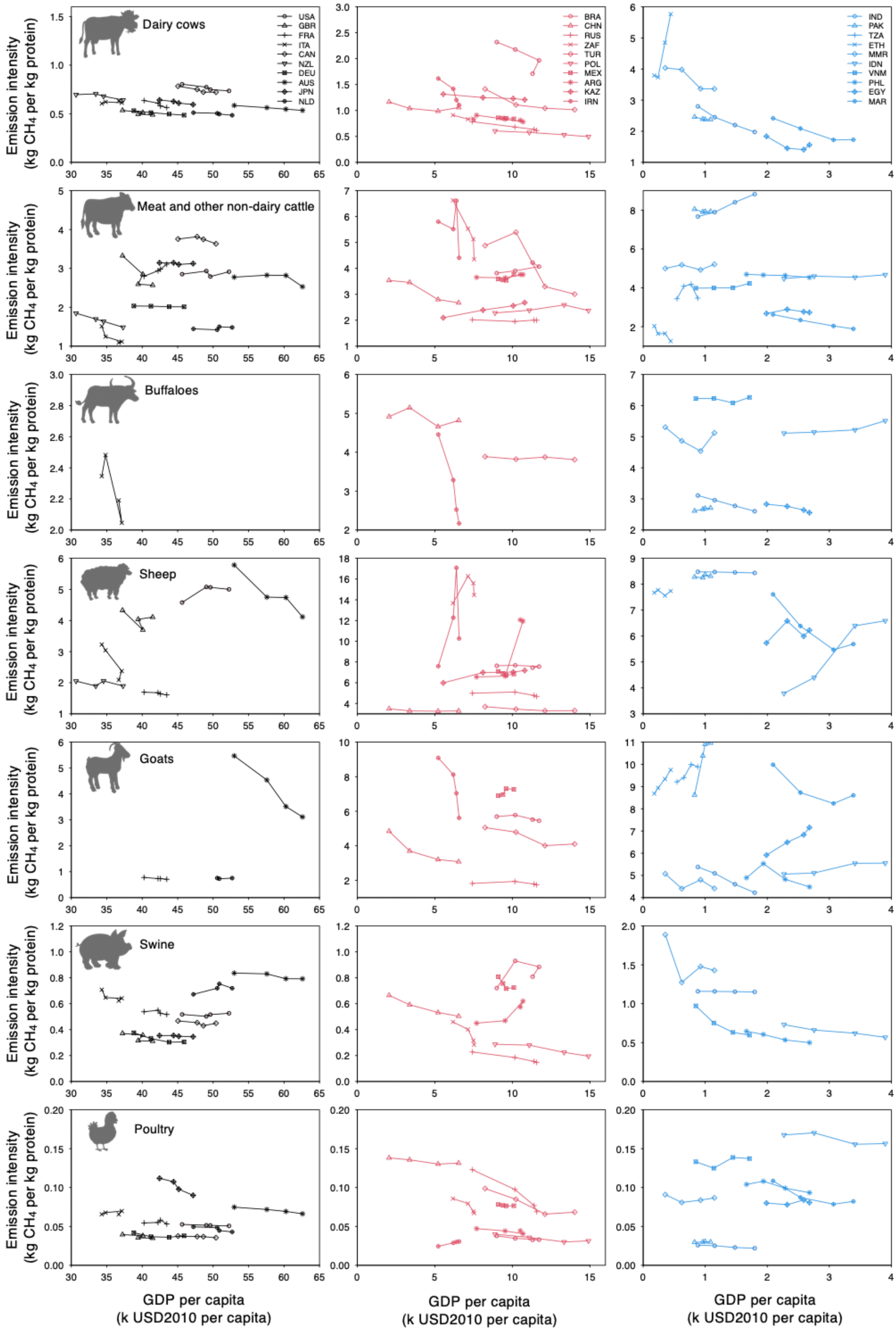


Figure S8. Changes in methane emission intensity per kg protein of each livestock category between the periods 2000-2004 and 2014-2018, resulting from the 2019 MT method, the 2019 T1 method, and the 2006 T1 method. Positive value indicates an increase in emission intensity per kg protein from 2000-2004 to 2014-2018, and negative value indicates a decrease in emission intensity per kg protein during the past two decades. Blank in the maps indicates that the livestock category does not exist in the country/area.



Dairy cows
Meat and other non-dairy cattle
Buffaloes
Sheep
Goats
Swine
Poultry
USA
GBR
FRA
ITA
CAN
NZL
DEU
AUS
JPN
NLD
BRA
CHN
RUS
ZAF
TUR
POL
MEX
ARG
KAZ
IRN
IND
PAK
TZA
ETH
MMR
IDN
VNM
PHL
EGY
MAR
Emission intensity (kg CH4 per kg protein)
GDP per capita (k USD2010 per capita)

Figure S9. Examples of the historical trends in emission intensity for major livestock categories from the 2019 MT method in relate to the development of GDP per capita. To avoid the strong inter-annual variation in emission intensity due to the variations in statistics, average emission intensity over four periods (2000-2004, 2005-2009, 2010-2014, 2014-2017) and the corresponding GDP per capita were shown. Here, we chose 30 countries as examples. They cover different ranges of GDP per capita, and represents a majority of livestock production for each category. For each livestock category, only countries within the top 30 producing countries were shown.

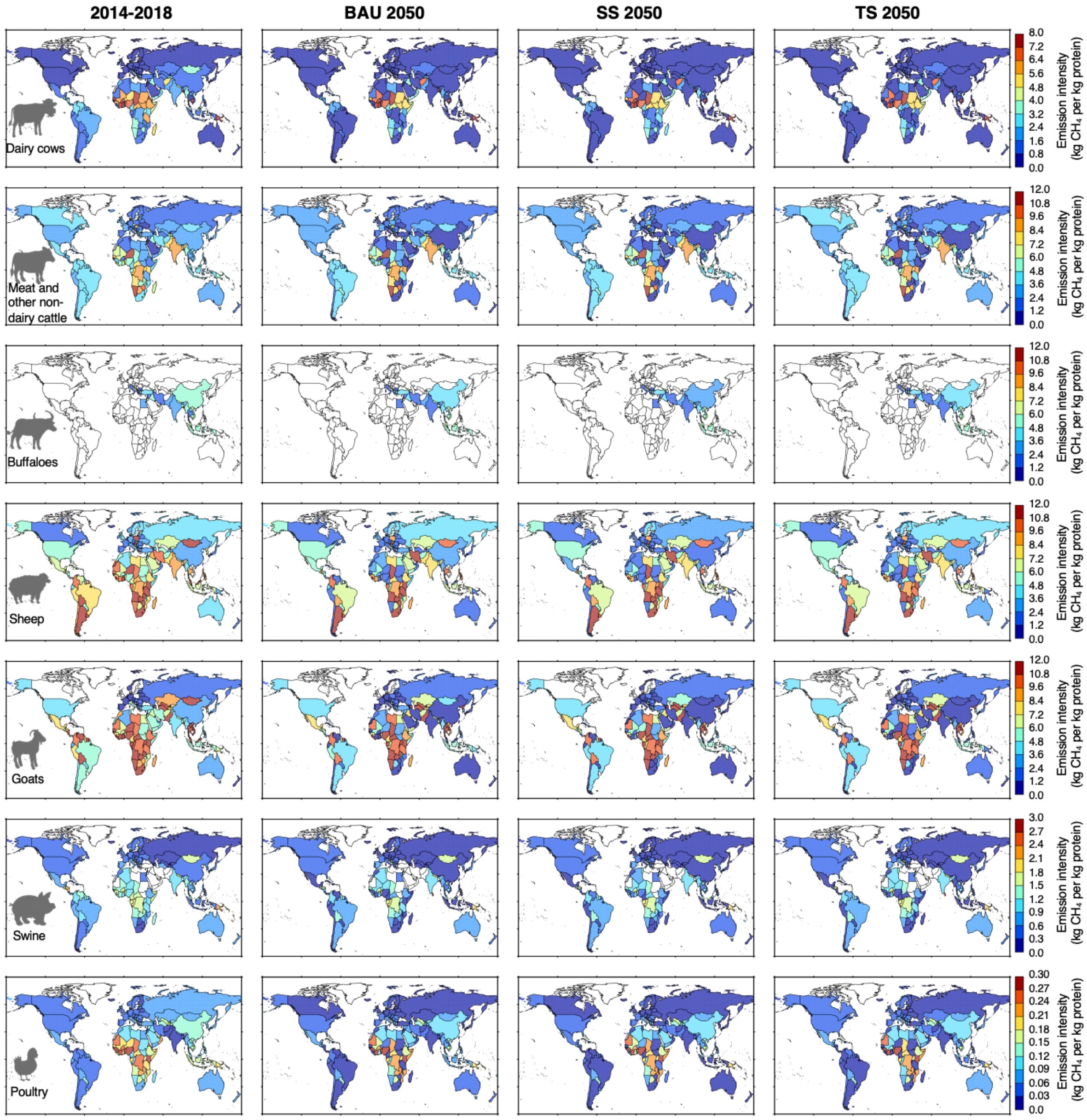


Figure S10. Methane emission intensity per kg protein of each livestock category during the period 2014-2018 and that projected by 2050 under different socio-economic scenarios resulting from the 2019 MT method. Socio-economic scenarios: Business As Usual (BAU), Stratified Societies (SS), and Toward Sustainability (TS).

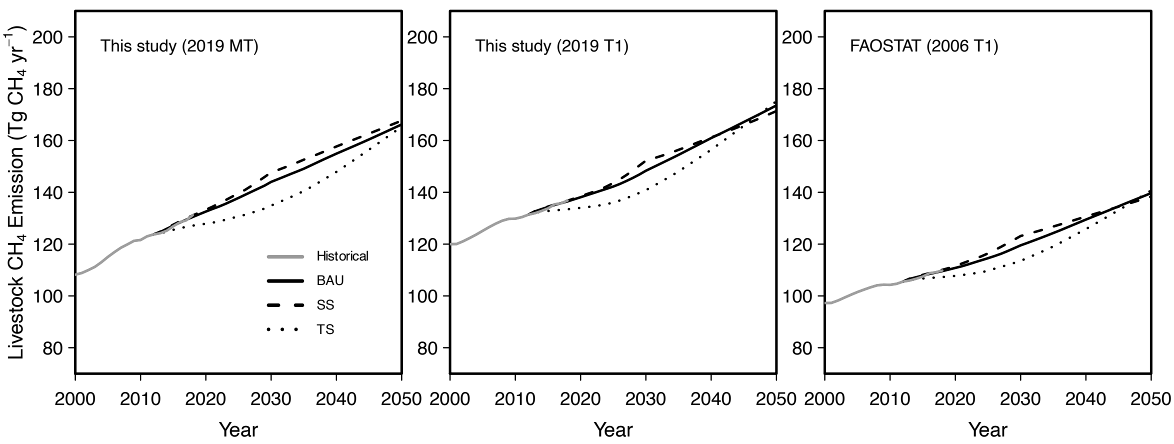


Figure S11. Projections of global livestock methane emissions under different socio-economic scenarios with a continuation of country-specific past trend with the development of GDP per capita allowing both increasing or decreasing emission intensity in the future. Socio-economic scenarios: Business As Usual (BAU), Stratified Societies (SS), and Toward Sustainability (TS).

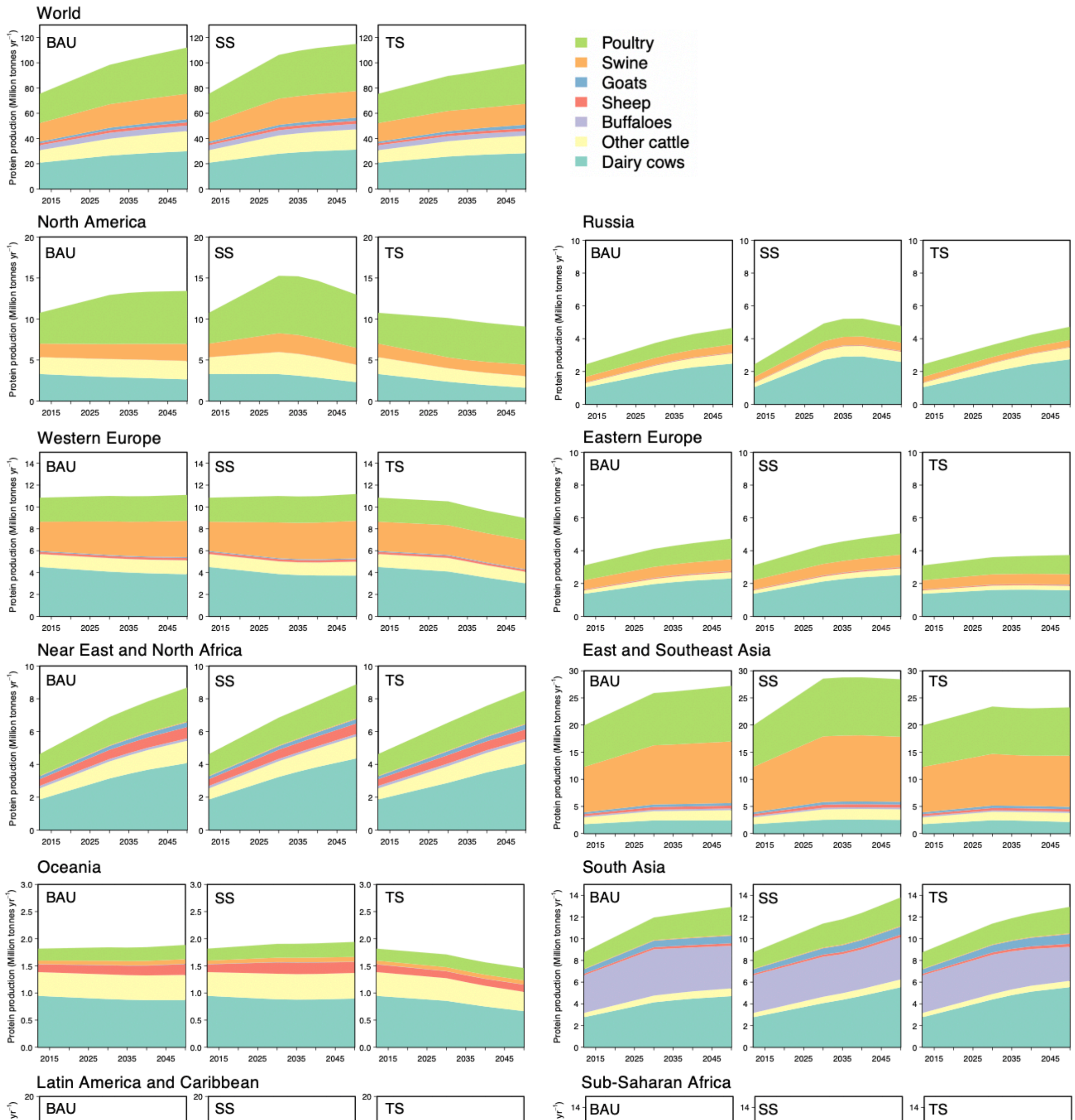


Figure S12. Projections of regional livestock protein production under different socio-economic scenarios. Socio-economic scenarios: Business As Usual (BAU), Stratified Societies (SS), and Toward Sustainability (TS). The projections for each livestock production was calculated as the protein production in year 2012 multiply the relative changes in protein production calculated in Eqn (7) of the main text.

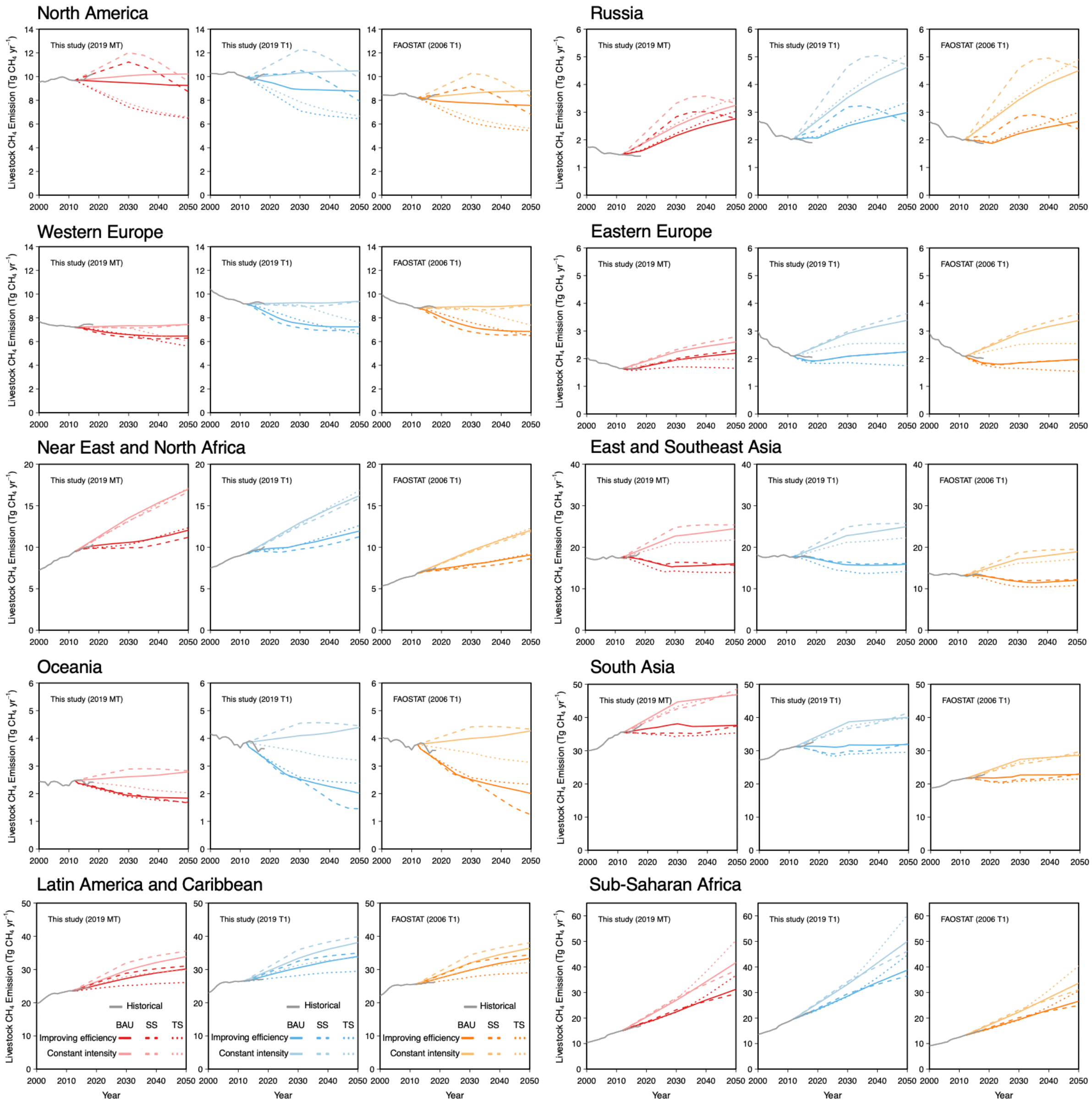


Figure S13. Projections of regional livestock methane emissions under different socio-economic scenarios and different emission intensity change pathways, resulting from the 2019 MT method, the 2019 T1 method, and the 2006 T1 method. Socio-economic scenarios: Business As Usual (BAU), Stratified Societies (SS), and Toward Sustainability (TS). Emission intensity change pathways: Constant emission intensity per kg protein and improving efficiency with decreasing emission intensity per kg protein. Regions are classified following the definition of the FAO Global Livestock Environmental Assessment Model (GLEAM): NAM, North America; RUS, Russia; WEU, western Europe; EEU, eastern Europe, NENA, Near East and North Africa; EAS, eastern Asia; OCE, Oceania; SAS, south Asia; LAC, Latin America and Caribbean; SSA, Sub-Saharan Africa.

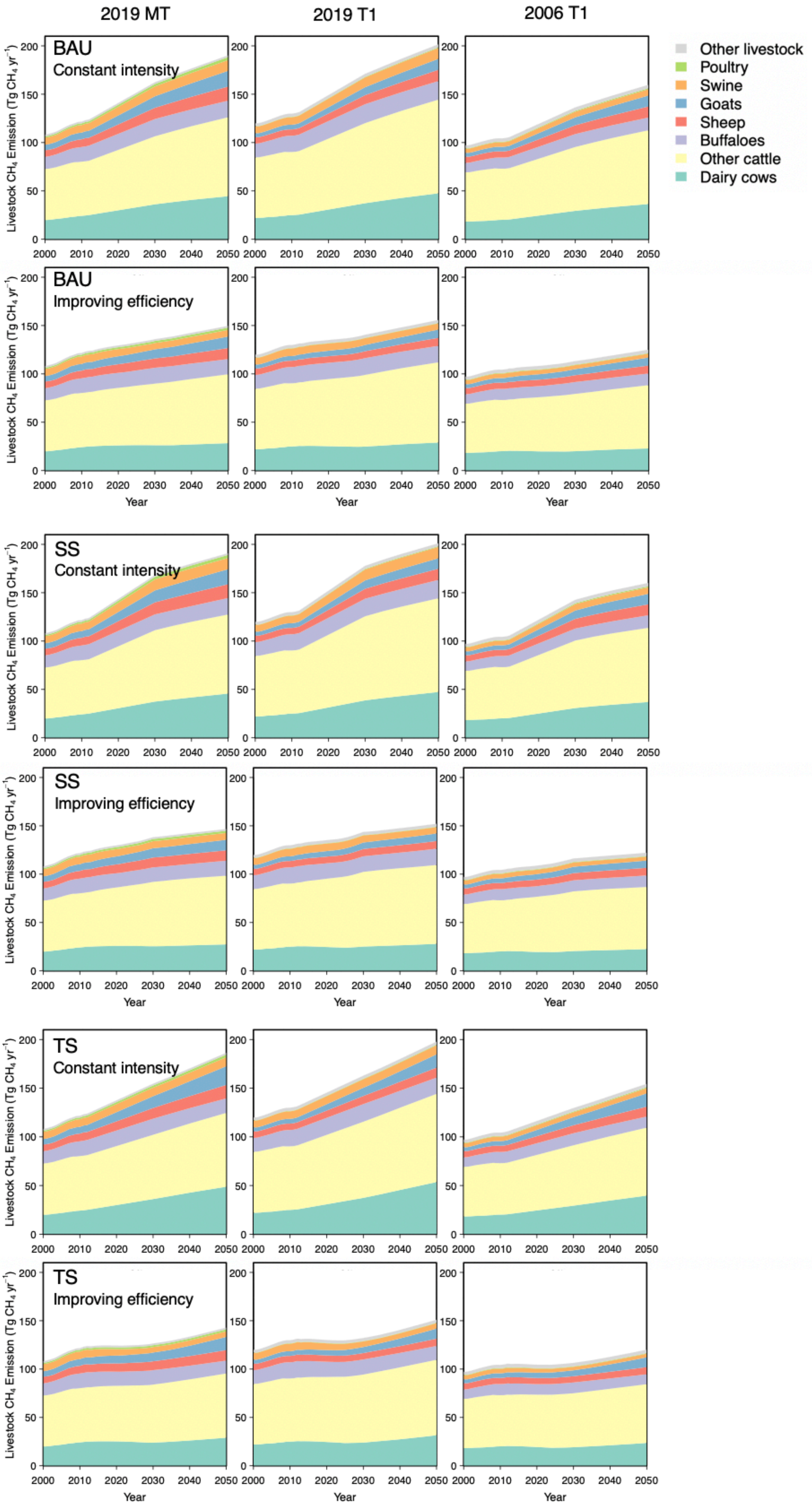

2019 MT
2019 T1
2006 T1
BAU
Constant intensity
BAU
Improving efficiency
SS
Constant intensity
SS
Improving efficiency
TS
Constant intensity
TS
Improving efficiency
Livestock CH4 Emission (Tg CH4 yr-1)
Year
Other livestock
Poultry
Swine
Goats
Sheep
Buffaloes
Other cattle
Dairy cows

Figure S14. Projections of global livestock methane emissions of each livestock category under different socio-economic scenarios and different emission intensity change pathways, resulting from the 2019 MT method, the 2019 T1 method, and the 2006 T1 method. Socio-economic scenarios: Business As Usual (BAU), Stratified Societies (SS), and Toward Sustainability (TS). Emission intensity change pathways: Constant emission intensity per kg protein and improving efficiency with decreasing emission intensity per kg protein. The values before 2012 are historical changes, and those after 2012 are projections.

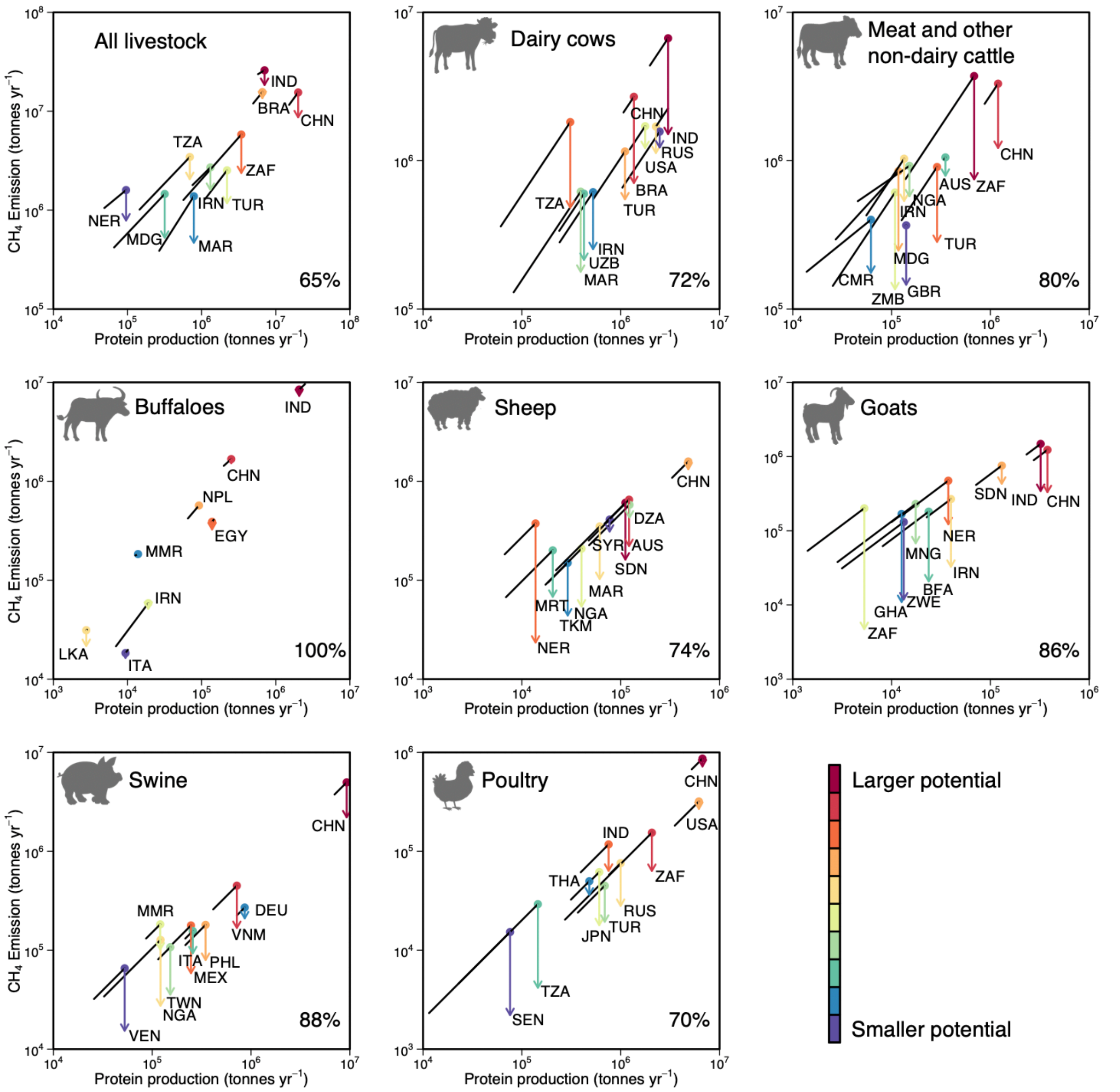


Figure S15. Projections on the increase in protein production, methane emission, and the effects of improving efficiency on reducing livestock methane emissions under the BAU scenarios, resulting from the 2019 MT method. The black lines indicate the protein production (x-axis) and methane emission (y-axis) from 2012 (start of black lines) to 2050 (dots). The arrows indicate the emission reduction potential by 2050 due to improving efficiency compared to the baseline where emission intensity is constant in the future. Results for the top ten countries/areas with the largest mitigation potential for all livestock and each livestock category were presented, with their ISO3 country codes (http://www.fao.org/countryprofiles/iso3list/en/) annotated near the dots or arrows. The red-yellow-violet color scheme represents the mitigation potential from large to small. The numbers (presented in percentage) in the sub-plots indicate the contribution of these ten countries/areas in global total mitigation potential for all livestock and each livestock category.

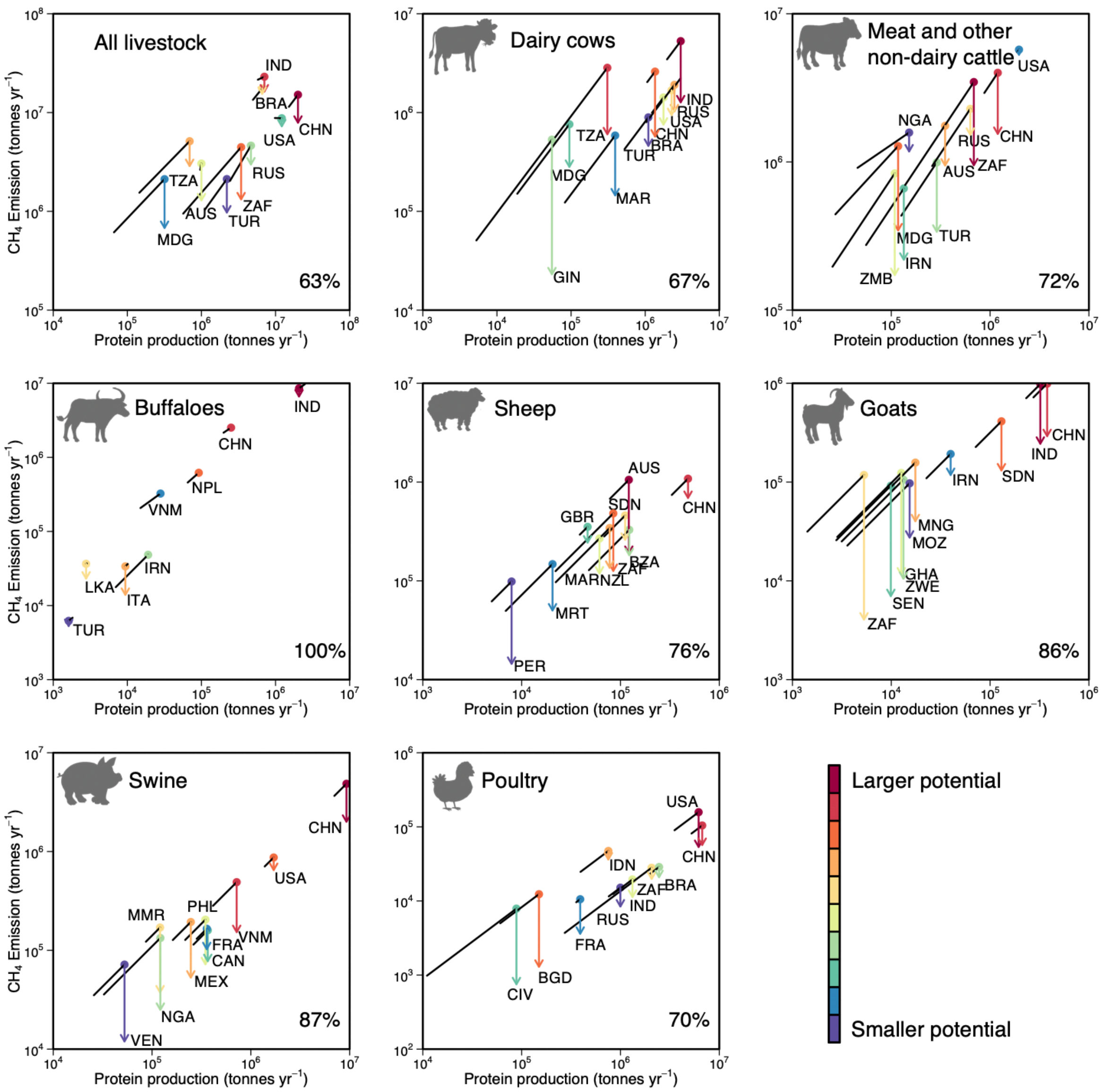


Figure S16. Projections on the increase in protein production, methane emission, and the effects of improving efficiency on reducing livestock methane emissions under the BAU scenarios, resulting from the 2019 T1 method. The black lines indicate the protein production (x-axis) and methane emission (y-axis) from 2012 (start of black lines) to 2050 (dots). The arrows indicate the emission reduction potential by 2050 due to improving efficiency compared to the baseline where emission intensity is constant in the future. Results for the top ten countries/areas with the largest mitigation potential for all livestock and each livestock category were presented, with their ISO3 country codes (http://www.fao.org/countryprofiles/iso3list/en/) annotated near the dots or arrows. The red-yellow-violet color scheme represents the mitigation potential from large to small. The numbers (presented in percentage) in the sub-plots indicate the contribution of these ten countries/areas in global total mitigation potential for all livestock and each livestock category.

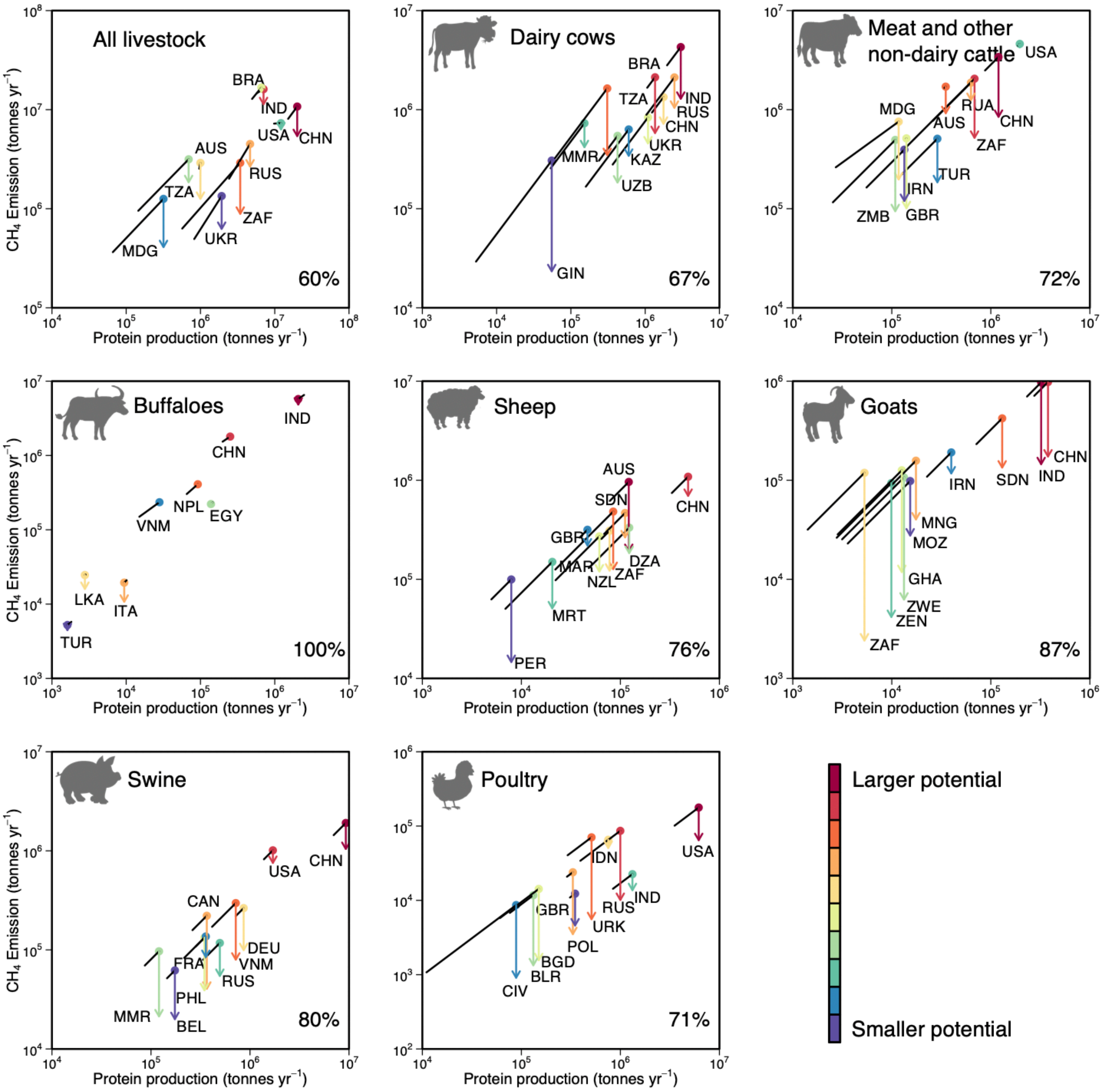


Figure S17. Projections on the increase in protein production, methane emission, and the effects of improving efficiency on reducing livestock methane emissions under the BAU scenarios, resulting from the 2006 T1 method. The black lines indicate the protein production (x-axis) and methane emission (y-axis) from 2012 (start of black lines) to 2050 (dots). The arrows indicate the emission reduction potential by 2050 due to improving efficiency compared to the baseline where emission intensity is constant in the future. Results for the top ten countries/areas with the largest mitigation potential for all livestock and each livestock category were presented, with their ISO3 country codes (http://www.fao.org/countryprofiles/iso3list/en/) annotated near the dots or arrows. The red-yellow-violet color scheme represents the mitigation potential from large to small. The numbers (presented in percentage) in the sub-plots indicate the contribution of these ten countries/areas in global total mitigation potential for all livestock and each livestock category.

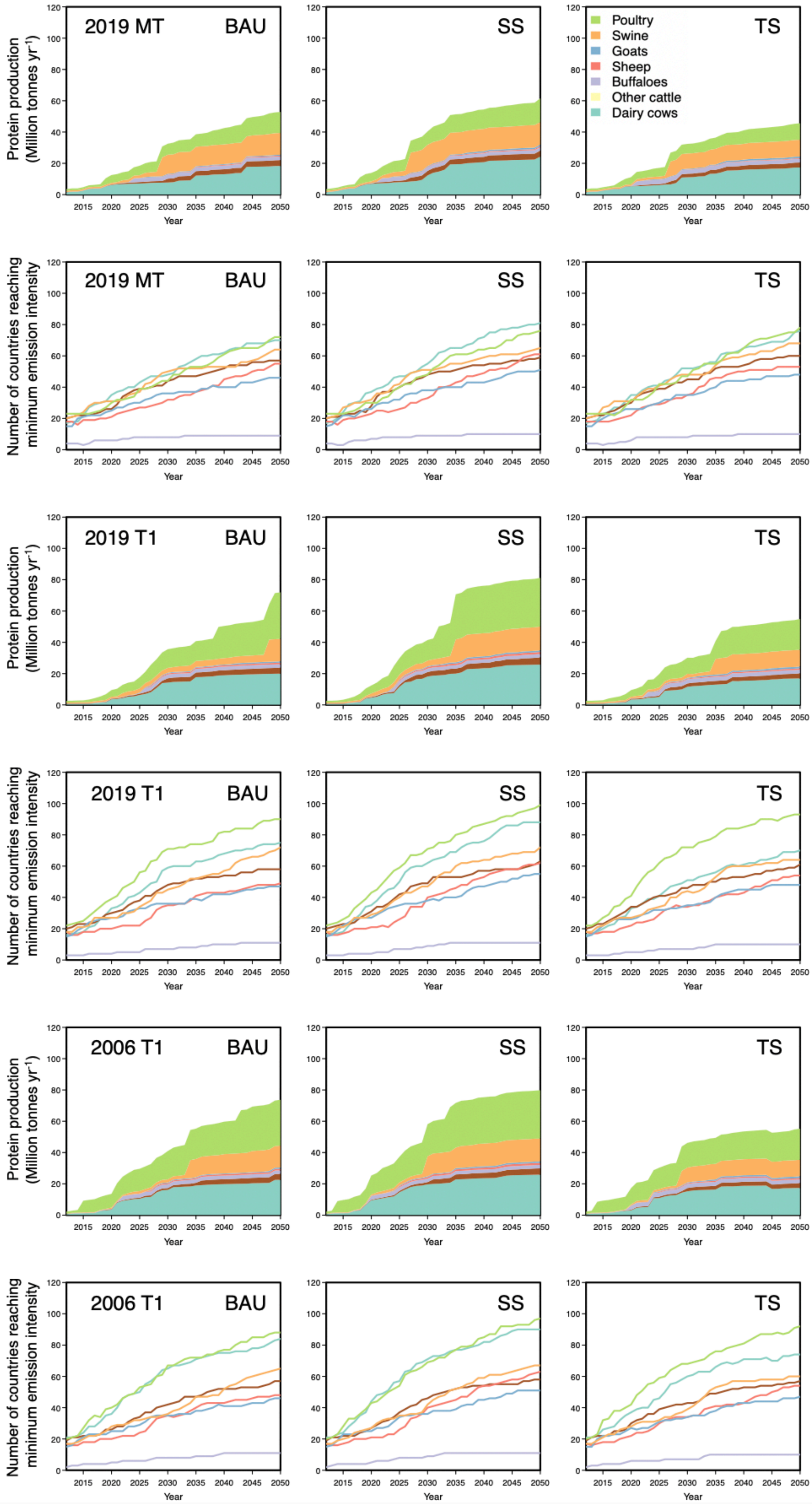

2019 MT
BAU
SS
TS
Poultry
Swine
Goats
Sheep
Buffaloes
Other cattle
Dairy cows
Protein production (Million tonnes yr⁻¹)
Number of countries reaching minimum emission intensity
2019 T1
2006 T1
Year

Figure S18. Number of countries/areas reaches the minimum emission intensity of each livestock category under different socio-economic scenarios, resulting from the 2019 MT method, the 2019 T1 method, and the 2006 T1 method. Socio-economic scenarios: Business As Usual (BAU), Stratified Societies (SS), and Toward Sustainability (TS).

Table S1. Comparison of global livestock methane emissions in the year 2010 and the methodologies used.

	Methane emissions (Tg CH_4 yr^{-1})			Methodology		
Dataset	Enteric fermentation	Manure management	Total livestock emissions	Enteric fermentation	Manure management	Name of the methods
This study (2019 MT)	108 ± 13	14 ± 1	122 ± 13	Based on the 2019 IPCC Tier 2 method for dairy cows, meat and other non-dairy cattle, buffaloes, sheep, and goats ((IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.21) based on gross energy intake of livestock (GE) and a conversion factor Ym calculated from regional digestibility of feed (DE), and the 2019 IPCC Tier 1 method for other livestock categories (see Methods for detail)	Based on the 2019 Tier 2 method ((IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.23), which calculates the emission factor using gross energy based estimate of *VS*, maximum methane producing capacity for manure produced by livestock (B_0), and methane conversion factors for each manure management system and each climate region (*MCF; see Methods for detail*)	2019 IPCC Mixed Tiers
This study (2019 T1)	116 ± 14	14 ± 1	130 ± 14	Based on the 2019 IPCC Tier 1 method ((IPCC, 2019) Vol.	The 2019 IPCC refinement revised the Tier 1 method	2019 IPCC Tier 1

				4, Chapter 10, Eqn 10.19) by multiplying livestock numbers and emission factors for enteric fermentation	((IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.22) by using livestock numbers, typical animal mass, volatile solid excreted (*VS*) by livestock, animal waste management system characteristics (*AWMS*), and methane emission factors (*MCF*) per unit of *VS* excretions	
(FAOSTAT, 2020) (2006 T1)	95	9	104	Based on the 2006 IPCC Tier 1 method by multiplying livestock numbers and emission factors for enteric fermentation ((IPCC, 2006) Vol. 4, Chapter 10, Eqn 10.19) and manure management ((IPCC, 2006) Vol. 4, Chapter 10, Eqn 10.22)		2006 IPCC Tier 1
EDGAR v5.0 (Crippa et al., 2020) (hybrid 2006 T1)	102	12	113	Based on the 2006 IPCC Tier 1 method, but uses country-specific milk yield and carcass weight trend for cattle emissions (not for other animal types like sheep and goats)		Hybrid 2006 IPCC Tier 1
EDGAR v4.3.2 (Janssens-Maenhout et	103	12	115	Same as EDGAR v5.0		Hybrid 2006 IPCC Tier 1

al., 2019)(hybrid 2006 T1)					
Wolf et al., 2017(Wolf et al., 2017)	105 ± 16	13 ± 2	118 ± 18	Based on the 2006 IPCC Tier 1 method with revised emission factors accounting for recent changes in animal body mass, feed quality and quantity, milk productivity, and management of animals and manure.	Revised 2006 IPCC Tier 1
EPA, 2012(EPA, 2012)	92	11	103	Based on the 2006 IPCC Tier 1 method and supplemented with country-reported inventory data (EPA, 2012 pp.1), with most of the enteric CH_4 emissions being from country-reported inventory data (Appendices of (EPA, 2012) pp. G-8 to G-9).	2006 IPCC Mixed Tiers[*]

[*] Given the fact that the majority of the reported data were derived from the UNFCCC flexible query system using higher IPCC Tiers, we called the method used by U.S. EPA data Mixed IPCC Tiers.

Table S2. Livestock methane emissions from each livestock category for the year 2018 and the methodologies used.

Livestock category	Methods / emission factors	Enteric fermentation emissions $F_{CH4-Enteric}$ (Gg CH_4 yr^{-1}) This study (2019 MT)	This study (2019 T1/T1a)	FAOSTAT (2006 T1)	Source of spatial distribution
Dairy cows	IPCC Tier 2	23319 ± 4850	22367 ± 4473 [22251 ± 4450]	17916	GLW3 Cattle
Meat and other non-dairy cattle	IPCC Tier 2	57798 ± 12020	66402 ± 13707 [66525 ± 13732]	54028	GLW3 Cattle
Sheep	IPCC Tier 2	8527 ± 1191	6984 ± 1352	6750	GLW3 Sheep
Goats	IPCC Tier 2	7607 ± 1438	5324 ± 1067	5230	GLW3 Goats
Buffalo	IPCC Tier 2	16597 ± 3452	17096 ± 3387	11363	GLW3 Buffaloes
Swine[§]	IPCC Tier 1[*]	1071 ± 215	1120 ± 204 [1239 ± 225]	1123	GLW3 Pigs
Chicken[¶]	-	0	0	0	GLW3 Chickens
Duck	-	0	0	0	GLW3 Ducks
Turkeys	-	0	0	0	GLW3 Chickens
Horses	IPCC Tier 1[*]	612 ± 130	1026 ± 217	1040	GLW3 Horses
Asses	IPCC Tier 1[*]	314 ± 66	505 ± 106	505	GLW3 Cattle
Camels	IPCC Tier 1[*]	612 ± 128	1410 ± 294	1634	GLW3 Cattle
Mules	IPCC Tier 1[*]	53 ± 11	85 ± 18	85	GLW3 Cattle
Llamas	IPCC Tier 1[*]	73 ± 14	73 ± 14	269	GLW3 Cattle
Total		116583 ± 13366	122391 ± 15004 [122517 ± 15020]	99942	

Livestock category	Method/emission factors	Manure management emissions $F_{CH4-Manure}$ (Gg CH_4 yr^{-1}) This study (2019 MT)	This study (2019 T1)	FAOSTAT (2006 T1)	Source of spatial distribution
Dairy cows	IPCC Tier 2	2402 ± 364	2756 ± 417	2063	GLW3 Cattle

Meat and other non-dairy cattle	IPCC Tier 2	2015 ± 298	3108 ± 460	1898	GLW3 Cattle
Sheep	IPCC Tier 2	109 ± 17	131± 20	194	GLW3 Sheep
Goats	IPCC Tier 2	208 ± 32	164 ± 25	181	GLW3 Goats
Buffalo	IPCC Tier 2	616 ± 91	814 ± 120	859	GLW3 Buffaloes
Swine[§]	Mixed IPCC Tiers [†]	7051 ± 1127	6748 ± 980	3710	GLW3 Pigs
Chicken[¶]	Mixed IPCC Tiers [†]	2062 ± 271	495 ± 67	667	GLW3 Chickens
Duck	Mixed IPCC Tiers [†]	7 ± 1	21 ± 3	16	GLW3 Ducks
Turkeys	Mixed IPCC Tiers [†]	51 ± 8	42 ± 7	34	GLW3 Chickens
Horses	Mixed IPCC Tiers [†]	82 ± 13	97 ± 15	89	GLW3 Horses
Asses	Mixed IPCC Tiers [†]	36 ± 5	42 ± 6	49	GLW3 Cattle
Camels	Mixed IPCC Tiers [†]	39 ± 6	51 ± 8	84	GLW3 Cattle
Mules	Mixed IPCC Tiers [†]	5 ± 1	7 ± 1	7	GLW3 Cattle
Llamas	Mixed IPCC Tiers [†]	1 ± 0	3 ± 1	11	GLW3 Cattle
Total		14627 ± 1250	14416 ± 1168	9863	

[#] Numbers in the brackets are estimates using the IPCC Tier 1a method (IPCC, 2019 Vol. 4, Chapter 10).

[§] Swine includes breeding and market swine.

[¶] Chicken includes broilers and layers.

[*] We applied an adjusted IPCC Tier 1 method (IPCC, 2006 Vol. 4, Chapter 10, Eqn 10.19) accounting for changes in liveweight (Sect. 2.3).

[†] We mixed Tier 1 and Tier 2 methods (IPCC, 2019 Vol. 4, Chapter 10), where volatile solids (*VS*) were calculated through Eqn 10.22A (Tier 1) and were applied in Equation 10.23 (Tier 2) for calculating manure management emissions.

Table S3. The minimum and maximum methane emission intensities for different livestock categories ($EF_{protein,k,min}$ and $EF_{protein,k,max}$) as the thresholds. The thresholds are derived as the 0.05-quantile (minimum) and 0.95-quantile (maximum) emission intensities per kg protein from all countries with more than 100 tonnes of protein production per year for each livestock category during the most recent 5-year period (2014-2018).

	minimum			maximum		
	This study (2019 MT)	This study (2019 T1)	FAOSTAT (2006 T1)	This study (2019 MT)	This study (2019 T1)	FAOSTAT (2006 T1)
	kg CH_4 per kg protein produced			kg CH_4 per kg protein produced		
Dairy cows	0.50	0.42	0.42	7.55	11.28	7.27
Meat and other non-dairy cattle	1.03	1.31	0.72	8.51	10.93	7.40
Buffaloes	2.21	1.89	1.45	6.25	8.68	5.85
Goats	0.86	0.76	0.45	16.82	14.43	14.58
Sheep	1.61	1.42	1.43	13.95	13.06	12.53
Swine	0.24	0.22	0.11	2.58	3.39	2.61
Poultry	0.029	0.009	0.010	0.280	0.082	0.115

Table S4. Comparison of enteric fermentation emission factors per head of livestock in the 2010s derived from the 2019 MT method in this study and the values for the Tier 1 method (the 2006 or 2019 T1 method). The enteric fermentation emission factors were calculated from the regional/global enteric fermentation emissions divided by the regional/global number of livestock for each category.

Emission factor per head of livestock (kg CH_4 per head)	**Dairy Cows**			**Meat and other non-dairy Cattle**			**Goats**	
	This study (2019 MT)	2019 T1[#]	2006 T1	This study (2019 MT)	2019 T1[#]	2006 T1	This study (2019 MT)	2006/2019 T1
North America	145	138	128	61	64	53	4	5 (2006 IPCC Guidelines); 9 / 5 (2019 Refinement)[§]
Russia	78	93	99	35	58	58	9	
Western Europe	95	126	117	39	52	57	8	
Eastern Europe	83	93	99	37	58	58	6	
Near East and North Africa	79	76 (94/62)	46	43	60 (61/55)	31	9	
East and Southeast Asia	90	78 (96/71)	68	50	54 (43/56)	47	7	
Oceania	84	93	90	37	63	60	4	
South Asia	93	73 (70/74)	58	54	46 (41/47)	27	8	
Latin America and Caribbean	96	87 (103/78)	72	48	56 (55/58)	56	7	
Sub-Saharan Africa	53	76 (86/66)	46	38	52 (60/48)	31	6	
Global	85	85	68	47	54	44	7	

Emission factor per head of livestock (kg CH_4 per head)	**Sheep**		**Buffaloes**			**Swine**	
	This study (2019 MT)	2006/2019 T1	This study (2019 MT)	2019 T1	2006 T1	This study (2019 MT)	2006/2019 T1

North America	9		-	-		1.3	
Russia	6		-	-		1.2	
Western Europe	5		50	78		1.2	
Eastern Europe	7		50	68		1.2	
Near East and North Africa	8	8 / 5 (2006 IPCC Guidelines) [§]; 9 / 5 (2019 Refinement) [§]	95	67	55	1.1	1.5 / 1 (2006 IPCC Guidelines and 2019 Refinement) [§]
East and Southeast Asia	7		47	76		1.2	
Oceania	5		-	-		0.9	
South Asia	9		85	85		0.7	
Latin America and Caribbean	5		54	68		1.3	
Sub-Saharan Africa	7		66	81		0.8	
Global	7		77	83		1.2	

[#] For Latin America, Asia, Africa, Middle East, and Indian Subcontinent, reginal mean emission factors are presented first, followed by emission factors for high/low productivity systems shown in the brackets.

[§] Values are presented as emission factors for high/low productivity systems, respectively following (IPCC, 2019 Vol. 4, Chapter 10).

Reference

Crippa, M., Solazzo, E., Huang, G., Guizzardi, D., Koffi, E., Muntean, M., et al. (2020). High resolution temporal profiles in the Emissions Database for Global Atmospheric Research. *Scientific Data, 7*(1), 121. https://doi.org/10.1038/s41597-020-0462-2

EPA. (2012). Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030. . *United States Environment Protection Agency, Washington DC. .*

FAO. (2017). Global livestock environmental assessment model - Model Description Version 2.0 (GLEAM 2.0). *Rome.*

FAOSTAT. (2020). *http://www.fao.org/faostat/en/#home (Accessed: 2020-09-22).*

Fischer, G., Nachtergaele, F., Prieler, S., Van Velthuizen, H., Verelst, L., & Wiberg, D. (2008). Global agro-ecological zones assessment for agriculture (GAEZ 2008). *IIASA, Laxenburg, Austria and FAO, Rome, Italy, 10.*

Gilbert, M., Nicolas, G., Cinardi, G., Van Boeckel, T. P., Vanwambeke, S. O., Wint, G. R. W., & Robinson, T. P. (2018). Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010. *Scientific Data, 5*, 180227. Data Descriptor. https://doi.org/10.1038/sdata.2018.227

Harris, I. C. (2019). *CRU JRA v1. 1: A forcings dataset of gridded land surface blend of Climatic Research Unit (CRU) and Japanese reanalysis (JRA) data* (2905 ed. Vol. 2905): University of East Anglia Climatic Research Unit Centre for Environmental Data Analysis.

IPCC. (2006). *2006 IPCC guidelines for national greenhouse gas inventories. Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. (eds)* (Vol. 4). Hayama, Japan: Institute for Global Environmental Strategies.

IPCC. (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds)* (Vol. 4). Switzerland: IPCC.

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., et al. (2019). EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012. *Earth Syst. Sci. Data, 11*(3), 959-1002. https://www.earth-syst-sci-data.net/11/959/2019/

Müller, D. W. H., Codron, D., Meloro, C., Munn, A., Schwarm, A., Hummel, J., & Clauss, M. (2013). Assessing the Jarman–Bell Principle: Scaling of intake, digestibility, retention time and gut fill with body mass in mammalian herbivores. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology, 164*(1), 129-140. http://www.sciencedirect.com/science/article/pii/S1095643312004795

Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M., et al. (2013). Greenhouse gas emissions from ruminant supply chains–A global life cycle assessment. *Food and agriculture organization of the United Nations (FAO), Rome*, 1-214.

U.S. Congress, O. o. T. A. (1991). *Energy in Developing Countries, OTA-E-486 (Washington, DC: U.S. Government Printing Office, January 1991)*. Retrieved from

Wolf, J., Asrar, G. R., & West, T. O. (2017). Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock. *Carbon balance and management, 12*(1), 16.

Zomer, R., Bossio, D., Trabucco, A., Yuanjie, L., Gupta, D., & Singh, V. (2007). Trees and Water: Smallholder Agroforestry on Irrigated Lands in Northern India. Colombo, Sri Lanka: International Water Management Institute. pp 45. (IWMI Research Report 122).

Zomer, R., Trabucco, A., Bossio, D., & Verchot, L. V. (2008). Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. *Agriculture, Ecosystems & Environment, 126*(1-2), 67-80.