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2 **The key role of production efficiency changes in livestock methane emission**
3 **mitigation**
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21 **Key Points:**

- 22 • Emission intensity decreased for most livestock categories globally during 2000-2018,
23 with an increasing protein-production efficiency
- 24 • The continuation of the past decreases in emission intensity provides a large potential
25 to mitigate livestock emissions
- 26 • Improving production efficiency has a much greater mitigating effect than demand-
27 side efforts, and should be prioritized in a few countries
28

29 **Abstract**

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

43 **Plain Language Summary**

44 Livestock production represents a third of the global anthropogenic methane emissions
45 nowadays, and the emissions are expected to keep increasing in the future. Using three sets of
46 methodologies and emission factors from two versions of IPCC guidelines (the 2006 and the
47 2019 refinement), we re-assess global livestock methane emissions over the past two decades
48 and project the emissions till 2050. We find a decreasing trend of methane emission intensity
49 per kg protein produced during the past two decades. We show that promoting balanced, healthy
50 and environmentally sustainable diets in most countries can mitigate future livestock methane
51 emissions, but a larger mitigation potential is projected if the past trend in decreasing emission
52 intensity (i.e., increasing production efficiency) can be continued. We further identify major
53 countries that have the largest mitigation potential through increasing production efficiency.

54

55 **1 Introduction**

56 Methane is the second-largest anthropogenic driver of current global radiative forcing after CO₂
57 (Myhre et al., 2013) and all representative concentration pathways (RCPs; (Collins et al., 2013))
58 show it maintaining this ranking in the future, thus becoming of critical importance in
59 mitigation strategies for attaining low-warming targets. The largest anthropogenic methane
60 source is livestock production, with the main components being the enteric fermentation of
61 ruminants and manure management. Currently, livestock production represents a third of the
62 global anthropogenic methane emissions, comparable to the magnitude of fossil fuels methane
63 emissions (Saunio et al., 2020).

64 Livestock emissions reported by countries to the UNFCCC are based on common
65 methodologies provided by the IPCC Guidelines (IPCC, 1997, 2000, 2003, 2006, 2019). These
66 guidelines give the possibility to make inventories with various levels of detail, depending on
67 country capability, from the simplest Tier 1 to the most detailed Tier 3, and are periodically
68 updated to reflect the latest expert knowledge on methodologies and emission factors. In
69 parallel, global inventories have been developed to quantify livestock methane emissions for
70 the past few decades (Chang et al., 2019; Crippa et al., 2020; Dangal et al., 2017; EPA, 2012;
71 FAOSTAT, 2020; Janssens-Maenhout et al., 2019; Wolf et al., 2017) or for some specific years
72 (Gerber, Steinfeld, et al., 2013; Herrero et al., 2013). These datasets cover either all livestock
73 types (Crippa et al., 2020; EPA, 2012; FAOSTAT, 2020; Janssens-Maenhout et al., 2019; Wolf
74 et al., 2017) or major categories (Chang et al., 2019; Dangal et al., 2017; Gerber, Steinfeld, et
75 al., 2013; Herrero et al., 2013). Livestock methane emission estimates from inventories differ
76 substantially depending on the choice of the methodological tier, emission factors, and livestock
77 activity data (e.g. from globally available FAOSTAT statistics or from national/regional
78 information). For example, estimates of emissions from enteric fermentation of ruminants in
79 2000, obtained from different inventories (Chang et al., 2019), range from 60.9 to 86.3 Tg CH₄
80 yr⁻¹.

81 The spread between inventory estimates of livestock emissions arises from uncertainties in the
82 intensity of emission per head of livestock, or per unit of production, such as per amount of
83 protein. The IPCC Guidelines (*2019 IPCC Refinement (IPCC, 2019)*) recently updated their
84 Tier 1 methodology for manure management emissions and revised many emission factors for
85 livestock emissions. This major revision impacts global estimated emissions and their
86 intensities. To our knowledge, no study has compared emission intensities derived from
87 different methods at the global scale, although (Gerber, Steinfeld, et al., 2013) produced an

88 assessment of these quantities for a single year (2005) using the Global Livestock
89 Environmental Accounting model (GLEAM).

90 According to (FAOSTAT, 2020), livestock methane emissions increased by 51.4% between
91 1961 and 2018, following the increase in ruminant numbers and manure excretion from various
92 livestock categories. This increasing trend will probably continue in the future, given the
93 projected rising demand for livestock products (FAO, 2018). In developing countries, in
94 particular, large increases in livestock production are projected, driven by the increase in per
95 capita income and/or population. The uncertainty in emission intensities induced by the choice
96 of method affects the future projections of livestock methane emissions, and thus climate
97 projections.

98 In this study, we constructed two new estimates of global livestock methane emissions at a
99 spatial resolution of 5 arc-min for the period 2000-2018, using both a combined Tier 1 and Tier
100 2 method (hereafter, 2019 Mixed Tiers, MT method) and a Tier 1 method (hereafter, 2019 T1
101 method) based on the latest IPCC Guidelines (*IPCC, 2019*) Vol. 4, Chapter 10 (Table S1).
102 Further, we derived new estimates of emission intensities, expressed as emissions per kg of
103 protein in products including milk and meat from cattle, buffaloes, goats and sheep, meat from
104 swine, and meat and eggs from poultry, by combining our emission estimates with FAOSTAT
105 production statistics (FAOSTAT, 2020). Finally, we investigated how our update to emission
106 calculations using the latest IPCC Guidelines affects future projections from this sector by the
107 year 2050 for three global socio-economic scenarios (FAO, 2018) and contrasted pathways of
108 livestock production efficiency changes. To facilitate the usage of these new methods for
109 assessing livestock methane emissions, we have provided a full package of R code on Zenodo
110 for producing these two new estimates and associated projections.

111

112 **2 Materials and Methods**

113 **2.1 Estimating livestock CH₄ emissions using mixed IPCC Tier 1 and Tier 2 methods from** 114 **2019 Refinement (the 2019 MT method)**

115 The first set of livestock CH₄ emissions was estimated using a mixture of IPCC Tier 1 and Tier
116 2 methods from the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse*
117 *Gas Inventories* (IPCC, 2019) Vol. 4, Chapter 10. Enteric fermentation CH₄ emissions from
118 dairy cows, meat and other non-dairy cattle, buffaloes, sheep, and goats were estimated using
119 the IPCC Tier 2 method ((IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.21) based on the gross energy

120 intake of livestock (GE) and a conversion factor Y_m calculated from regional digestibility of
121 feed (DE). For enteric fermentation emissions of other livestock, an adjusted IPCC Tier 1
122 method ((IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.19), accounting for changes in liveweight,
123 was used to estimate CH_4 emissions from enteric fermentation. Text S1 presents a detailed
124 description of the methods used for estimating enteric fermentation emissions.

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

135 **2.2 Estimating livestock CH_4 emissions using IPCC Tier 1 methods from the 2019** 136 **Refinement (the 2019 T1 method)**

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

149 For emissions from manure management, we used methane emission factors per unit of volatile
150 solid (VS) excreted by livestock category, multiplying by the corresponding VS excretions. VS
151 excretion for each livestock category and productivity system were calculated following Eqn
152 10.22A of (IPCC, 2019) Vol. 4, Chapter 10. The regional VS excretion rate for each

153 productivity system was obtained from Table 10.13A of (IPCC, 2019) Vol. 4, Chapter 10, and
 154 the typical animal mass for each region and productivity system was obtained from Table 10A.5
 155 of (IPCC, 2019) Vol. 4, Chapter 10. We assumed North America, Europe and Oceania to have
 156 only high productivity systems, while the regional shares between high ($S_{high,r}$) and low
 157 productivity systems ($S_{low,r}$) for Latin America, Africa, Middle East, Asia and India sub-
 158 continents were derived according to the regional mean live weights ($Weight_{mean,r}$), and live
 159 weights for high ($Weight_{high,r}$) and low productivity systems ($Weight_{low,r}$):

$$160 \quad S_{high,r} = \frac{Weight_{mean,r} - Weight_{low,r}}{Weight_{high,r} - Weight_{low,r}} \quad (1)$$

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

175 The 2019 IPCC Refinement (IPCC, 2019) also introduced new Tier 1a emission factors for
 176 enteric fermentation to account for increases in production levels by livestock raised in
 177 countries that apply a Tier 1 methodology for estimating enteric CH_4 emissions. For comparison,
 178 we additionally estimated another set of CH_4 emissions from enteric fermentation using the
 179 Tier 1a method (the 2019 T1a method). For dairy cows, meat and other non-dairy cattle and
 180 swine in Latin America, Africa, Middle East, Asia and India sub-continent, regional CH_4 Tier
 181 1a emission factors from Table 10.10 and Table 10.11 of (IPCC, 2019) Vol. 4, Chapter 10 and
 182 the regional shares between high ($S_{high,r}$) and low productivity systems ($S_{low,r}$) calculated by
 183 Eqn (1) above were used. Due to the limited regional information on the production systems
 184 and on their time variation from the IPCC guideline, emissions from other livestock categories

185 are the same as those of the 2019 T1 method, and the shares between high and low productivity
186 systems are time-invariant in our estimate.

187 **2.3 Uncertainty estimates**

188 For estimates of enteric fermentation CH₄ emission from dairy cows, meat and other non-dairy
189 cattle, buffaloes, sheep, and goats using the 2019 MT method, we assessed uncertainties due to
190 the conversion factor Y_m . Following Table 10.12 and 10.13 of (IPCC, 2019) Vol. 4, Chapter 10,
191 a standard deviation of 20% was applied for dairy cows, meat and other non-dairy cattle and
192 buffaloes, while a standard deviation of 13.4% for sheep and 18.2% for goats were applied.
193 Table 10.10 of IPCC, 2006 Vol. 4, Chapter 10 gives an uncertainty of ± 30 -50% for the Tier 1
194 emission factors (validated also by (IPCC, 2019) Vol. 4, Chapter 10), which is defined as 1.96
195 times of the standard deviation of the mean. For uncertainty estimates of enteric fermentation
196 CH₄ emission from other livestock using the 2019 MT method, and from all livestock using the
197 2019 T1 method, we applied a median standard deviation of $40\%/1.96=20.4\%$ (using 40% as a
198 median of ± 30 -50%). For all uncertainty estimates of manure management CH₄ emission using
199 the 2019 MT and 2019 T1 methods, we applied a standard deviation of $30\%/1.96=15.3\%$, as
200 an uncertainty of $\pm 30\%$ was given for methane conversion factors (MCF) used in the 2019 MT
201 method (Table 10.17 of (IPCC, 2019) Vol. 4, Chapter 10), and also for emission factor used in
202 the 2019 T1 method (Table 10.14 and 10.15 of (IPCC, 2019) Vol. 4, Chapter 10). Uncertainties
203 were derived from Monte Carlo ensembles ($n = 1000$) from the range of uncertainties reported
204 for the above parameters and / or emission factors used in the calculations. In the Monte Carlo
205 ensembles, we assumed independent uncertainties for each livestock category, and for methane
206 emissions from enteric fermentation and manure management.

207 **2.4 Estimating gridded livestock CH₄ emissions**

208 The Gridded Livestock of the World v3.0 dataset (hereafter referred to as GLW3; (Gilbert et
209 al., 2018)) provides global spatial distribution data for cattle, buffaloes, horses, sheep, goats,
210 swine, chickens and ducks in the year 2010 at a spatial resolution of 5 arc min. We estimated
211 the gridded enteric fermentation emissions by distributing country emissions into grid cells
212 following the GLW3 livestock distribution data (data produced from dasymetric (DA) model in
213 (Gilbert et al., 2018) were used; Table S2). We assumed no changes in the distribution of
214 livestock during the period 2000-2018 in the gridded products, as time-variable livestock
215 distribution data, to our knowledge, is not available at the global scale. Gridded enteric

216 fermentation emission in grid cell i of country j for livestock category k at year m
 217 ($F_{CH4-Enteric,i,j,k,m}$) was calculated as:

$$218 \quad F_{CH4-Enteric,i,j,k,m} = F_{CH4-Enteric,j,k,m} \times \frac{D_{GLW3,i,j,k} \times A_i}{\sum_{i \in j} D_{GLW3,i,j,k} \times A_i} \quad (2)$$

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

224 The same method was used to distribute country-level VS (for both Tier 1 and Tier 2 methods),
 225 which then were used to estimate livestock CH₄ emissions from manure management at the
 226 grid cell level.

227 **2.5 Revisiting emission intensities for livestock production and individual livestock**

228 For economic output, we derived the methane emission intensities (including enteric
 229 fermentation and manure management emissions) per kg protein produced for category k in
 230 country j and year m ($EF_{protein,j,k,m}$; unit: kg CH₄ per kg protein) as:

$$231 \quad EF_{protein,j,k,m} = \frac{F_{CH4-Enteric,j,k,m} + F_{CH4-Manure,j,k,m}}{P_{protein,j,k,m}} \quad (3)$$

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

$$234 \quad P_{protein,j,k,m} = P_{meat/milk,j,k,m} \times c_{meat/milk,k} \quad (4)$$

235 where $P_{meat/milk,j,k,m}$ is the meat and/or milk production (unit: kg) by livestock category k in
 236 country j and year m (production quantity from (FAOSTAT, 2020) “Livestock Primary”
 237 domain), and $c_{meat/milk,k}$ is the protein content of the meat or milk of livestock category k (unit:
 238 kg protein per kg meat/milk). Here, we used a protein content of 0.158 kg protein per kg bovine
 239 carcass weight (cattle and buffaloes), 0.141 kg protein per kg sheep carcass weight, 0.134 kg
 240 protein per kg goat carcass weight, 0.131 kg protein per kg pig carcass weight, 0.143 kg protein
 241 per kg poultry carcass weight, 0.124 kg protein per kg eggs, and 0.033 kg protein per kg milk.
 242 The protein content of meat and carcass weights were derived from Table 9.1 of the GLEAM
 243 v2.0 Documentation (FAO, 2017), and the protein content of milk was calculated as $1.9 + 0.4$
 244 $\times \%Fat$ ($Milk\ PR\%$ in (IPCC, 2019) Vol. 4, Chapter 10, Eqn 10.33) with a typical %Fat of 3.5%

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

251 The enteric fermentation emission intensities of country j for livestock category k (here, cattle,
 252 sheep, goats, and buffaloes) in year m ($EF_{head-Enteric,j,k,m}$; unit: kg CH₄ per head) are
 253 calculated as:

$$254 \quad EF_{head,j,k,m} = \frac{F_{CH_4-Enteric,j,k,m} + F_{CH_4-Manure,j,k,m}}{N_{head,j,k,m}} \quad (5)$$

255 where $N_{head,j,k,m}$ is the number of livestock (unit: head) for category k in country j and year m .
 256 For dairy cows, $N_{head,j,cows,m}$ is the number of producing animals obtained from the
 257 (FAOSTAT, 2020) “Livestock Primary” domain; for meat and other non-dairy cattle,
 258 $N_{head,j,other\ cattle,m}$ is the total stock (the (FAOSTAT, 2020) “Live Animals” domain) minus
 259 the number of dairy cows; for sheep, goats and buffaloes, $N_{head,j,k,m}$ is the total stock from the
 260 (FAOSTAT, 2020) “Live Animals” domain; for swine, $N_{head,j,swine,m}$ is the slaughtered
 261 number from the (FAOSTAT, 2020) “Livestock Primary” domain, given their life span is
 262 usually shorter than one year.

263 **2.6 Projecting livestock methane emissions**

264 Future livestock methane emissions depend on changes in livestock production (usually
 265 expressed in kg of protein) and emission intensities per livestock production (i.e., kg CH₄ per
 266 kg protein produced). Here, we projected livestock methane emissions forward until 2050,
 267 using the projected relative changes in protein production from major livestock categories under
 268 different socio-economic scenarios, and assuming different pathways of emission intensity
 269 changes. Three socio-economic scenarios: Business As Usual (BAU), Stratified Societies (SS),
 270 and Toward Sustainability (TS), and two pathways where we made contrasted assumptions
 271 about production efficiency changes: constant emission intensity and improving efficiency (i.e.,
 272 decreasing emission intensity) were used. Future livestock CH₄ emissions for product p (milk
 273 or meat) of livestock category k in country j and year m under socio-economic scenario s and
 274 emission intensity change pathway w during the period 2012-2050 were calculated as:

$$\begin{aligned}
275 \quad F_{CH_4,j,k,m,s,w} &= F_{CH_4-prod,j,k,2012} \times P_{rel,j,k,m,s} \times EF_{rel-protein,j,k,m,w} + F_{CH_4-draft,j,k,2012} \times \\
276 \quad I_{rel-draft,j,k,m,w} & \hspace{15em} (6)
\end{aligned}$$

277 where $F_{CH_4-prod,j,k,2012}$ and $F_{CH_4-draft,j,k,2012}$ are the methane emissions from livestock
278 category k in country j and year 2012 used for production and for draft power, respectively
279 (draft animals are meat and other non-dairy cattle and buffaloes used as draft power in
280 developing countries only; see section 2.5 for details of the emissions of draft animals);
281 $P_{rel,j,k,m,s}$ is the change in protein production for livestock category k in country j and year m
282 relative to 2012 under socio-economic scenario s ; $EF_{rel-protein,j,k,m,w}$ is the change in
283 production efficiency (emission intensity per livestock production; $EF_{protein,j,k,m}$) for livestock
284 category k in country j and year m relative to the 2012 value under emission intensity change
285 pathway w ; $I_{rel-draft,j,k,m,w}$ is the change in the number of draft animals for livestock category
286 k in country j and year m relative to the 2012 value under production efficiency change pathway
287 w . We used the year 2012 as the start of the projection since the FAO projections for livestock
288 production started in 2012 (FAO, 2018). For livestock other than cattle, buffaloes, sheep, goats,
289 pigs and poultry, we assumed dynamic emissions to have their historical values during 2012-
290 2018 and constant emissions their values in 2018 for the period of 2019-2050.

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

$$301 \quad P_{rel,j,k,m,s} = \frac{\sum_p Y_{p,j,k,m,s} \times H_{j,k,m,s} \times C_{protein,p,j}}{\sum_p Y_{p,j,k,2012,s} \times H_{p,j,k,2012,s} \times C_{protein,p,j}} \quad (7)$$

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

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

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

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

315 We found decreasing trends in emission intensity for major livestock categories during the past
 316 two decades, due to increasing production efficiency. Based on this finding, we constructed our
 317 “*improving efficiency*” pathway, assuming a continuing decrease of emission intensity. Under
 318 this pathway, the future will see 1) a continuation of the country-specific historical trends of
 319 the development of GDP per capita for countries showing decreasing emission intensity during
 320 the past two decades; and 2) constant emission intensities for countries that experienced no
 321 change or an increasing emission intensity in the past two decades. For each country, a
 322 regression between the emission intensity per kg protein over four periods (2000-2004, 2005-
 323 2009, 2010-2014, 2014-2017) and the corresponding GDP per capita was calculated to derive
 324 the country-specific trends of emission intensities from projections of GDP per capita. Note
 325 that the last period only contains four years because GDP per capita from (FAOSTAT, 2020)
 326 is only available until 2017. We calculated the regression for these periods, rather than on an
 327 annual basis, to avoid the impact of potentially strong inter-annual variation of the emission
 328 intensities due to temporary effects such as livestock epidemics or economic shocks. We
 329 calculated the emission intensity per kg protein production for livestock category k in country
 330 j and year m relative to 2012 $EF_{rel-protein,j,k,m,s}$ as:

$$331 \quad EF_{rel-protein,j,k,m,s} = \frac{EF_{protein,j,k,m,s}}{EF_{protein,j,k,2012}} \quad (8)$$

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

$$336 \quad EF_{protein,j,k,m,s} = a_{j,k} \times GDPperCapita_{j,s} + b_{j,k} \quad , \text{ when } a_{j,k} < 0 \quad (9)$$

337 where $GDPperCapita_{j,s}$ is the GDP per capita in country j in year m under socio-economic
338 scenario s given by (FAO, 2018); $a_{j,k}$ and $b_{j,k}$ are the regression coefficients representing the
339 trend and intercept, respectively, from the regression between the emission intensity per kg
340 protein over four periods (2000-2004, 2005-2009, 2010-2014, 2014-2017) and the
341 corresponding GDP per capita during the historical period. Equation (9) only applies to
342 countries showing decreasing emission intensities during the past two decades (i.e., $a_{j,k} < 0$).
343 For countries with no change or increasing emission intensities in the past two decades (i.e.,
344 $a_{j,k} \geq 0$), a constant emission intensity is applied. Furthermore, to avoid unrealistically low
345 emission intensities in the future, we set a minimum emission intensity per kg protein for each
346 livestock category k ($EF_{protein,k,min}$) as a threshold. This is derived as the 0.05-quantile of the
347 emission intensities per kg protein from all countries with more than 100 tonnes of protein
348 production per year for that livestock category during the most recent 5-year period (2014-
349 2018). The thresholds varied with the different methods used (the 2019 MT, the 2019 T1, or
350 the 2006 T1 method) and are listed in Table S3. Figure S17 provides the number of countries
351 that reach the minimum emission intensity per kg protein for each livestock category by 2050,
352 and the protein production of these countries under the “*improving efficiency*” pathway.

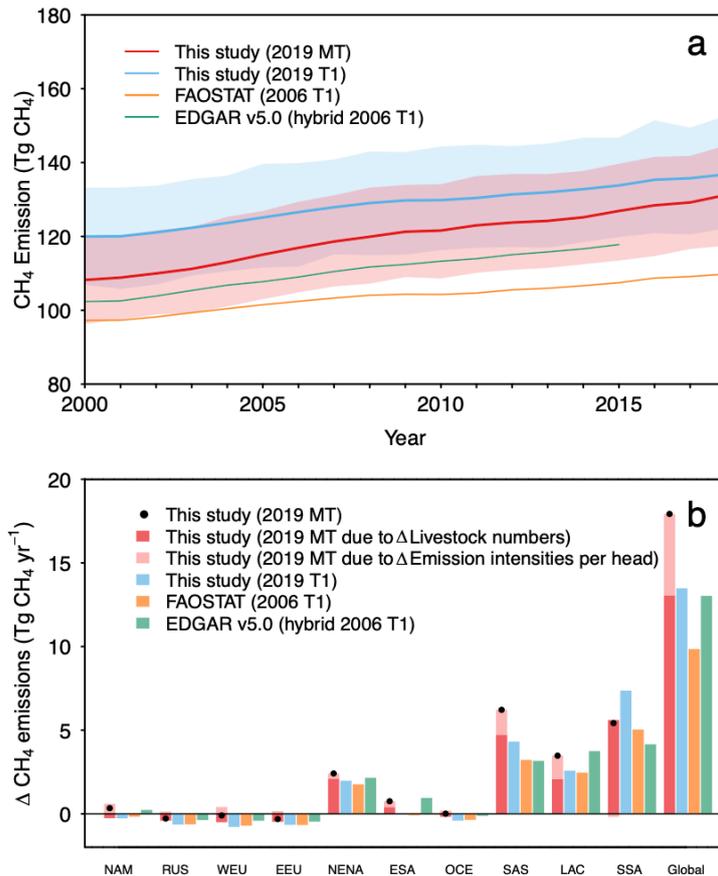
353 Additional sensitivity pathway of production efficiency changes (i.e., methane emission
354 intensity changes per kg protein produced) was considered: 1) a continuation of the country-
355 specific trend of the development of GDP per capita for countries showing decreasing emission
356 intensity during the past two decades; and 2) a continuation of the country-specific trend of the
357 development of GDP per capita for countries showing increasing emission intensity during the
358 past two decades. For countries showing decreasing emission intensities, same as the
359 “*improving efficiency*” pathway, we set a minimum emission intensity per kg protein for each
360 livestock category k ($EF_{protein,k,min}$) as a threshold to avoid unrealistically low emission
361 intensities. Similarly, to avoid unrealistically low emission intensities for countries showing
362 increasing emission intensities, we set a maximum emission intensity per kg protein for each
363 livestock category k ($EF_{protein,k,max}$) as a threshold. This is derived as the 0.95-quantile of the
364 emission intensities per kg protein from all countries with more than 100 tonnes of protein
365 production per year for that livestock category during the most recent 5-year period (2014-
366 2018). The thresholds varied with the different methods used (the 2019 MT, the 2019 T1, or
367 the 2006 T1 method) and are listed in Table S4.

368

369 3 Estimated livestock methane emissions and recent changes

370 The magnitude of global livestock methane emissions estimated for 2010 using our 2019 MT
371 method (122 ± 13 Tg CH₄ yr⁻¹; Fig. 1a) is consistent with that estimated by EDGAR v4.3.2
372 (Janssens-Maenhout et al., 2019) (115 Tg CH₄ yr⁻¹), EDGAR v5.0 (Crippa et al., 2020) (113
373 Tg CH₄ yr⁻¹), and (Wolf et al., 2017) (118 ± 18 Tg CH₄ yr⁻¹). All these datasets consider trends
374 in liveweight and/or productivity of livestock (Table S1). They are all higher than those of the
375 most recent FAOSTAT (FAOSTAT, 2020) data (104 Tg CH₄ yr⁻¹) and the U.S. EPA dataset
376 (EPA, 2012) (103 Tg CH₄ yr⁻¹). FAOSTAT used default 2006 T1 emission factors, while the
377 U.S. EPA dataset (EPA, 2012) used 2006 T1 supplemented by country-reported inventory data.
378 We found a higher estimate using the new 2019 T1 method (130 ± 14 Tg CH₄ yr⁻¹), which is
379 explained by higher emission factors (Table S4) for both enteric fermentation and manure
380 management, and changes in the method used for estimating manure management to reflect the
381 latest livestock characteristics. Global estimates using the 2019 T1a method (see section 2.2)
382 are nearly the same as that using the 2019 T1 method (< 0.2% differences; Table S2) with
383 differences ranging from 0.01% to 3.4% in regional estimates, thus we do not discuss the
384 emissions using the 2019 T1a method hereafter. It should be kept in mind that it is a purely
385 academic exercise to show the effect of the different Tiers on total livestock methane emissions.
386 As emphasized in the *2019 IPCC Refinement (IPCC, 2019)* Vol.4 Chapter 10 Section 10.3.1,
387 “the Tier 2 method should be used if enteric fermentation is a key source category for the animal
388 category that represents a large portion of the country’s total emissions”, and “the Tier 1 method
389 is likely to be suitable for most animal species in countries where enteric fermentation is not a
390 key source category, or where enhanced characterization data are not available”.

391



392

393 **Figure 1. Global livestock methane emission changes from 2000 to 2018 (a), and global**
 394 **and regional changes in livestock methane emissions between the periods 2000-2004 and**
 395 **2014-2018 (b).** The shaded area indicates the 1-sigma standard deviation of the estimates using
 396 the 2019 MT and the 2019 T1 methods in this study. Uncertainties were derived from Monte
 397 Carlo ensembles ($n = 1000$) from the range of uncertainties reported for various parameters
 398 and/or emission factors used in the calculations (see Methods). In the Monte Carlo ensembles,
 399 we assume independent uncertainties for each livestock category, and for methane emissions
 400 from enteric fermentation and manure management. Contributions due to the changes in
 401 livestock numbers and to the changes in emission intensities per head are shown separately in
 402 (b). For EDGAR v5.0, the changes in (b) are between the periods 2000-2004 and 2014-2015.
 403 Regions are classified following the definition of the FAO Global Livestock Environmental
 404 Assessment Model (GLEAM): NAM, North America; RUS, Russia; WEU, western Europe;
 405 EEU, eastern Europe, NENA, Near East and North Africa; EAS, eastern Asia; OCE, Oceania;
 406 SAS, south Asia; LAC, Latin America and Caribbean; SSA, Sub-Saharan Africa.

407

408 Globally, we found that 88% to 91% of the livestock methane emissions come from enteric
409 fermentation (Table S2), and are dominated by cattle, sheep, goats and buffaloes. The share of
410 the total emissions attributed to different livestock categories varies between regions, while the
411 pattern are similar between our two estimates and (FAOSTAT, 2020) (Figure S1). There are
412 significant regional differences in livestock methane emissions between the four datasets
413 (Figure S2), mainly due to the revised Tier 1 enteric fermentation emission factors used in the
414 2019 Guidelines and the Tier 2 method (the 2019 MT in Figure S2). We also established gridded
415 livestock methane emission fields by downscaling our national totals (Figure S3), which can
416 provide valuable high-resolution prior information for atmospheric inverse studies. These
417 emission maps show higher livestock methane emission intensity per area of land, compared to
418 EDGAR v5.0 (Crippa et al., 2020), in the Sahel countries, Eastern Africa, South Asia, Eastern
419 China, and Northeast Australia, but lower values in Europe and Latin America (Figure S4a,c).

420 Temporal changes of livestock methane emissions in the last two decades or so (2000-2018)
421 were quantified as the difference between the values in 2000-2004 and those in 2014-2018. We
422 found that global emissions increased by +10 to +18 Tg CH₄ yr⁻¹ between these two periods
423 (Fig. 1b), the largest increase being found with our 2019 MT method and the lowest with
424 FAOSTAT. The 2019 MT method accounts for changes in productivity through varying
425 liveweight and production (see Methods), and thus allows attribution of the increase to changes
426 in livestock numbers versus emission intensities per head. We estimated that 73% of the
427 increase in global emissions between the two periods is explained by increasing livestock
428 numbers, the remaining 27% due to increasing emission intensities per head in most regions
429 (i.e., larger mean body size, and higher meat and milk production per head).

430 Regional analysis gives however a more nuanced picture of the role of these two drivers (Fig.
431 1b; Figure S5). The most noticeable increases in emissions between the two periods were found
432 in South Asia (+3 to +6 Tg CH₄ yr⁻¹) and Sub-Saharan Africa (+4 to +7 Tg CH₄ yr⁻¹; see also
433 Figure S6). For the 2019 MT emission estimates, 24% of the increase in South Asia during the
434 period 2000-2018 can be attributed to changes in emission factors per head, while the entire
435 increase in emissions in Sub-Saharan Africa is explained by rising livestock numbers. Moderate
436 increases were found in Latin America, Near East and North Africa, and East and Southeast
437 Asia. On the other hand, estimated emissions decreased in the developed regions between the
438 two periods when using the Tier 1 methods, while estimates using the 2019 MT method showed
439 slightly increased emissions in North America and almost constant emissions in other
440 developed regions as increasing yield and liveweight were accounted for.

441 Dairy cows (+2 to +6 Tg CH₄ yr⁻¹) and meat and other non-dairy cattle (+2 to +4 Tg CH₄ yr⁻¹)
442 in developing countries are the major contributors to the increase of livestock methane
443 emissions during 2000-2018, followed by buffaloes in South Asia (+2 to +3 Tg CH₄ yr⁻¹; Figure
444 S5). Sheep in Near East and North Africa, East and Southeast Asia, and Sub-Saharan Africa,
445 goats in Sub-Saharan Africa, and swine in East and Southeast Asia also contributed
446 significantly to the regional emission increases (Figure S5).

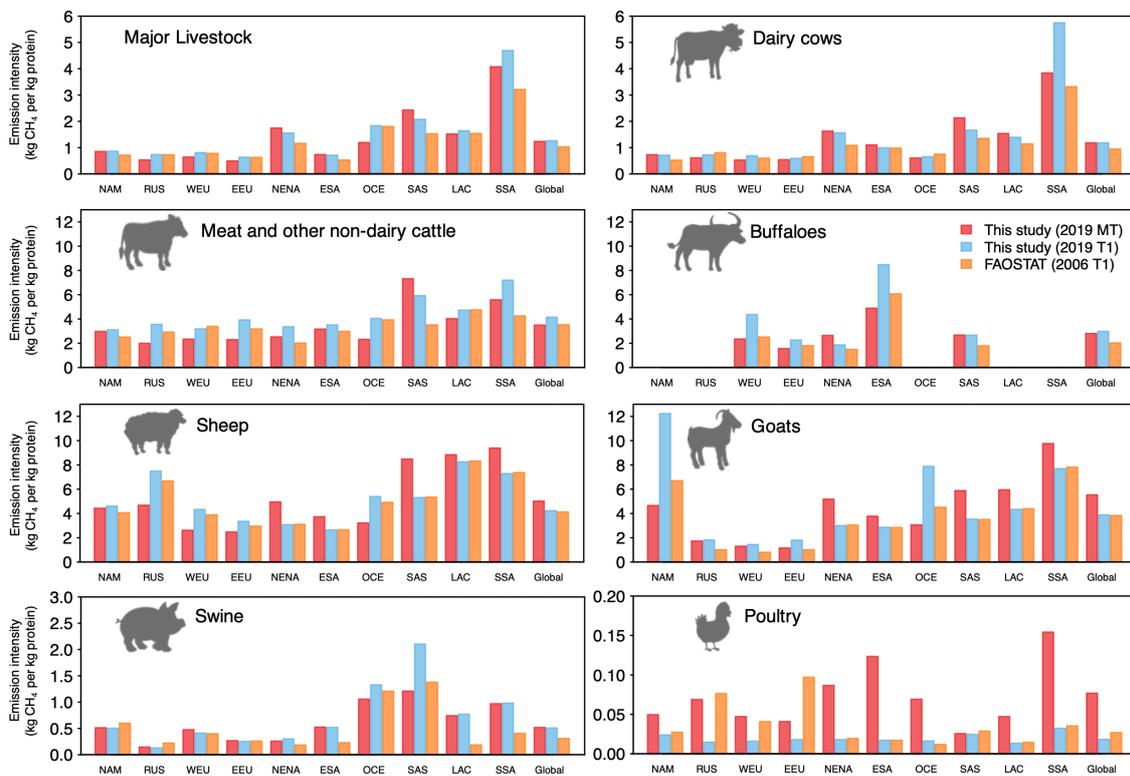
447

448 **4 Revised estimates of emission intensities for livestock protein production and the recent** 449 **changes**

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

455 During 2014-2018, methane emission intensity per kg of protein produced, is the lowest for
456 poultry meat and eggs (0.02-0.08 kg CH₄ per kg protein at global scale) followed by swine meat
457 (0.3-0.5 kg CH₄ per kg protein), because of negligible enteric fermentation emissions from
458 monogastric (Fig. 2). Ruminant meats have the highest methane emission intensity per kg of
459 protein among major livestock products. At the global scale, we estimated intensities of 3.5-4.2
460 kg CH₄ per kg protein for beef cattle, 3.8-5.5 kg CH₄ per kg protein for goats and 4.1-5.0 kg
461 CH₄ per kg protein for sheep. Higher methane emission intensities of goats and sheep meat than
462 that of beef are mainly due to the low digestibility of feed (low-quality roughage). On the other
463 hand, it means that goats and sheep depend less on human-edible feed and avoid food-feed
464 competition (Mottet et al., 2017; Van Zanten et al., 2018). Cow milk production has a global
465 average methane emission intensity of 1.0-1.2 kg CH₄ per kg protein, lower than meat
466 production because of 1) the higher protein production efficiency of milk compared with meat
467 and 2) a more protein-rich and digestible diet given to milking cows. Buffaloes are mostly used
468 as draft animals in Asia with only a small fraction of them used for meat and milk production.
469 Excluding the emissions from draft animals, the global average methane emission intensity for
470 buffalo meat and milk, which is essentially only produced in Asia and some European countries,
471 ranges from 2.0-3.0 kg CH₄ per kg protein. Accounting for all the above seven major protein-
472 producing livestock, globally the weighted average emission intensity ranges from 1.0-1.3 kg
473 CH₄ per kg protein (Fig. 2).

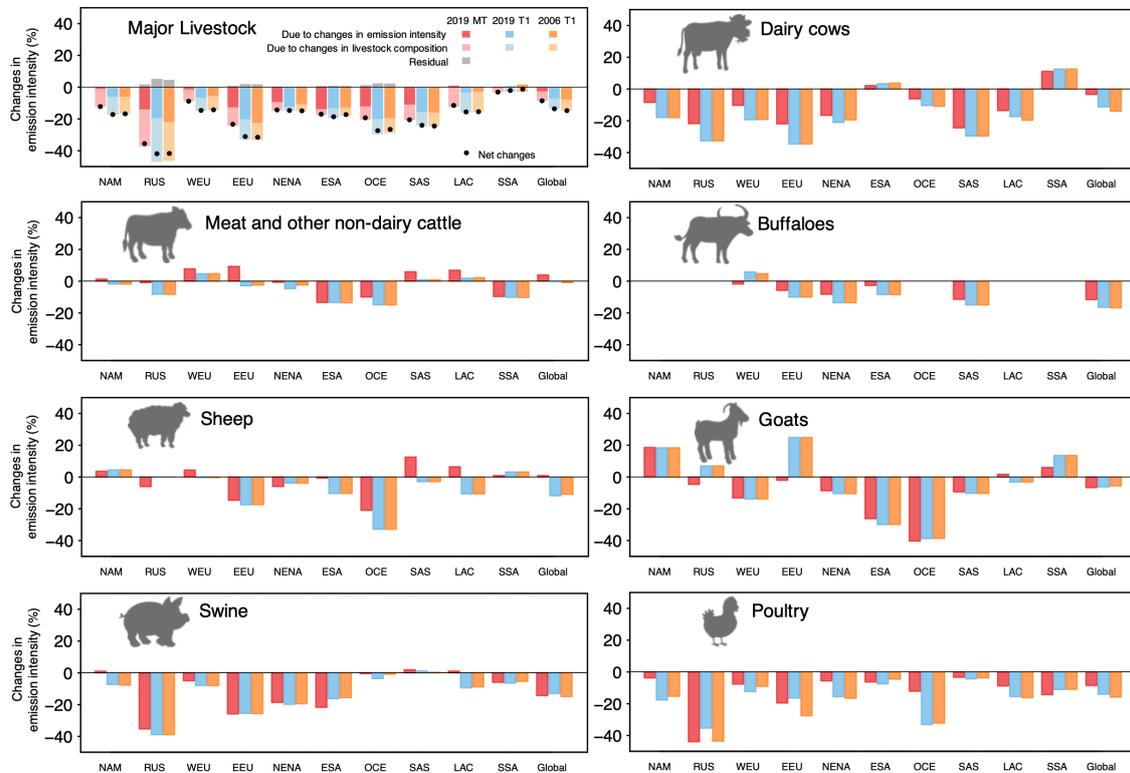
474 For ruminant products, intensity differences between regions are mainly due to differences in
 475 productivity, themselves explained by differences in diet and/or grazing intensity, with a less
 476 nutritious/digestible diet (e.g., low protein and high fiber) and/or more extensive grazing
 477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



485

486 **Figure 2. Livestock CH₄ emission intensities (including enteric fermentation and manure**
 487 **management emissions) per kg of protein produced during the period 2014-2018 for**
 488 **major livestock categories.** Emissions from draft animals were excluded from the calculation.
 489 Regions are classified following the definition of the FAO Global Livestock Environmental
 490 Assessment Model (GLEAM): NAM, North America; RUS, Russia; WEU, western Europe;

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



493

494 **Figure 3. Relative changes in livestock CH₄ emission intensities per kg of protein produced**
 495 **from 2000-2004 to 2014-2018 for major livestock categories.** For a livestock category, the
 496 changes between the two periods were expressed as percentage change of emission intensities
 497 during 2014-2018 compared to that during 2000-2004. For the seven major livestock categories
 498 together, the net changes in emission intensities (black points) were attributed: 1) to the changes
 499 due to the changes in emission intensity of each livestock category; 2) to the changes in the
 500 livestock composition; and 3) to the residual between the net changes and the sum of 1) and 2).
 501 Emissions from draft animals were excluded from the calculation.

502

503 During the past two decades, the emission intensity decreased for most livestock categories at
 504 the global scale (but not in all countries), indicating an increasing protein-production efficiency
 505 (Fig. 3). The emission intensity for meat and other non-dairy cattle, however, shows slight
 506 changes. Using the 2019 MT method, globally the weighted average emission intensity of the
 507 seven major protein-producing livestock categories decreased by 9% (Fig. 3). The attribution

508 shows that 30% of the changes are due to changes in the emission per kg protein of different
509 livestock categories, while 66% are due to changes in the mixture of livestock categories. The
510 latter comes from the faster increase in protein from poultry with low emission intensities (+51%
511 between 2000-2004 and 2014-2018) than that from ruminants with high emission intensities
512 (+28% between 2000-2004 and 2014-2018; Figure S7). Using the 2006 or 2019 T1 methods,
513 however, larger decreases in the weighted average emission intensity were estimated (around
514 14%), and they were mainly attributed to changes in the emission intensities per kg protein of
515 different livestock categories (53%).

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

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

536

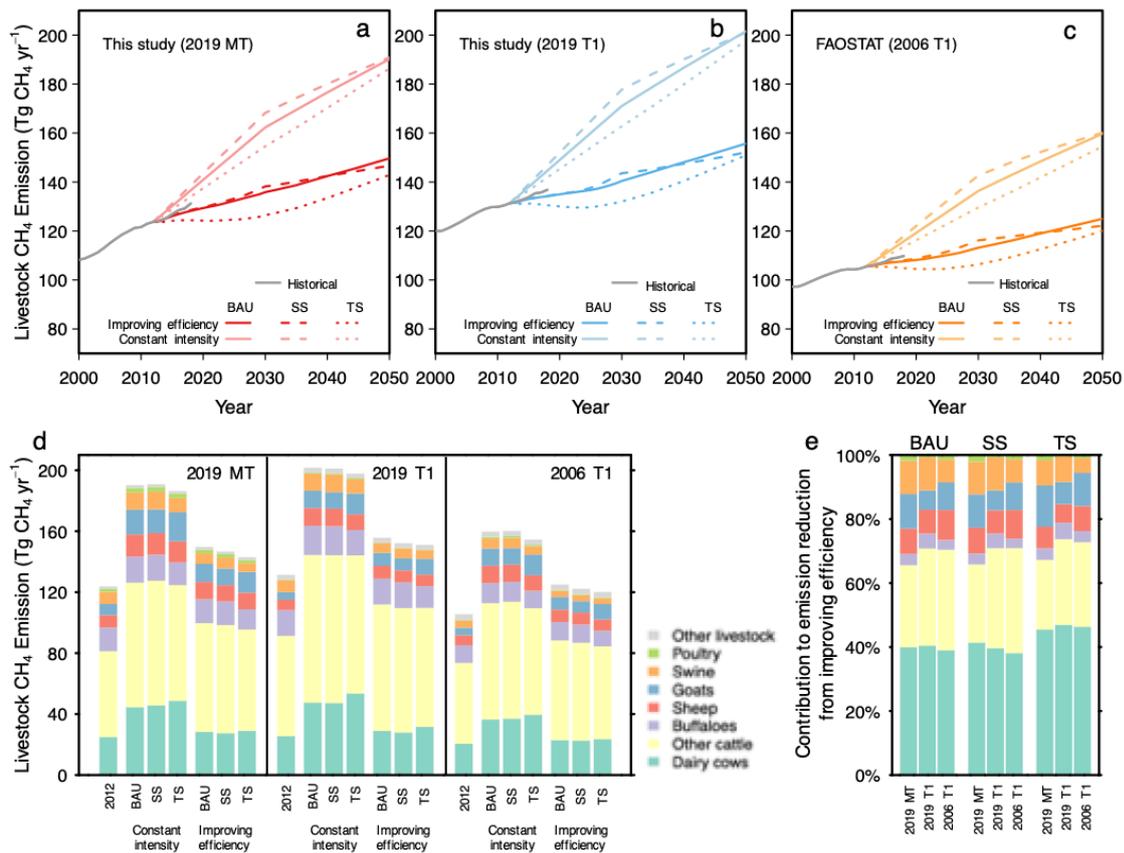
537 **5 Future projections of livestock methane emissions**

538 Combining category-specific methane emission intensities per kg protein (dairy cows, meat and
539 other non-dairy cattle, buffaloes, sheep, goats, swine and poultry) and the FAO's projections

540 on future livestock production (FAO, 2018), we projected future livestock methane emissions
 541 up to 2050 under different socio-economic scenarios (see Methods).

542 Assuming constant emission intensities, as in the period 2014-2018 (referred to as “Constant
 543 intensity” pathway), and keeping emission intensities values from the new 2019 MT method,
 544 the global livestock methane emissions were projected to increase by 51-54% from 2012 to
 545 2050 under different socio-economic scenarios (FAO, 2018) (i.e., reach 186-191 Tg CH₄ yr⁻¹
 546 in 2050; Fig. 4a). The relative increases are similar with the 2006 T1 (46-52%) and 2019 T1
 547 methods (51-53%; Fig. 4b-c) because of the same changes in protein production from (FAO,
 548 2018) and constant emission intensities in this projection.

549



550

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

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

558

559 For the past two decades, we have shown in the previous section that methane emission
560 intensity per kg protein for various livestock categories in each region has been observed to
561 decrease (Fig. 3; Figure S8) following the increases in productivity. The changes in productivity
562 could be empirically related to the development of gross domestic product (GDP) per capita.
563 Country-specific past trends in emission intensity for major livestock categories were estimated
564 from regressions between the emission intensity and GDP per capita (see section 2.6, and Figure
565 S9 as examples). In the “Improving efficiency” pathway (i.e., decreasing emission intensity per
566 kg protein), we assumed: 1) a continuation of the country-specific past trend with the
567 development of GDP per capita for countries showing decreasing emission intensity during the
568 past two decades; and 2) constant emission intensity for countries with no changes or increasing
569 emission intensity in the past (Figure S8). We find that this reasonable scenario of “Improving
570 efficiency” (e.g., Figure S10) can reduce future livestock emissions by a large amount
571 compared to baselines where intensity is constant in the future (Fig. 4d). Global livestock
572 methane emissions were projected to increase by only 15-21% from 2012 to 2050 using the
573 new 2019 MT method (reach 143-150 Tg CH₄ yr⁻¹ by 2050; Fig. 4a). Similar relative increases
574 were estimated using the 2006 T1 (15-19%) and 2019 T1 methods (14-18%; Fig. 4b-c).
575 Additional sensitivity projections were conducted with a continuation of the country-specific
576 past trend with the development of GDP per capita allowing both increasing or decreasing
577 emission intensity in the future (see Methods). Global livestock methane emissions were
578 projected to increase from 2012 to 2050 by 34-35%, 30-33%, and 31-33% using the 2019 MT,
579 the 2019 T1, and the 2006 T1 methods, respectively (Figure S11).

580 The higher emission intensities per kg protein from either the 2019 MT or the 2019 T1 method,
581 compared to the 2006 T1 method, led to projections of larger livestock methane emissions in
582 the future, for a given scenario of livestock numbers and production from (FAO, 2018). The
583 projections using the new 2019 MT and 2019 T1 methods are 18-21% and 24-28% higher,
584 respectively, than that given by the 2006 T1 method (Fig. 4a-c). Moving to the methodology of
585 the *2019 IPCC Refinement* (IPCC, 2019) is important, as the differences can be substantial,
586 particularly in regions such as Sub-Saharan Africa, Near East and North Africa, and South Asia,
587 where large positive trends on livestock production (Figure S12) and emissions (Figure S13)
588 are projected in the future scenarios. In the SSP database (Riahi et al., 2017)

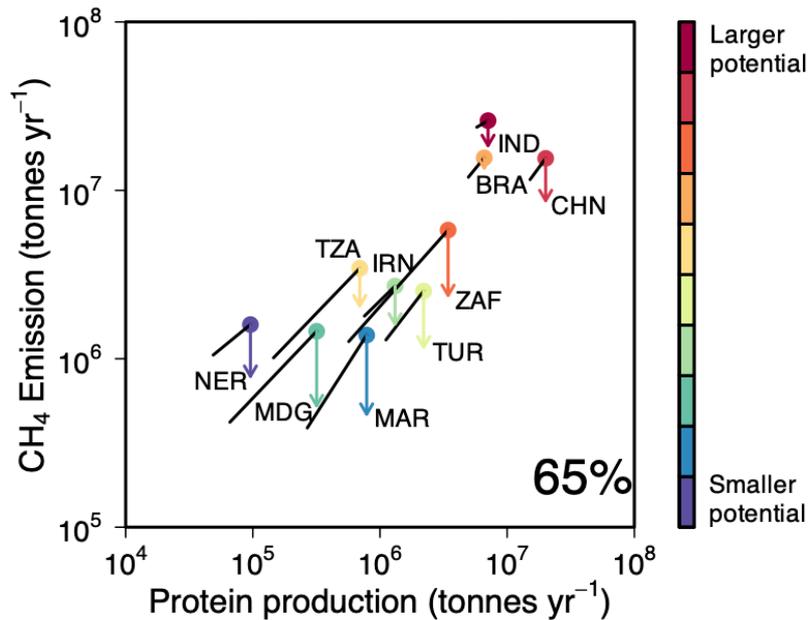
589 (<https://tntcat.iiasa.ac.at/SspDb/>), the projections for greenhouse gas emissions by Integrated
590 Assessment Models (IAMs) were first harmonized for a base year of 2015 to the historical
591 inventory from FAOSTAT. Our results suggest that using historical emissions from FAOSTAT
592 as a reference in the IAMs underestimates future emissions. The updated historical emissions
593 by the 2019 MT and 2019 T1 methods in this study could be used as references in the IAMs.
594 We further provided alternative pathways on emission intensity per kg protein production based
595 on country-specific past trend with the development of GDP per capita. They can be considered
596 as supplementary scenarios of emission intensities for IAMs projections.

597

598 **6 The key role of production efficiency changes in emission mitigation**

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

611



612
 613 **Figure 5. Projections on the increase in protein production, methane emission, and the**
 614 **effects of improving efficiency on reducing livestock methane emissions for all livestock**
 615 **under BAU scenarios, resulting from the 2019 MT method.** The black lines indicate the
 616 protein production (x-axis) and methane emission (y-axis) from 2012 (start of black lines) to
 617 2050 (dots). The arrows indicate the emission reduction potential by 2050 due to improving
 618 efficiency compared to the baseline where emission intensity is constant in the future. Results
 619 for the top ten countries/areas with the largest mitigation potential for all livestock were
 620 presented, with their ISO3 country codes (<http://www.fao.org/countryprofiles/iso3list/en/>)
 621 annotated near the dots or arrows. The red-yellow-violet color scheme represents the mitigation
 622 potential from large to small. The number presented in percentage indicates the contribution of
 623 these ten countries/areas in global total mitigation potential. Countries/areas were presented as
 624 ISO3 country codes.

625

626 Livestock productivity of milk and beef in most developed countries is already high nowadays
 627 (methane emission intensity is already low; Fig. 2), and there is only little room for methane
 628 reduction through productivity increase (Figure S10). On the other hand, further productivity
 629 increase requires high shares of concentrates (i.e., potential competition with human nutrition
 630 from plant-based food (Gill et al., 2010)) and encounters potential health problems in cows (see
 631 review by (Herzog et al., 2018)). In addition, the intensive livestock breeding and management
 632 have resulted in fragile systems that do not adequately handle their manure causing air and

633 water pollution. There is a trend that some developing countries are moving from high
634 efficiency systems towards more extensive livestock systems (such as “free range” chicken and
635 grass-fed beef; e.g., (Cheung & McMahon, 2017)). Therefore, there is possibility that the
636 emission intensity per kg protein in those developed countries will increase, which is opposite
637 to our assumption of constant or decreasing emission intensity.

638 The potential is the largest in developing countries where the current efficiency is low (i.e.,
639 emission intensity per kg protein is high) and a large increase in livestock production is
640 projected. For example, in our projections under the Business As Usual (BAU) scenario, 60-
641 65% of the global reduction in livestock emissions by 2050 due to improving efficiency
642 (compared to baselines where intensity is constant in the future) can be contributed by the top
643 ten countries with the largest reduction potential (Fig. 5 and Figure S15-17). Most of them are
644 developing countries in Asia, South America and Africa.

645 The continuation of past decreases in emission intensity, especially in developing countries,
646 can be achieved through the transition of livestock production systems from extensive
647 rangeland systems to mixed crop-livestock systems (Frank et al., 2018; Havlík et al., 2014) and
648 through improving livestock management within the existing systems (Thornton & Herrero,
649 2010). Various factors can contribute to such a transition: for instance, better breeding, fertility
650 and health intervention (Gill et al., 2010), better quality feed (Gill et al., 2010; Johnson &
651 Johnson, 1995), and optimization of grazing management (e.g., forage storage to avoid losing
652 weight in winter (Thornton & Herrero, 2010)). In addition, new technologies such as feed
653 supplements can also reduce methane emissions from rumen (Caro et al., 2016; Gerber, Hristov,
654 et al., 2013), while methane emissions from manure management can be mitigated through
655 various options, such as improving housing systems, manure storage, composting, and
656 anaerobic digestion (Gerber, Hristov, et al., 2013). However, there are adaptability issues and
657 side-effects that must be considered when implementing these strategies. For example, breeding
658 practices from temperate regions may not adapt well to warm conditions in Africa. A shift in
659 productivity might involve an increase in the consumption of grain-based feed and/or high-
660 quality fodder in the diet, but it can also be effectively achieved through better roughage quality
661 and better grazing management. For example, in semi-arid regions where increasing crop
662 production for feeding livestock is impossible due to water limitations (e.g., central Asia),
663 improving grazing management to increase productivity should be prioritized as a sustainable
664 solution rather than moving from low to industrialized systems (i.e., landless livestock systems
665 with livestock fed by grain-based feed and/or high-quality fodder). Improving livestock

666 production efficiency should always be in line with the natural circumstances in the respective
667 regions. The optimal strategy should consider also other relevant sustainability goals like
668 biodiversity, water pollution through nutrient runoff, and potential implications for livelihoods
669 and resilience to climate change impacts.

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

676

677 **Acknowledgments**

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679 Sciences (Grant No. XDA26010303). P.C acknowledges support from the CLAND
680 Convergence Institute of the French National Research Agency (ANR).

681

682 **Data Availability Statement**

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

688

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