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Supporting Information for

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

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**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):

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

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):

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

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:

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

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:

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

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

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:

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

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

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:

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

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

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:

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

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, $N_{pop}$.

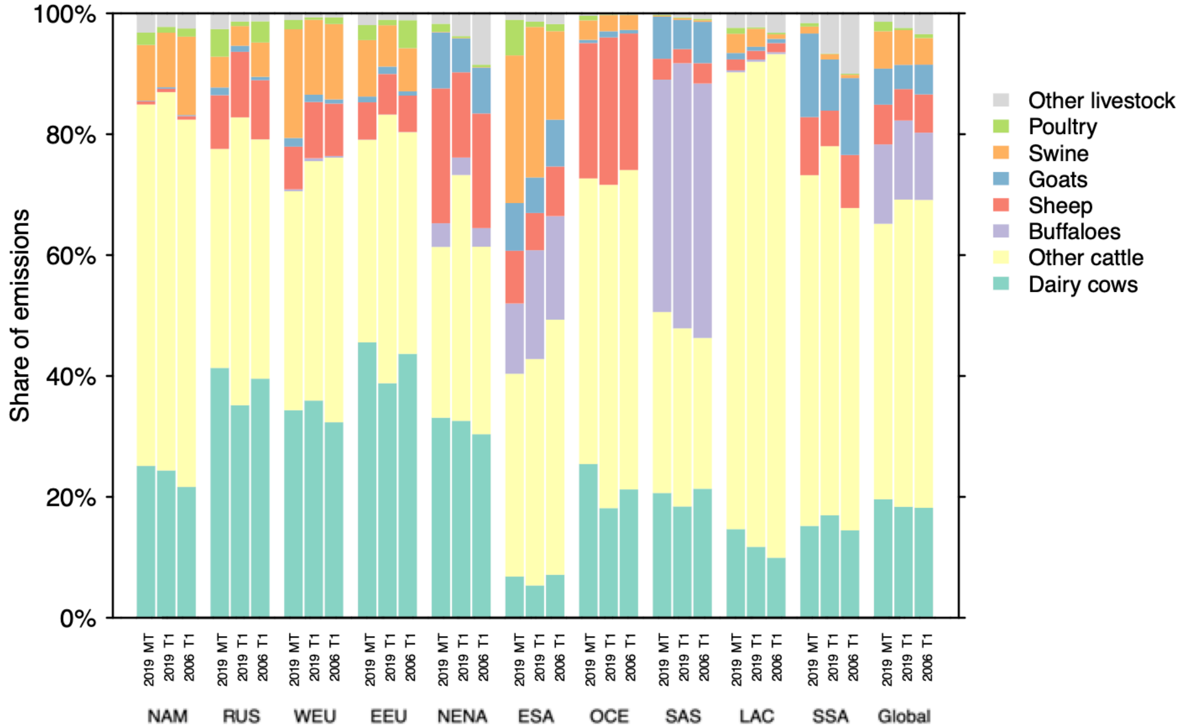



**Figure S1. Each livestock category's share of total methane emissions in 2018.**

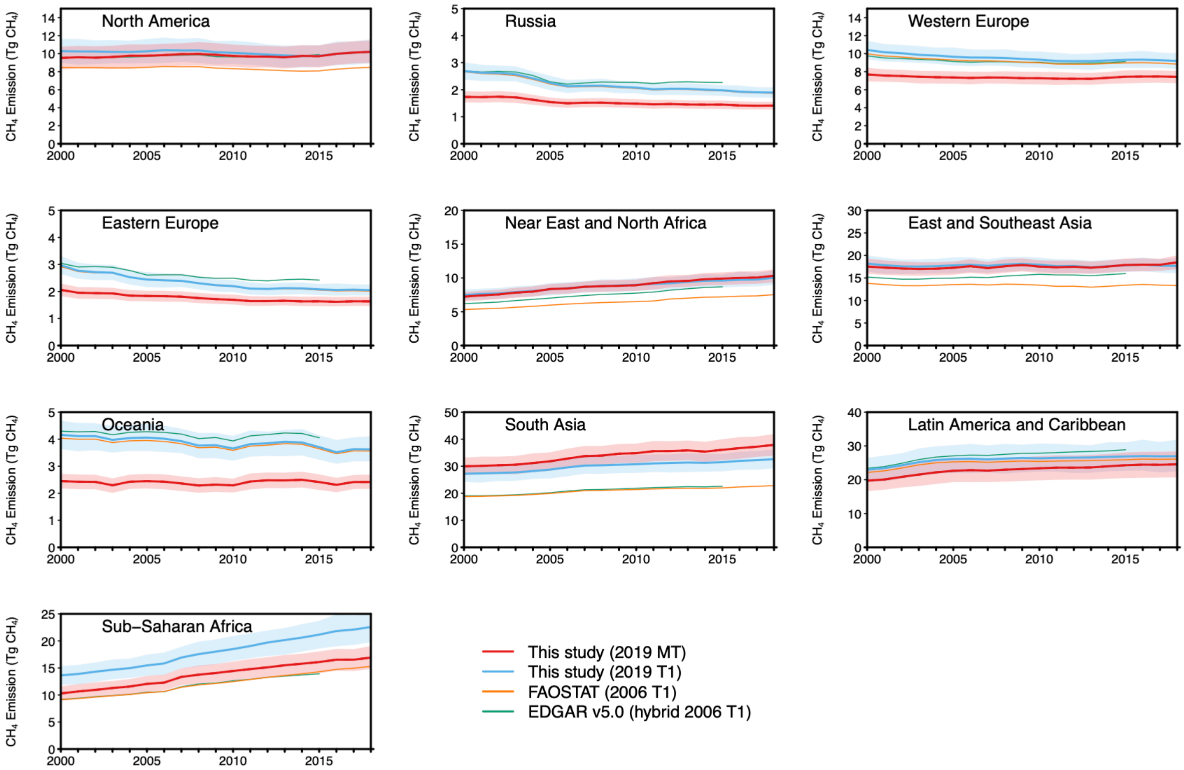



**Figure S2. Regional livestock methane emissions for the period 2000-2018.** Shaded areas indicate the 1-sigma standard deviation of the estimates using the 2019 MT method and the 2019 T1 method. Regions are classified following the definition of the FAO Global Livestock Environmental Assessment Model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

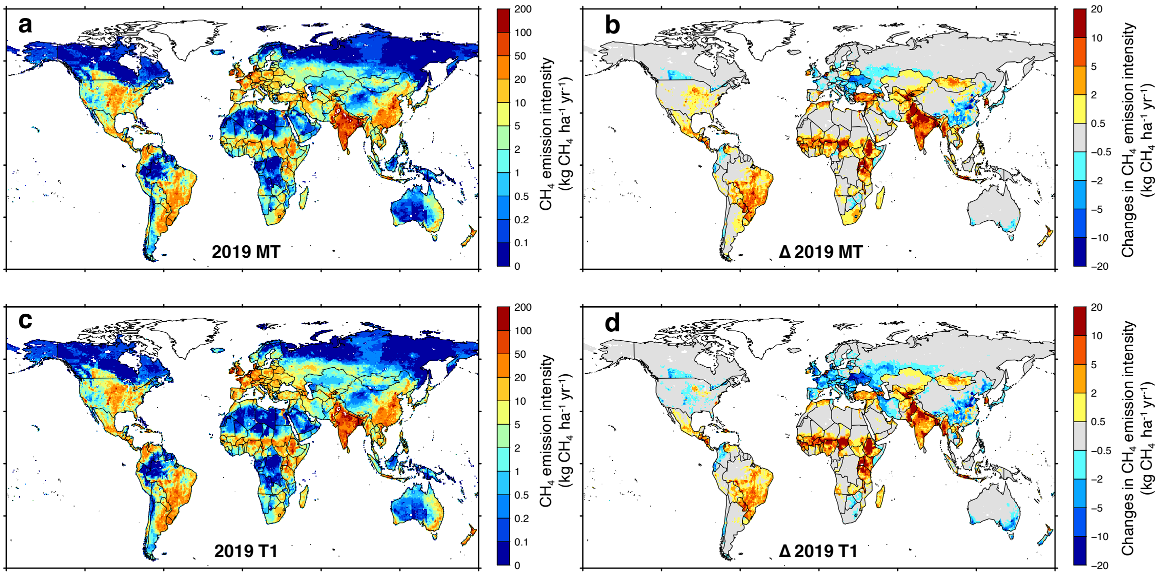



**Figure S3. Gridded livestock methane emission intensity per area of land for the period 2000-2018 (a and c), and the changes in emission intensity per area of land between the period 2000-2004 and the period 2014-2018 (b and d) using the 2019 MT method (a and b) and the 2019 T1 method (c and d).**

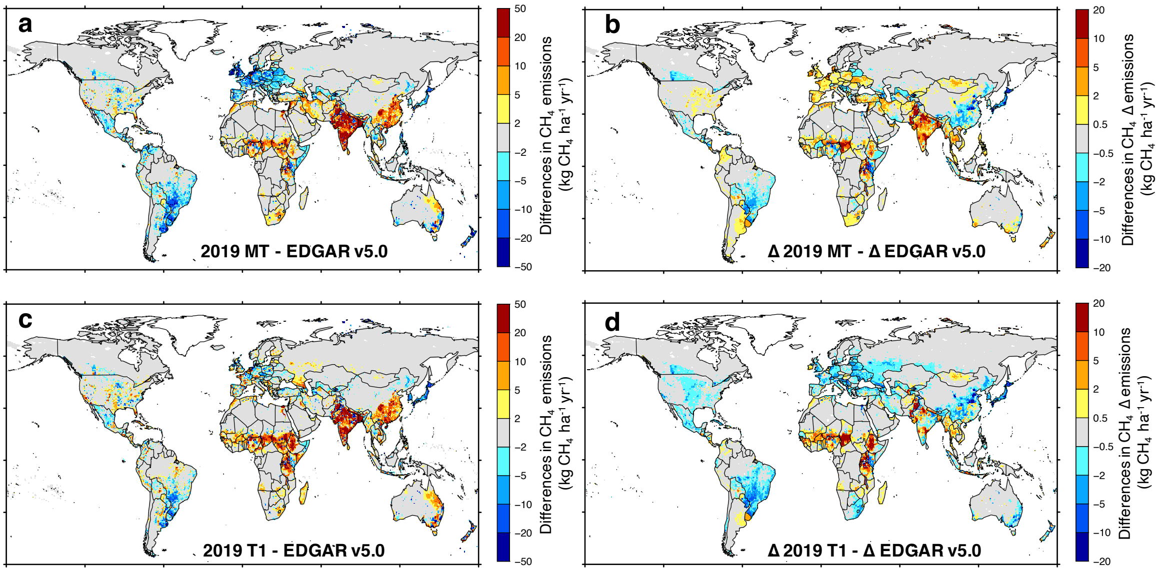



**Figure S4. Differences between the gridded livestock methane emission intensity per area of land for the period 2000-2015 using the 2019 MT method, the 2019 T1 method and the hybrid 2006 T1 method by EDGAR v5.0 (a and c), and differences of the changes in emission intensity per area of land between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

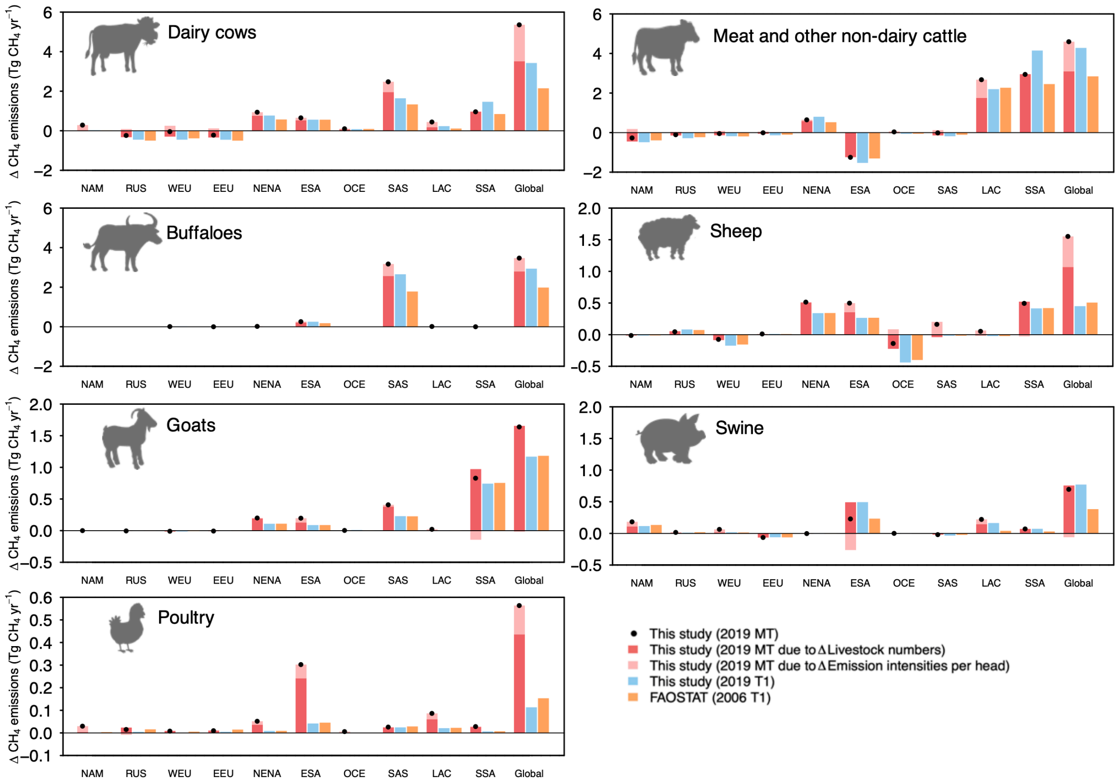



**Figure S5. Global and regional changes in methane emissions from each livestock category between the periods 2000-2004 and 2014-2018, and the contributions due to changes in livestock numbers and changes in emission factors.** Regions are classified following the definition of the FAO Global Livestock 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.

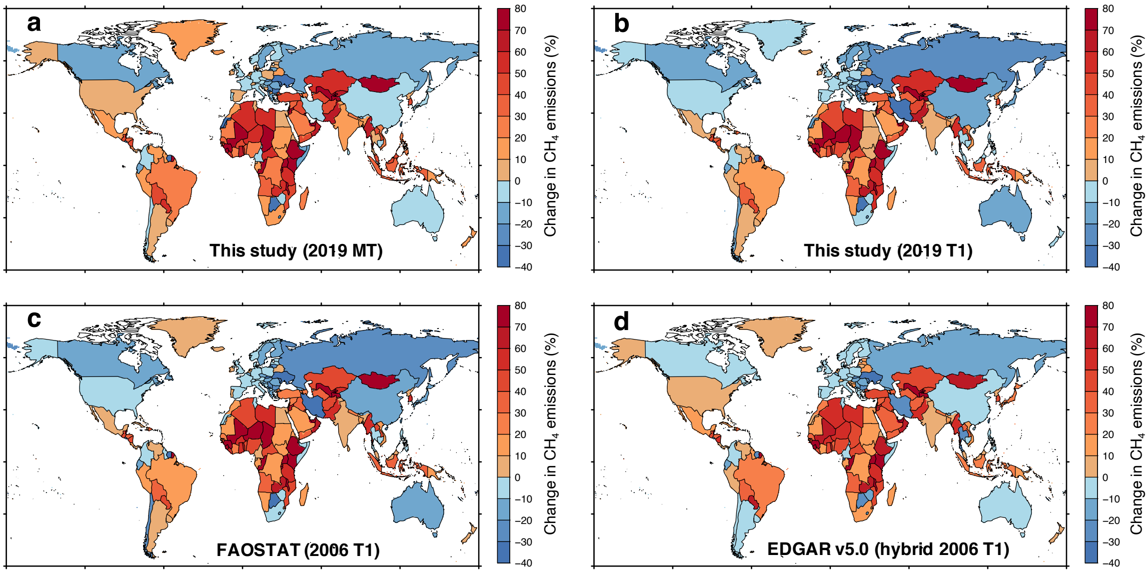



**Figure S6. Comparison of the changes of livestock methane emissions between the periods 2000-2004 and 2014-2018 from this study using (a) the 2019 MT method and (b) the 2019 T1 method, and values from (c) FAOSTAT and (d) EDGAR v5.0 datasets.** For the EDGAR v5.0 dataset, data for the period 2014-2015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

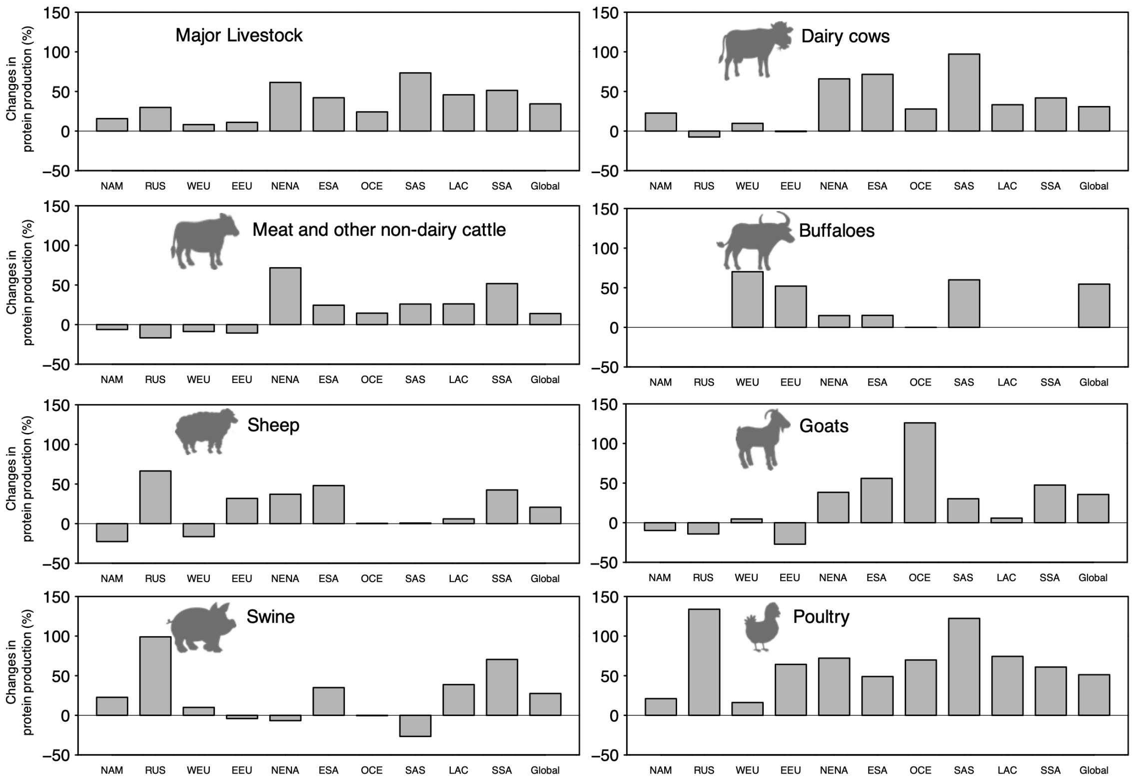



**Figure S7. Relative changes in livestock protein production during the periods 2000-2004 and 2014-2018 for major livestock categories.**

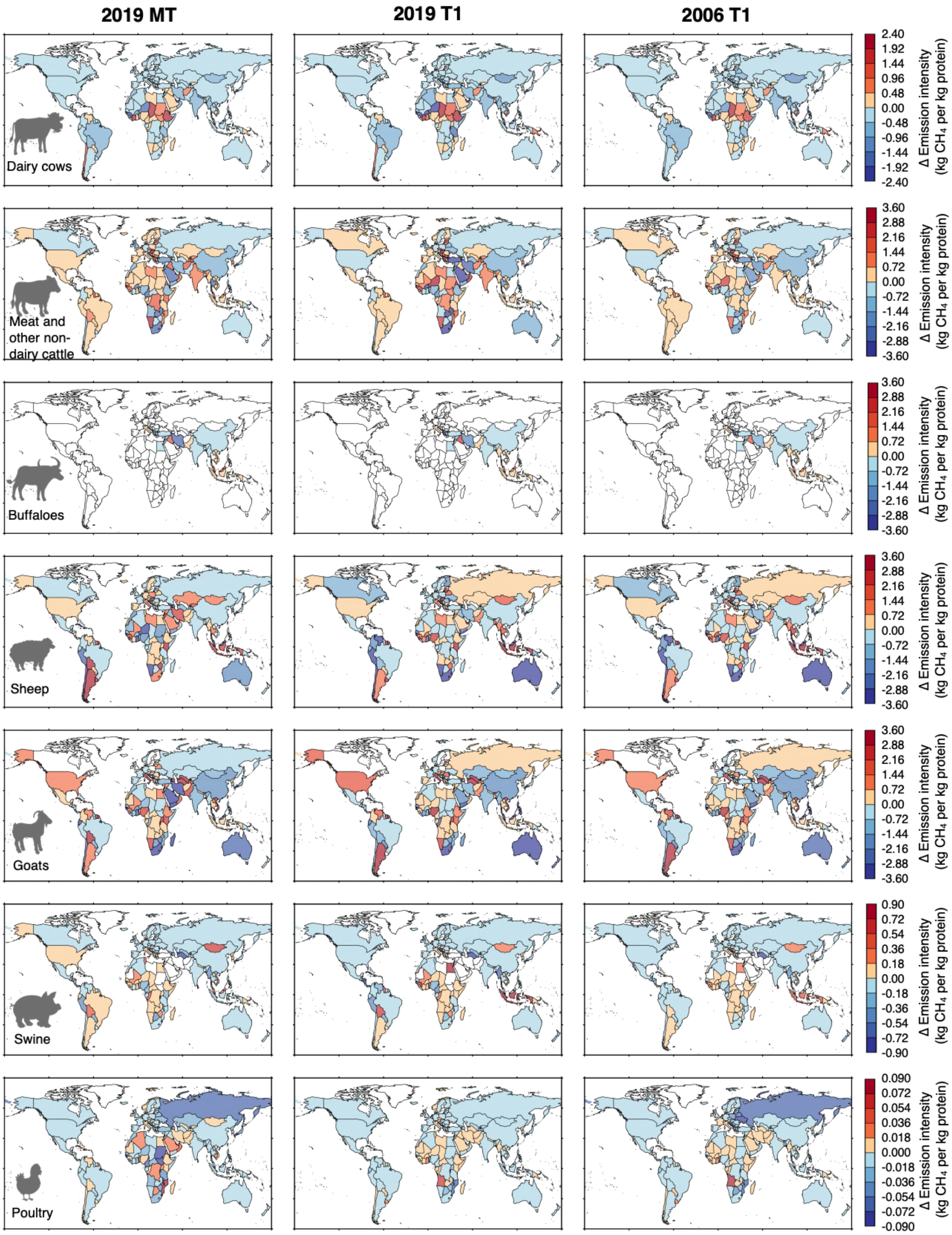
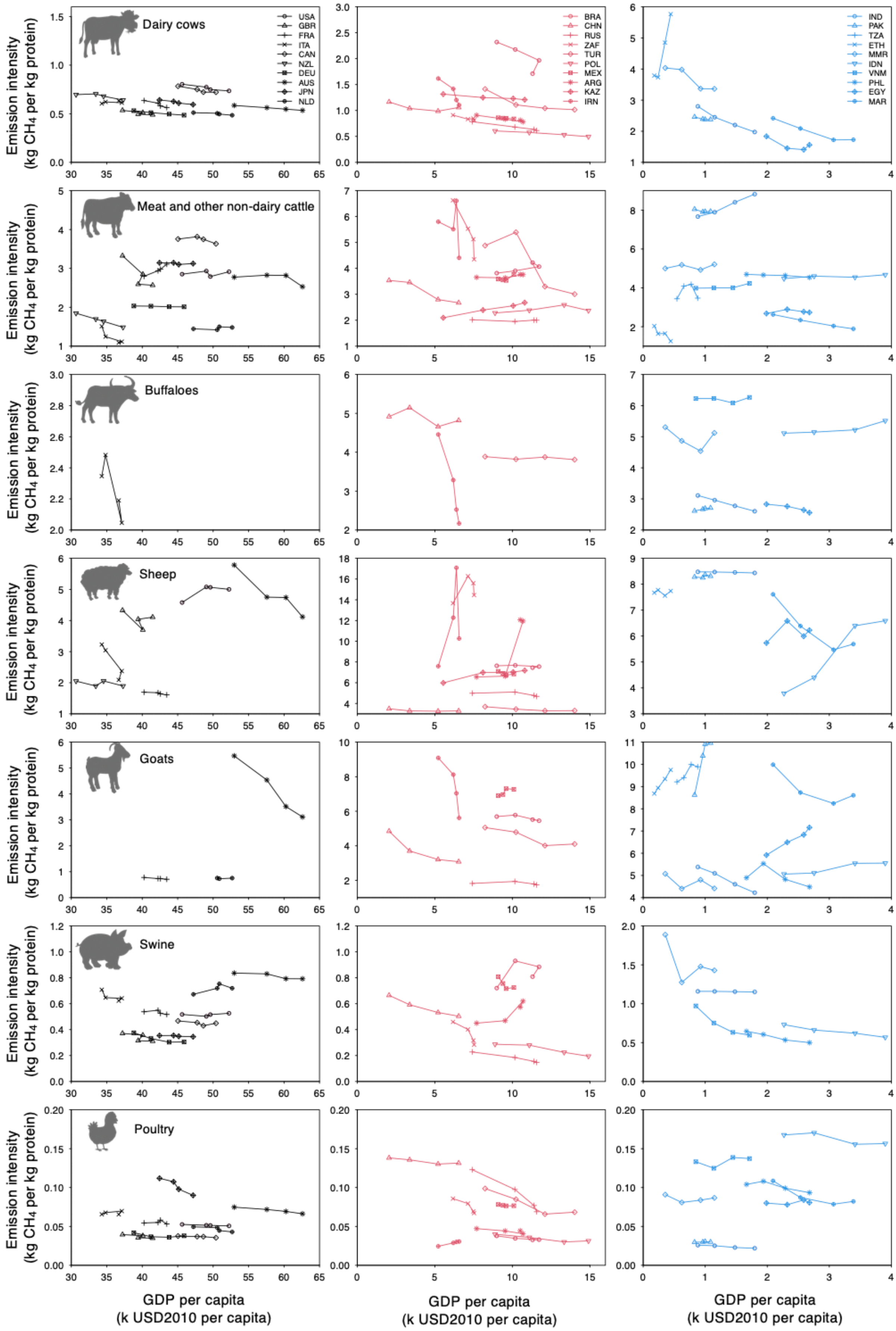



**Figure S8. Changes in methane emission intensity per kg protein of each livestock category between the periods 2000-2004 and 2014-2018, resulting from the 2019 MT method, the 2019 T1 method, and the 2006 T1 method.** Positive value indicates an increase in emission intensity per kg protein from 2000-2004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

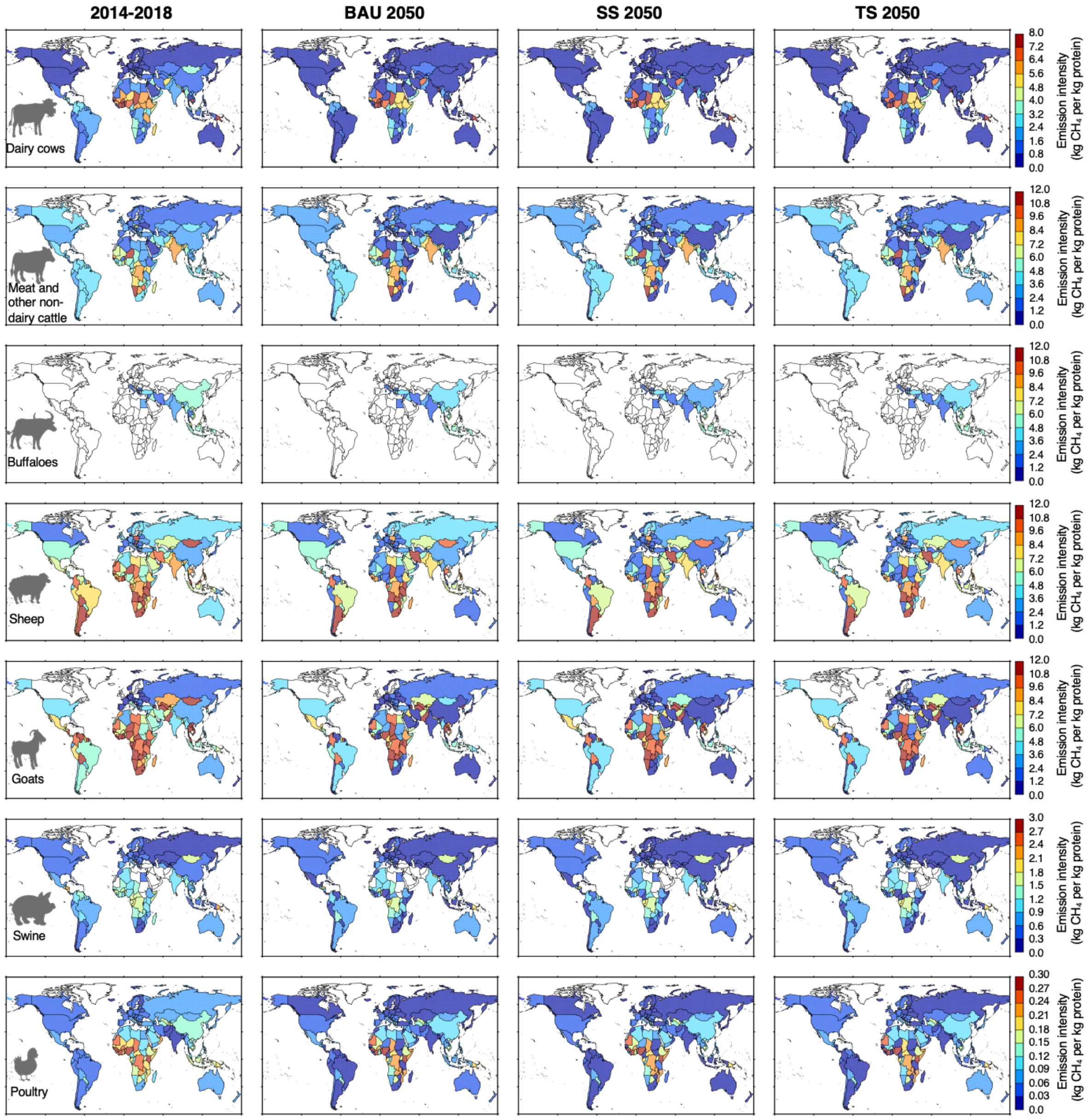



**Figure S10. Methane emission intensity per kg protein of each livestock category during the period 2014-2018 and that projected by 2050 under different socio-economic scenarios resulting from the 2019 MT method.** Socio-economic scenarios: Business As Usual (BAU), Stratified Societies (SS), and Toward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

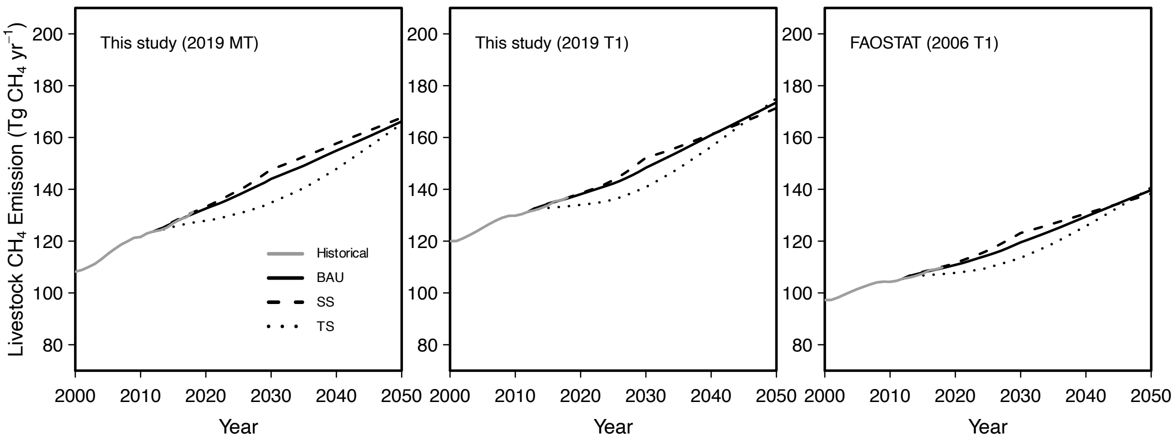



**Figure S11. Projections of global livestock methane emissions under different socio-economic scenarios with a continuation of country-specific past trend with the development of GDP per capita allowing both increasing or decreasing emission intensity in the future.** Socio-economic scenarios: Business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

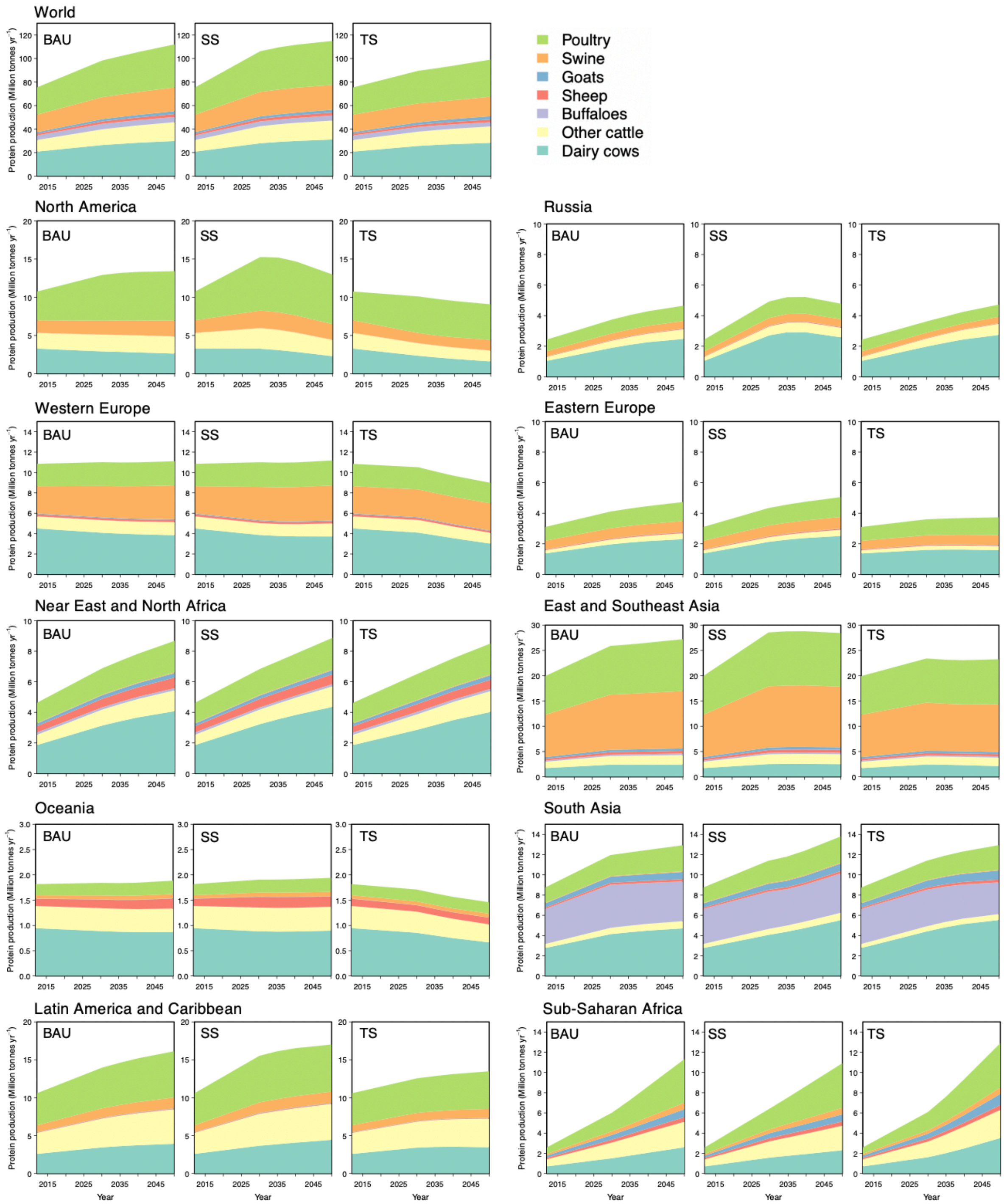



**Figure S12. Projections of regional livestock protein production under different socio-economic scenarios.** Socio-economic scenarios: Business As Usual (BAU), Stratified Societies (SS), and Toward Sustainability (TS). The projections for each livestock production was calculated as the protein production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

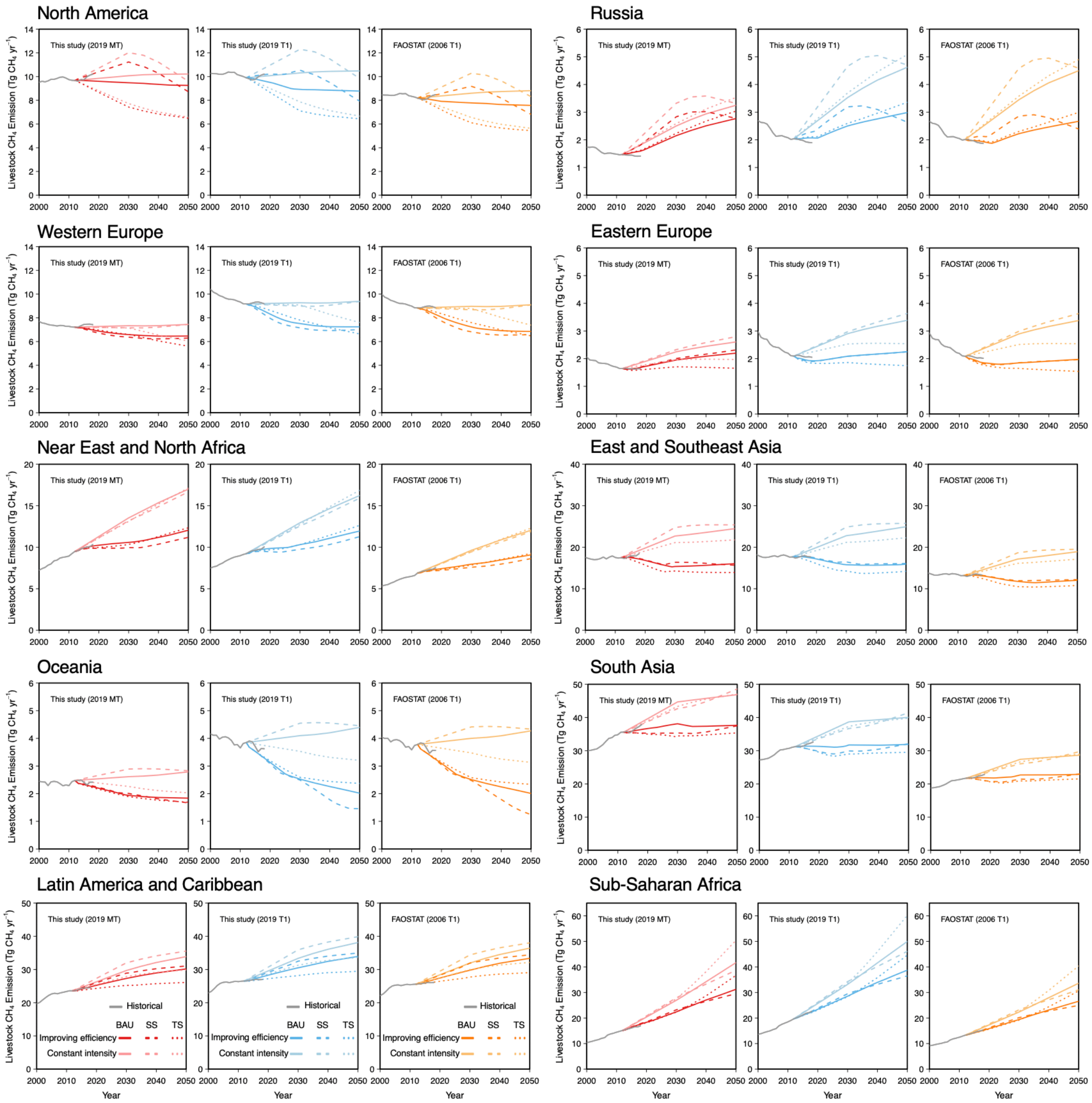



**Figure S13. Projections of regional livestock methane emissions under different socio-economic scenarios and different emission intensity change pathways, resulting from the 2019 MT method, the 2019 T1 method, and the 2006 T1 method.** Socio-economic scenarios: Business As Usual (BAU), Stratified Societies (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.

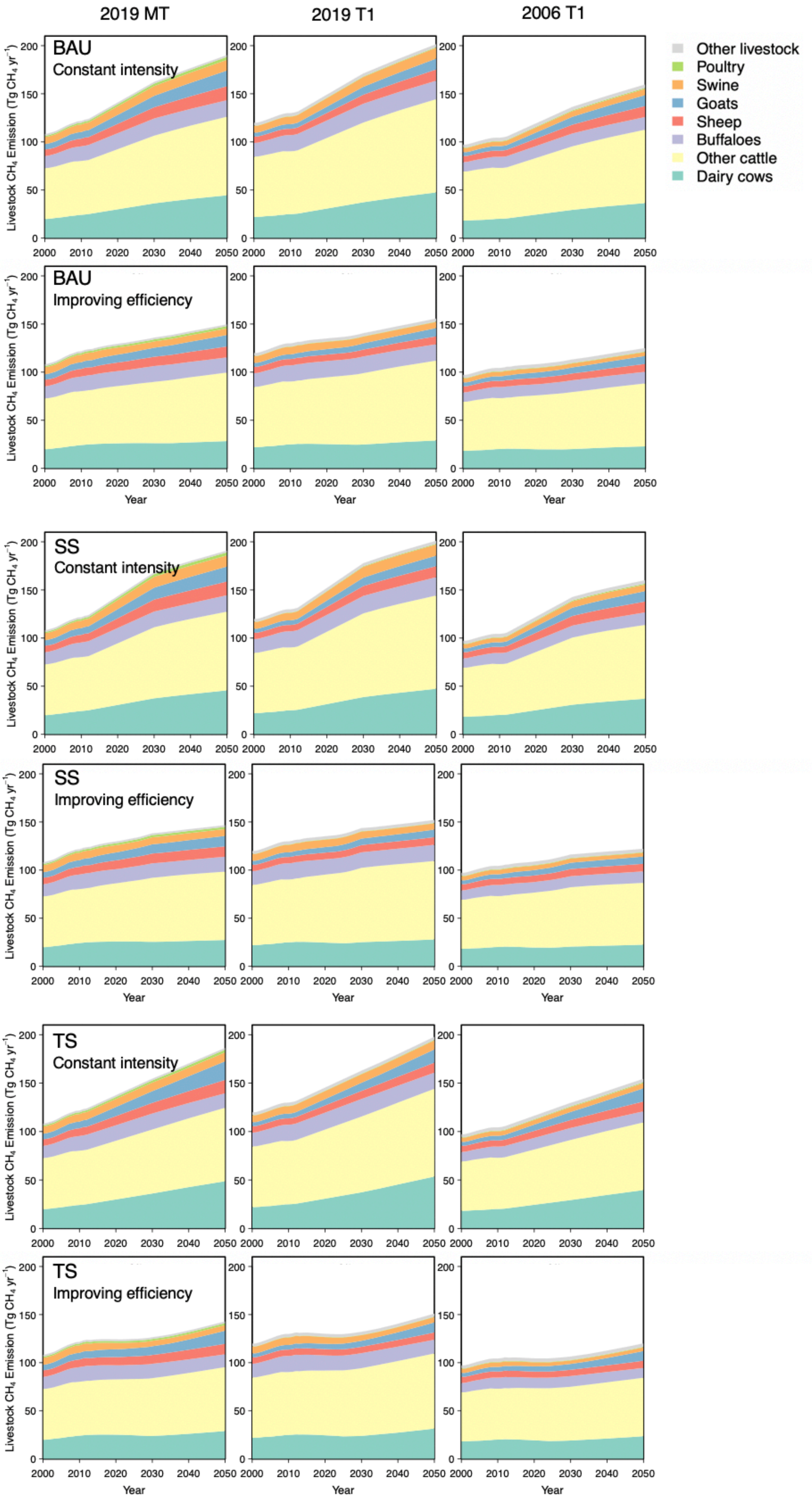

2019 MT
2019 T1
2006 T1
BAU
Constant intensity
BAU
Improving efficiency
SS
Constant intensity
SS
Improving efficiency
TS
Constant intensity
TS
Improving efficiency
Other livestock
Poultry
Swine
Goats
Sheep
Buffaloes
Other cattle
Dairy cows
Livestock CH4 Emission (Tg CH4 yr-1)
Year

**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.

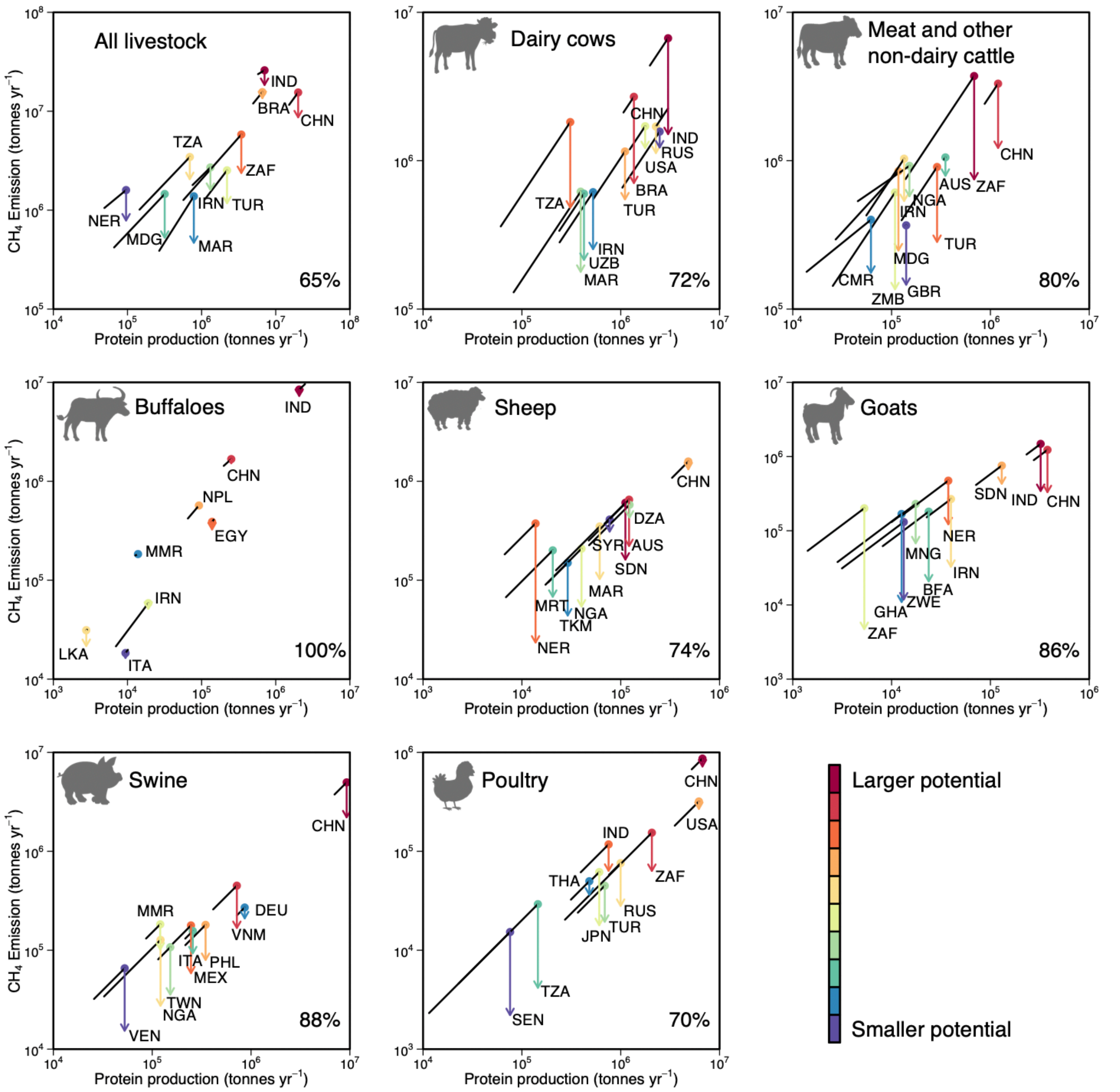



**Figure S15. Projections on the increase in protein production, methane emission, and the effects of improving efficiency on reducing livestock methane emissions under the BAU scenarios, resulting from the 2019 MT method.** The black lines indicate the protein production (x-axis) and methane emission (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.

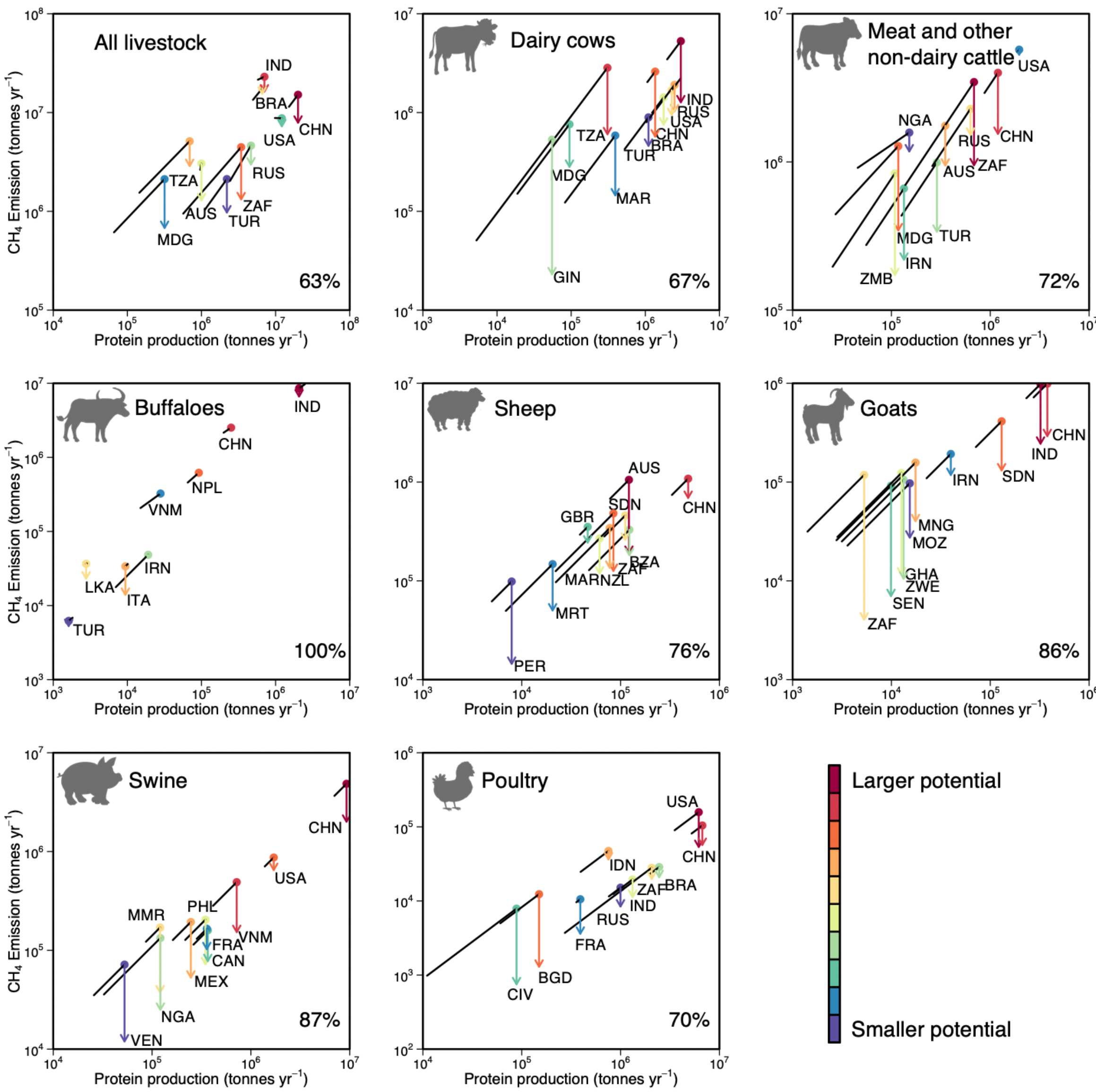



**Figure S16. Projections on the increase in protein production, methane emission, and the effects of improving efficiency on reducing livestock methane emissions under the BAU scenarios, resulting from the 2019 T1 method.** The black lines indicate the protein production (x-axis) and methane emission (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.

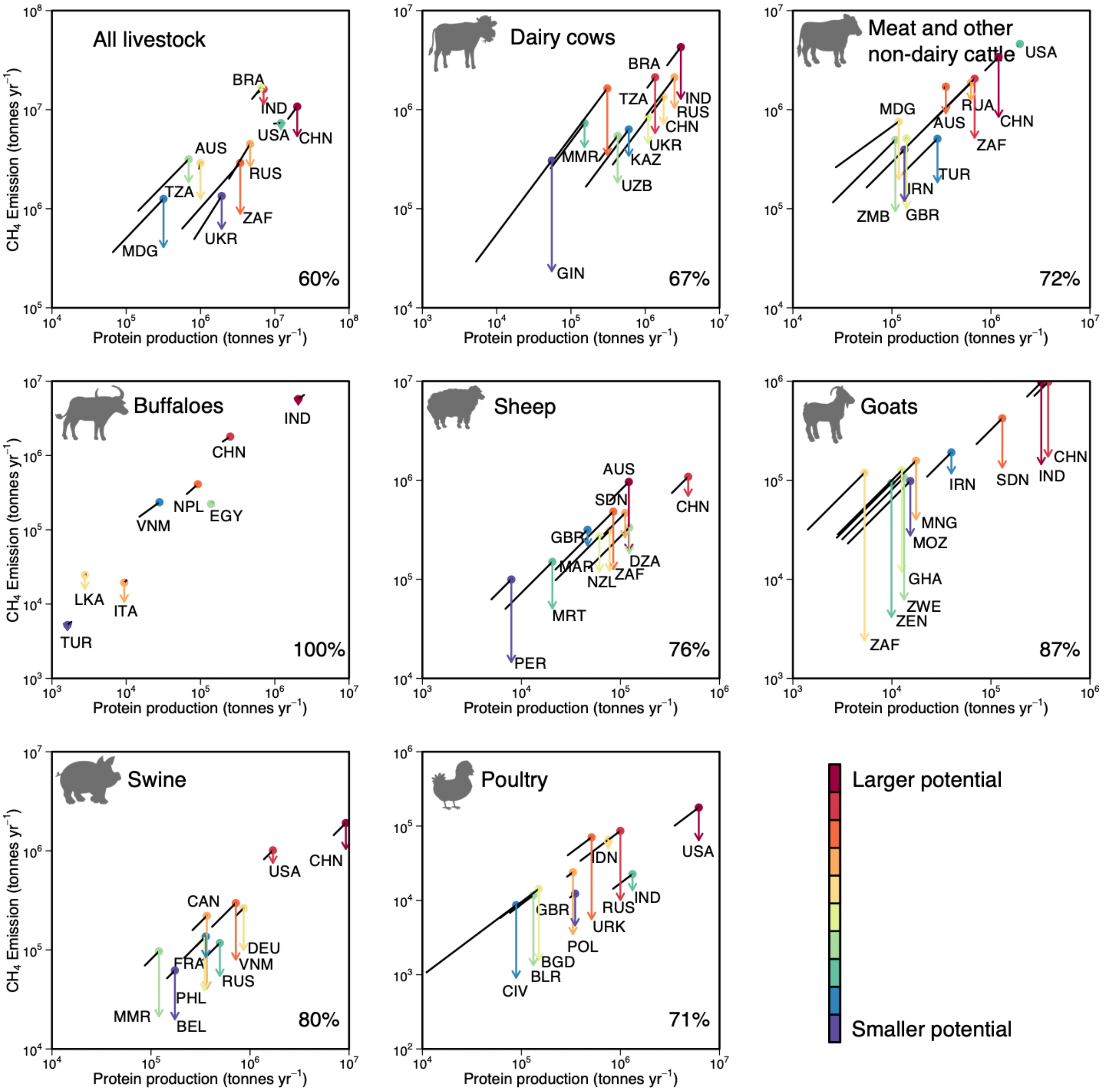
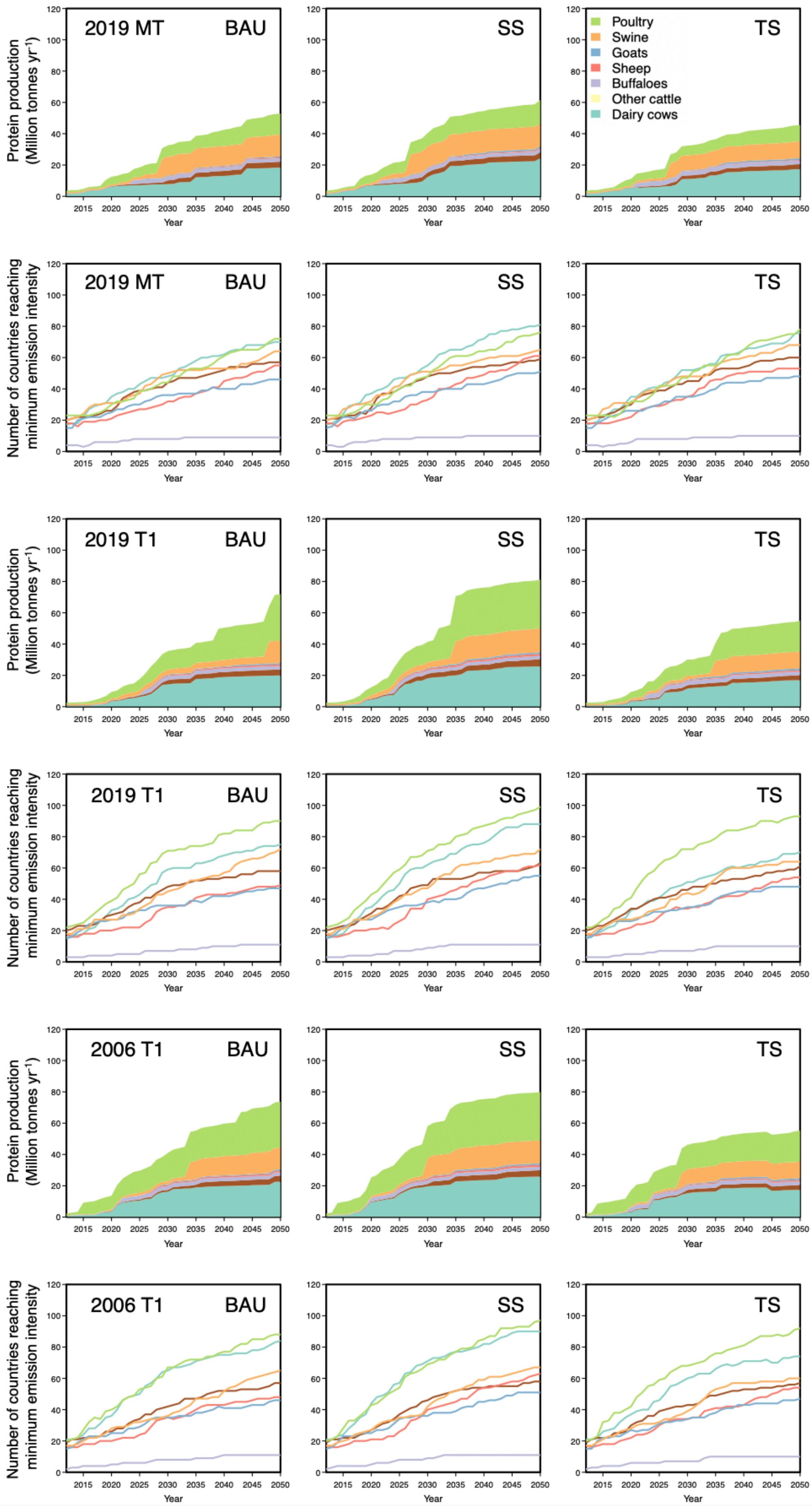



**Figure S17. Projections on the increase in protein production, methane emission, and the effects of improving efficiency on reducing livestock methane emissions under the BAU scenarios, resulting from the 2006 T1 method.** The black lines indicate the protein production (x-axis) and methane emission (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
2015
2020
2025
2030
2035
2040
2045
2050
0
20
40
60
80
100
120


560

**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 | |
| 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 | 5 (2006 IPCC Guidelines); 9 / 5 (2019 Refinement)[§] |
| 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).

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