

# Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 °C target by 2030 but not 2050

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### 2 Main Manuscript for

Full Adoption of The Most Effective Strategies to Mitigate Methane
Emissions by Ruminants Can Help Meet the 1.5°C Target by 2030
but Not 2050

| 7  | Claudia Arndt <sup>a*</sup> , Alexander N. Hristov <sup>b</sup> , William J. Price <sup>c</sup> , Shelby C. McClelland <sup>d</sup> , Amalia M.                            |
|----|--|
| 8  | Pelaez <sup>e</sup> , Sergio F. Cueva <sup>b</sup> , Joonpyo Oh <sup>b</sup> , André Bannink <sup>e</sup> , Ali R. Bayat <sup>f</sup> , Les A. Crompton <sup>g</sup> , Jan |
| 9  | Dijkstra <sup>e</sup> , Maguy A. Eugène <sup>h</sup> , D. Enahoro <sup>a</sup> , Ermias Kebreab <sup>i</sup> , Michael Kreuzer <sup>i</sup> , Mark McGee <sup>k</sup> ,    |
| 10 | Cécile Martin <sup>h</sup> , Charles J. Newbold <sup>I</sup> , Christopher K. Reynolds <sup>9</sup> , Angela Schwarm <sup>m</sup> , Kevin J.                               |
| 11 | Shingfield <sup>f**</sup> , Jolien B. Veneman <sup>n</sup> , David R. Yáñez-Ruiz <sup>o</sup> , and Zhongtang Yu <sup>p</sup> .  |
| 12 |  |
| 13 | <sup>a</sup> International Livestock Research Institute (ILRI), Nairobi 00100, Kenya; <sup>b</sup> The Pennsylvania State  |
| 14 | University, University Park, USA; <sup>c</sup> University of Idaho, Moscow, USA; <sup>d</sup> Colorado State University,   |
| 15 | Fort Collins, USA; <sup>e</sup> Wageningen University and Research, Wageningen, The  |
| 16 | Netherlands; <sup>f</sup> Natural Resources Institute Finland, Helsinki, Finland; <sup>9</sup> University of Reading,  |
| 17 | Earley Gate, Reading, UK; <sup>h</sup> INRAE, UCA-VAS, UMRH Centre ARA, Saint-Genès-Champanelle,   |
| 18 | France; <sup>i</sup> University of California, Davis, USA; <sup>j</sup> ETH Zurich, Zürich, Switzerland; <sup>k</sup> Teagasc, AGRIC,                                      |
| 19 | Grange, Ireland; <sup>I</sup> SRUC, Edinburgh, United Kingdom; <sup>m</sup> Norwegian University of Life Sciences,   |
|    |  |

- 20 Aas, Norway; <sup>n</sup>De Heus Animal Nutrition, Ede, The Netherlands; <sup>o</sup>Estación Experimental del
- 21 Zaidín, CSIC, Granada, Spain; <sup>P</sup>The Ohio State University, Columbus, USA.
- 22

23 \*Claudia Arndt

- 24 **Email:** claudia.arndt@cgiar.org
- 25
- 26 \*\*The author is deceased.
- 27
- Author Contributions: C.A., A.N.H., A.M.P., A.B., L.A.C., J.D., M.A.E., E.K., and M.K. conceived
- and designed the study, A.N.H., S.C.M., A.M.P., S.F.C., A.B., L.A.C., J.D., M.A.E., E.K., M.K.,
- 30 M.M., C.M., C.J.N., C.K.R., A.S., K.J.S., J.B.V., D.R.Y.-R. contributed data to the database, C.A.,
- A.N.H., S.C.M., A.M.P., S.F.C., and J.O. collated the database. W.J.P. analyzed the data, C.A.
- 32 wrote the first draft with A.N.H., W.J.P., S.C.M., A.R.B., L.A.C., J.D., M.A.E., D.E., M.K., M.M.,
- 33 C.M., C.K.R., A.S., Z.Y. contributing to further revisions.
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#### 38 This PDF file includes:

- 39 Main Text
- 40 Figure 1 to 3
- 41 Supplementary Figures
- 42 Supplementary Tables (Table 3 can be found in separate excel file)

#### 43 Abstract

44 To meet the 1.5°C target, methane (CH<sub>4</sub>) from ruminants must be reduced by 11 to 30% by 2030 45 and 24 to 47% by 2050 compared to 2010 levels. A meta-analysis identified strategies to 46 decrease product-based [PB;  $CH_4$  per unit meat or milk ( $CH_4I$ )] and absolute (ABS) enteric  $CH_4$ 47 emissions while maintaining or increasing animal productivity (AP; weight gain and milk yield). 48 Next the potential of different adoption rates of one PB and/or one ABS strategy to contribute to 49 the 1.5°C target was estimated. The database included findings from 430 peer-reviewed studies, 50 which reported 98 mitigation strategies that can be classified into three categories: animal and 51 feed management, diet formulation, and rumen manipulation. A random-effects meta-analysis 52 weighted by inverse variance was carried out. Three PB strategies, namely increasing feeding 53 level, decreasing grass maturity, and decreasing dietary forage-to-concentrate ratio, decreased 54 CH₄I by on average 12% and increased AP by a median of 17%. Five ABS strategies, namely 55 CH<sub>4</sub> inhibitors, tanniferous forages, electron sinks, oils and fats, and oilseeds, decreased daily 56 methane by on average 21%. Globally, only 100% adoption of the most effective PB and ABS 57 strategies can meet the 1.5°C target by 2030 but not 2050, because mitigation effects are offset 58 by projected increases in CH<sub>4</sub> due to increasing demand. Notably, by 2030 and 2050 low- and 59 middle-income countries may not meet their contribution to the 1.5°C target for this same reason, 60 whereas high income countries could meet their contributions due to only a minor projected 61 increase in enteric CH<sub>4</sub> emissions.

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#### 63 Significance Statement

Agricultural methane emissions must be decreased by 11 to 30% of the 2010 level by 2030 and by 24 to 47% by 2050 to meet the 1.5°C target. We identified three strategies to decrease product-based (PB) methane emissions while increasing animal productivity (AP) and five strategies to decrease absolute methane emissions (ABS) without reducing AP. Globally, 100% adoption of the most effective PB and ABS strategies can meet the 1.5°C target by 2030 but not

69 2050, because mitigation effects are offset by projected increases in methane. On a regional

70 level, Europe but not Africa may be able to meet their contribution to the 1.5°C target, highlighting

71 the different challenges by high and middle- and low-income countries, respectively.

72

#### 73 Main Text

#### 74 Introduction

- 75 Global food systems contribute to 30% of the worldwide greenhouse gas (GHG) emissions<sup>1</sup>. The
- 76 goal of the Paris Agreement, to limit global warming to 1.5°C above pre-industrial levels, is
- vnlikely to be achieved if food systems continue operating on a business-as-usual (BAU)
- scenario<sup>1</sup>. Among the food-related GHG emissions, methane (CH<sub>4</sub>) from livestock contributes
- 30% of the global anthropogenic  $CH_4$  emissions<sup>2</sup>,17% of the global food system GHG emissions,
- and 5% of global GHG emissions<sup>2,3</sup>. Eighty eight percent of the global livestock  $CH_4$  emissions is
- 81 contributed by enteric fermentation<sup>4</sup>.
- Methane is a short-lived climate pollutant. Given its perturbation lifetime in the atmosphere of
  around 12.5 years, CH<sub>4</sub> contributes significantly to near-term global warming<sup>5</sup>. Its Global Warming
  Potential is 84 or 28, for 20- or 100-year time horizons, respectively<sup>5</sup>. When evaluating the

85 contribution of global food systems to  $CH_4$  emissions over a 20-year period instead of the

86 commonly used 100-year time period for national GHG inventories, the contribution of CH<sub>4</sub> to

food system GHG emissions more than doubles from 17 to  $36\%^{3,5}$ .

The realization of Nationally Determined Contributions and 2050 climate neutrality goals depends upon the reduction of  $CH_4$  emissions. Within sectoral reductions of  $CH_4$  emissions, technical solutions to decrease  $CH_4$  from agricultural production, especially strategies to mitigate  $CH_4$  from enteric fermentation by ruminant livestock are integral to meeting these climate targets, but quantitative data on mitigation potentials are scarce<sup>6</sup>. Based on 2010, GHG emission levels, and different mitigation scenarios to limit global warming to  $1.5^{\circ}C$ , agricultural  $CH_4$  emissions need to be decreased by 11 to 30% by 2030 and by 24 to 47% by 2050<sup>7</sup>.

95 The global population is projected to increase by 23% between 2010 and 2030 with most of the increase occurring in low- and middle-income countries (LMIC)<sup>8</sup>. Ruminants contribute about half 96 of the animal protein produced by livestock<sup>4</sup>. In LMIC, ruminant livestock plays a crucial role in 97 food security<sup>9</sup>. Ruminants can convert human-inedible feeds like those from pastures and grain 98 99 commodity by-products produced on marginal lands or from subsistence agricultural production 100 systems into nutritionally dense human-edible foods. Ruminants also provide other benefits, such as traction and manure for fuel and fertilizer<sup>10</sup>. In addition, human population growth is generally 101 102 high in LMIC, while consumption of animal-sourced food is often below recommended dietary levels and/or reliant upon ruminant meat and milk for livelihoods and nutrition security<sup>10,11</sup>. Thus, 103 104 from a feed-food competition perspective, ruminant production increases in LMIC should rely on 105 human inedible feeds (i.e. forage and by-products). In contrast, in high income countries (HIC) 106 population growth is much lower and the consumption of animal protein is often above recommended dietary levels<sup>9,11</sup>. 107

108 Sustainable strategies for enteric CH<sub>4</sub> mitigation that align with the 1.5°C target should preferably avoid socioeconomic and environmental tradeoffs<sup>12</sup>, and, ideally, increase production yield per 109 110 unit of input. Reductions in both CH<sub>4</sub> emissions intensity, i.e., emissions per unit of milk and gain 111  $(CH_4I_M \text{ and } CH_4I_G, \text{ respectively})$ , and absolute  $CH_4$  emissions are therefore needed. Strategies 112 that reduce CH<sub>4</sub>I and increase production per unit of input could be used to expand food production from the existing ruminant population without increasing total CH<sub>4</sub> emissions<sup>13,14,15</sup>. 113 114 and thus contribute to the 1.5°C target as well as to Sustainable Development Goals (SDGs) that 115 are impacted by climate change. Several reviews indicate that animal and feed management, diet formulation, and rumen manipulation strategies could significantly decrease enteric CH<sub>4</sub> 116 emissions<sup>12,16,17</sup>. However, previous studies consisted of gualitative reviews<sup>12</sup>, examined the 117 quantitative effects of a single mitigation strategy<sup>18,19,20</sup>, or compared CH<sub>4</sub> yield (CH<sub>4</sub>Y; CH<sub>4</sub> per 118 unit of feed intake) between multiple mitigation strategies<sup>17</sup>. Methane yield is only one relevant 119 120 measure, and other major CH<sub>4</sub> emission and animal performance metrics must be considered to 121 determine the effectiveness and feasibility of mitigation strategies. Only one recent publication 122 examined the quantitative effects of multiple mitigation strategies on CH<sub>4</sub> emission and animal

123 performance metrics, but the analysis was limited to Latin America<sup>21</sup>. Important CH<sub>4</sub> emission

124 metrics include daily CH<sub>4</sub> emissions, CH<sub>4</sub>Y or CH<sub>4</sub>-energy conversion factor [Y<sub>m</sub>; CH<sub>4</sub> energy as a

125 proportion of gross energy intake; a component of the Tier 2 calculation for national GHG

inventories recommended by the Intergovernmental Panel on Climate Change<sup>22</sup>], CH<sub>4</sub>I<sub>G</sub>, and

- 127 CH<sub>4</sub>I<sub>M</sub>. Important animal performance metrics include feed intake, nutrient digestibility, and animal
- 128 production.

129 The objective of this study was to conduct a comprehensive meta-analysis of enteric CH<sub>4</sub>

130 mitigation strategies published in peer-reviewed journals by examining their quantitative effect on

131 the aforementioned *in-vivo* CH<sub>4</sub> emissions and animal performance metrics and to estimate their

132 potential to contribute to the 1.5°C target. As outlined above, there is an urgent need for

133 strategies that can effectively mitigate enteric CH<sub>4</sub> emissions without negatively affecting AP by

focusing exclusively on strategies that decouple  $CH_4$  emissions from animal production<sup>23</sup>.

135 Mitigation effects were quantified on global level as well as on a regional level. The African and

136 European region were selected to represent LMIC and HIC, respectively.

137

#### 138 Results and Discussion

139 The meta-analysis included 98 mitigation strategies reported in 430 peer-reviewed journal 140 publications (Table S1). Mitigation strategies were classified into three main categories: animal 141 and feed management, diet formulation, or rumen manipulation strategies. Of the strategies 142 included, 63 did not significantly (adjusted  $P \ge 0.05$ ) decrease daily CH<sub>4</sub> emissions; the remaining 143 35 strategies decreased daily CH<sub>4</sub> emissions by on average 18% (ranging from 5 to 43%). These 144 strategies were classified as 'effective' in decreasing product-based CH<sub>4</sub> (PB strategies) if they 145 significantly decreased  $CH_4I_M$  or  $CH_4I_G$  and  $CH_4Y$  while significantly (adjusted P < 0.05) 146 increasing AP. Strategies were classified as 'effective' in decreasing absolute CH4 emissions 147 (ABS strategies) if they significantly decreased daily CH<sub>4</sub> emissions, CH<sub>4</sub>I<sub>M</sub> or CH<sub>4</sub>I<sub>G</sub>, and CH<sub>4</sub>Y 148 without decreasing AP (weight gain of growing animals or milk yield of lactating dairy animals) 149 when productivity data were present.

A summary of the studied mitigation strategies is presented in Fig. 1, and the full list of the studied mitigation strategies and their effects on enteric  $CH_4$  emission and animal performance metrics are presented in Tables S2 and S3, respectively. Effective mitigation strategies and their impact on  $CH_4I_M$ ,  $CH_4I_G$ , daily  $CH_4$ ,  $CH_4Y$ , as well as their relevance for different systems (feedlot, mixed, and grassland) are presented in Fig. 2 from highest to lowest efficacy in reducing  $CH_4I_M$ . All other strategies that were not classified as effective but had a significant effect on  $CH_4$ ,  $CH_4Y$ ,  $Y_m$ ,  $CH_4I_G$  or  $CH_4I_M$  are presented in Fig. S1 to S3.

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159 The meta-analysis identified three effective PB strategies, namely increasing feeding level, 160 decreasing grass maturity, and decreasing dietary forage-to-concentrate ratio. These PB 161 strategies decreased CH<sub>4</sub>I by on average 12% (range 9 to 17%) and increased AP by a median 162 of 17% (range 9 to 162%). Furthermore, there were five effective ABS strategies, namely  $CH_4$ 163 inhibitors, tanniferous forages, electron sinks, oils and fats, and oilseeds (only for lactating 164 animals since oilseed supplementation significantly decreased weight gain in growing animals). 165 These ABS strategies decreased CH₄I by on average 17% (ranging from 12 to 32%) and daily 166  $CH_4$  emissions by on average 21% (ranging from 12 to 35%) without negatively affecting AP.

167

Several mitigation strategies were excluded from the present evaluation or classified as ineffective because of insufficient publications. These include breeding low-CH<sub>4</sub> emitting animals and improving animal health. However, modeling studies have shown that strategies that improve animal health may significantly increase AP and reduce  $CH_4I^{24}$ . In the subsequent section, the effects of mitigation strategies are reported in parenthesis as mean, 95% confidence interval (95% CI), and the number of treatment comparisons (n). Reported differences were significant (adjusted P < 0.05) unless indicated otherwise.

175

#### 176 Strategies that decrease product-based CH<sub>4</sub> emissions and increase production

177 **Increasing feeding level** (mean = 58%, 95% CI = 47 to 71%, n = 47) decreased CH<sub>4</sub>I<sub>M</sub> (17%, 9 178 to 23%, 5). No data were available for CH<sub>4</sub>I<sub>G</sub>. Fiber digestibility was decreased (7%, 2 to 12%,

18), likely due to increased rumen passage rates<sup>25</sup>. Increasing feed intake resulted in increased 179 180 weight gain (162%, 38 to 398%, 7) and milk yield (17%, 10 to 25%, 8). Increasing feed intake to improve AP significantly decreases  $CH_4I_G$  and  $CH_4I_M^{12,26}$  as well as the overall carbon footprint of 181 animal-sourced food<sup>27</sup> when diet composition remains unchanged. This strategy directs energy 182 for CH<sub>4</sub> towards animal production<sup>28</sup> but also decreases energy requirements for maintenance 183 184 relative to milk production and reduces the time to slaughter for growing animals. Potential effects 185 of this practice on manure CH<sub>4</sub> emissions, as a result of decreased fiber digestibility, need to be 186 evaluated. The practice is applicable to feedlots, mixed, and grassland systems, but particularly 187 the latter and especially in certain climatic regions where animals are underfed due to insufficient or low nutritive forage<sup>29</sup>. 188

189

190 **Decreasing grass maturity** decreased  $CH_4I_M$  (13%, 7 to 18%, 6), did not affect feed intake but 191 increased milk yield (9%, 1 to 18%, 6). Furthermore, it improved fiber digestibility (15%, 9 to 21%, 9), which can potentially decrease manure  $CH_4$  emissions<sup>22</sup>. The positive effect of decreasing 192 grass maturity on milk yield is likely attributed to greater digestible energy and protein content. 193 Increased protein content, however, can lead to increased nitrogen intake and excretion<sup>30</sup>. Thus, 194 195 possible tradeoffs associated with direct and indirect manure nitrous oxide emissions require 196 further evaluation. This strategy is applicable to all production systems. Although decreasing 197 grass maturity increases the overall efficiency of dietary nutrient use for milk production (kg milk 198 per unit of feed intake), it was not deemed to be cost-effective in the Netherlands; however, it was more cost-effective than supplementation with nitrate or linseed<sup>31</sup>. 199

200

201 Decreasing dietary forage-to-concentrate ratio decreased  $CH_4I_M$  (9%, 4 to 14%, 19) and

CH<sub>4</sub>I<sub>G</sub> (9%, 3 to 15%, 16). It increased feed intake (9%, 5 to 14%, 85), which led to an increase in weight gain (21%, 13 to 29%, 32) and milk yield (17%, 10 to 24%, 26) but did not increase absolute CH<sub>4</sub> emissions or reduce fiber digestibility. Reduced CH<sub>4</sub>Y (13%, 10 to 16%, 69) was the result of increased feed intake, which most likely resulted in a shift in rumen fermentation patterns and a decrease in rumen pH, which inhibits methanogens<sup>32</sup>. However, the supplementation of

207 grain-based concentrate needs to be limited because overfeeding can lead to subacute ruminal 208 acidosis. Subacute ruminal acidosis is a nutritional disease that is associated with perturbation of 209 rumen fermentation, and decreased fiber digestibility, milk fat content, and animal health are mostly found in the feedlot and high-yielding dairy cattle<sup>33</sup>. In addition, the promotion of increased 210 211 use of (food-quality) grain-based concentrate in ruminant diets will likely intensify feed-food 212 competition. In contrast, if concentrate-rich diets are mainly based on food industry by-products, 213 the feed-food competition may be avoided. The cost-effectiveness of this strategy will depend on 214 forage and concentrate costs as well as associated increases in animal production and the price 215 of animal products (meat and milk).

216

#### 217 Strategies that decrease absolute CH<sub>4</sub> emissions

218 Rumen manipulation by feeding CH<sub>4</sub> inhibitors 3-nitrooxypropanol (3-NOP) effectively

219 decreased CH<sub>4</sub>I<sub>M</sub> (31%, 21 to 40%, 2) without affecting feed intake or milk yield. 3-

220 nitrooxypropanol acts on a key enzyme of the methanogenesis pathway that is used by

221 methanogenesis to produce CH<sub>4</sub><sup>34</sup>. Insufficient data were available in the database to evaluate its

222 effect on weight gain or fiber digestibility in this analysis. However, in recent studies, 3-NOP did

not show adverse effects on weight gain of growing beef cattle<sup>35</sup> or fiber digestibility in early-

lactation dairy cows<sup>36</sup> and decreased daily CH<sub>4</sub> emissions throughout a 15-week experiment<sup>37</sup>. A

 $\label{eq:225} \mbox{recent meta-analysis showed that 3-NOP decreased daily CH_4 emissions in a dose-dependent}$ 

226 manner, that its mitigation effect was greater for dairy than beef cattle, and that its effectiveness

decreased with increasing dietary fiber content<sup>18</sup>. In its current form, 3-NOP can only be used in

228 confinement systems because it is more effective when fed continuously<sup>36,38</sup>, but ongoing

research is developing mechanisms for its application under grazing conditions<sup>39</sup>.

230 Supplementation of 3-NOP increased milk fat content in dairy cattle<sup>29</sup> and feed efficiency in

231 feedlot cattle<sup>40</sup>, which may help offset its cost and stimulate adoption. A limitation of 3-NOP is that

its use as a feed additive requires regulatory approval by various countries. Another CH<sub>4</sub> inhibitor

233 strategy is supplementation with seaweed (e.g. Asparagopsis taxiformis), which can decrease

234 daily CH<sub>4</sub> emissions by up to 80%<sup>41</sup>. However, more research is warranted on dietary inclusion

levels, effects on animal feed intake and production<sup>42</sup>, the implications and safety of feeding
bromoform<sup>43</sup>, its main active compound<sup>44</sup>, the extremely high iodine content of *Asparagopsis*species (which limits how much can be fed in many countries), as well as the environmental
effects of cultivating seaweed<sup>45</sup> before it can be recommended as a mitigation strategy.

239

Dietary inclusion of tanniferous forages decreased CH<sub>4</sub>I<sub>M</sub> (18%, 8 to 26%, 7). However, it also 240 241 decreased fiber digestibility (7%, 2 to 12%, 21), which could potentially increase manure  $CH_4$ emissions<sup>22</sup>. Daily CH₄ emissions were also decreased (12%, 7 to 16%, 42) and feed intake or 242 243 animal production were unaffected. There are differences in efficacy among tannin sources. 244 Sericea lespedeza (Lespedeza cuneata) and Lotus (corniculatus and pedunculatus) were 245 determined as the most promising tanniferous forage as they significantly decreased daily CH<sub>4</sub> 246 emissions (32% and 8%, respectively) without affecting feed intake. Sericea lespedeza 247 (Lespedeza cuneata) decreased daily CH₄ emissions (32%, 24 to 39%, 5) without affecting feed 248 intake in goats and it has been effective in decreasing daily CH₄ emissions throughout a 12-week 249 experiment<sup>46</sup>. Other tanniferous forages that may potentially decrease daily CH<sub>4</sub> emissions are 250 Leucaena (8%, 0 to 16%, 12, P = 0.10) and Lotus (corniculatus and pedunculatus) (8%, 3 to 251 13%, 3). Although this meta-analysis did not reveal any effect on feed intake, tanniferous forages have been associated with decreased palatability and feed intake<sup>47</sup>. In addition, tannins can bind 252 253 to dietary protein and thus decrease protein digestion and animal production, especially when 254 dietary protein is limiting. Nevertheless, when dietary protein is excessive or highly degradable, 255 tannins may be beneficial, because they reduce the excretion of nitrogen in urine, which decreases ammonia and nitrous oxide emissions from manure<sup>48</sup>. The cost-effectiveness of their 256 257 supplementation still needs to be evaluated. Among the identified effective ABS strategies, 258 dietary inclusion of tanniferous forages is the only one applicable to grassland besides feedlot 259 and mixed systems. As 37% of global enteric CH₄ emissions from ruminant livestock is attributed 260 to grazing systems<sup>4</sup>, it will be important to identify other effective ABS strategies that are 261 applicable to grassland systems.

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263 Rumen manipulation with electron sinks decreased  $CH_4I_M$  (13%, 9 to 16%, 12) and  $CH_4I_G$ 264 (12%, 2 to 20%, 3). Although they led to small decreases in feed intake (2%, 1 to 3%, 49), small 265 increases in milk yield (3%, 1 to 5%, 13) were observed. Electron sinks accept hydrogen that would otherwise be used by methanogens for CH<sub>4</sub> production in the rumen<sup>32</sup>. Of the studied 266 267 electron sinks (fumaric acid and nitrate), only nitrate was classified as effective. Nitrate has been 268 shown to decrease daily  $CH_4$  emissions and  $CH_4Y$  in a dose-dependent manner with no loss of effectiveness and effectively decreased daily  $CH_4$  emissions over the long-term<sup>20,49</sup>. Similar to 3-269 270 NOP, nitrate was more effective in decreasing daily  $CH_4$  emissions and  $CH_4Y$  in dairy than in beef cattle<sup>20</sup>. Although nitrate can be toxic, early research on nitrate supplementation in ruminant diets 271 272 reported a decrease in feed intake and no toxicity symptoms; however, toxicity can occur if 273 animals are not properly acclimatized<sup>50</sup>. Acclimatization of animals to dietary nitrate is required to 274 avoid methemoglobinemia, a blood disorder in which too little oxygen is delivered to the cells. 275 However, this acclimatization can be lost within three weeks when nitrate is not fed daily<sup>51</sup>. 276 Simultaneous sulfate supplementation has been shown to help protect cattle against nitrate toxicity<sup>52</sup>. Nitrate supplementation may increase enteric and possibly manure nitrous oxide 277 emissions<sup>53</sup>. Studies in France<sup>54</sup> and the Netherlands<sup>31</sup> found that nitrate supplementation was 278 279 not cost-effective.

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**Dietary inclusion of oil and fat** decreased  $CH_4I_M$  (12%, 6 to 18%, 24) and  $CH_4I_G$  (22%, 8 to 281 282 35%, 6); however, possible effects on manure CH<sub>4</sub> emissions due to decreased fiber digestibility (4%, 2 to 7%, 37) need to be evaluated<sup>22</sup>. Weight gain in growing animals or milk production in 283 284 dairy animals was unaffected despite decreasing feed intake (6%, 3 to 8%, 58) and fiber 285 digestibility likely because of the high energy concentration of lipids compared with feeds it 286 replaces in livestock diets. Of the subcategories included in oil and fat supplementation, only 287 dietary inclusion of predominantly vegetable oils effectively decreased daily CH<sub>4</sub> emissions. This 288 effect can be attributed to increased supply of non-fermentable highly digestible energy, 289 decreased feed intake and fiber digestibility as well as inhibition of methanogenesis by 290 unsaturated (or medium-chain saturated) fatty acids, which are usually abundant in vegetable

oils. Oil inclusion reportedly decreases daily CH<sub>4</sub> emissions in a dose-response manner<sup>19</sup> and 291 292 over the long-term<sup>55,56</sup>. The amount of oil that can be included in ruminant diets, however, is 293 limited and inclusion level should not be at the expense of healthy rumen fermentation that may 294 negatively impact animal health and productivity<sup>57</sup>. Maximum oil inclusion levels in ruminant diets 295 depend on the animals' physiological stage, lipid and other nutrient composition of the basal diet, and fatty acid profile of the supplemental oil<sup>58</sup>. Dietary oils and fats are by-products of oilseed 296 297 production, which has been associated with nearly doubling of the GHG emissions per kg dry matter compared with other concentrate feeds (1.27 vs. 0.70 CO<sub>2</sub> equivalents kg dry matter<sup>-1)<sup>59</sup>.</sup> 298 299 Thus, upstream emissions are likely to increase when concentrate feeds are substituted by oil 300 and fat. However, enteric fermentation usually contributes substantially more GHG to the carbon footprint of ruminant products than feed production<sup>60,61</sup> and the dietary inclusion of oil is limited. 301 302 Thus, increases in upstream emissions are unlikely to offset GHG reduction through the 303 mitigation of enteric CH<sub>4</sub> emissions by oils or fats. Nevertheless, exact upstream offsets of oils 304 should be evaluated. The cost-effectiveness of feeding oils to decrease CH<sub>4</sub>I varies by region and 305 country, because the price of oil, as well as meat and milk, vary considerably therein. Studies in China<sup>62</sup>, France<sup>54</sup>, and The Netherlands<sup>31</sup> found that dietary inclusion of oils, for the purpose of 306 307 mitigating enteric CH<sub>4</sub> emissions, was not cost-effective, but trade-offs by concomitant 308 improvements in the fatty acid profile of milk and meat from a human-health perspective might 309 help to support the adoption of certain oils and oilseeds in animal diets.

310

Dietary inclusion of oilseeds (cracked or crushed) had similar effects on CH<sub>4</sub>I<sub>M</sub> (12%, 4 to 19%, 311 312 6) compared with oils and fat. Their supplementation tended to decrease feed intake (4%, 1 to 313 7%, 25, P = 0.06) and decreased fiber digestibility (8%, 6 to 11%, 13). Similar to oils, oilseeds 314 had no effect on milk yield but decreased weight gain in growing animals (13%, 6 to 20%, 8); 315 thus, dietary oilseed inclusion may only be recommended for lactating animals and not for 316 growing animals. Likewise, the amount of inclusion of oilseeds should be limited to avoid negative 317 impacts on rumen fermentation, animal health and production. However, as part of the oil in oilseeds is rumen-protected, dietary inclusion levels can be slightly higher than that of oils<sup>63</sup>. And 318

similar to oil inclusion, the possible impact to manure CH<sub>4</sub> emissions due to decreased fiber

320 digestibility needs to be evaluated. Oilseeds that tended to decrease CH<sub>4</sub>I<sub>M</sub> were cottonseed

321 (15%, 2 to 25%, 2, *P* = 0.07) and canola seed (13%, 2 to 23%, 3, *P* = 0.07).

322

#### 323 The potential of the identified strategies to decrease enteric methane emissions

324 The potential of the identified strategies to decrease enteric CH<sub>4</sub> emissions globally, in Africa and 325 in Europe, between 2012 and 2030 and between 2012 and 2050 was estimated using three 326 mitigation scenarios. The year 2012 was used as the baseline instead of 2010, because projections used for demand<sup>64</sup> and human population<sup>65</sup> only had figures for 2012 and not 2010. 327 328 The identified strategies in the current meta-analysis (Fig. 2) and BAU projections for per capita 329 red meat and dairy food protein demand<sup>64</sup> together with FAO projections for human population 330 growth<sup>65</sup> were used in the mitigation scenarios. Although international trade allows livestock 331 products to move across regions, it was assumed that demand increases in each of the modeled 332 regions would be met by livestock production within the same region, an assumption that 333 suggests technological, market and policy conditions would allow each region to produce enough 334 to meet their own livestock protein demand. A sensitivity analysis for 100%, 75%, 50%, and 25% 335 adoption rates of mitigation measures was performed. The three mitigation scenarios were: 1) 336 Adoption of one PB strategy, 2) Adoption of one ABS strategy, and 3) Simultaneous adoption of 337 one PB and one ABS.

338

Globally, only the 100% adoption of the most effective PB and ABS strategies (increasing feeding level and inclusion of a CH<sub>4</sub> inhibitor, respectively) decreased enteric CH<sub>4</sub> emissions sufficiently (14%) to meet the 1.5°C target by 2030 (Fig. 3A) but not by 2050 (Fig. S4A). In Africa, which was chosen to represent LMIC, none of the mitigation scenarios had the potential to meet the 1.5°C target by 2030 or 2050 (Fig. 3B and Fig. S4B). Although, the 100% adoption of the most effective PB and ABS strategies was estimated to mitigate enteric CH<sub>4</sub> emissions by 47% and 76% between 2012 and 2030 and 2012 and 2050, respectively, the mitigation effect was offset by

estimated increases in  $CH_4$  emissions in BAU scenario (87% and 220%, resepectively; Fig. 3B and Fig. S4B).

348 In contrast, in Europe, which was chosen to represent HIC, projected increases in enteric CH<sub>4</sub> 349 emissions between 2012 and 2030 and 2012 and 2050 without mitigation strategy were only 11% 350 (Fig. 3C and Fig S4C). By 2030, Europe could meet the 1.5°C target under the following 351 mitigation scenarios (Fig. 3C): 1) The simultaneous 100% and 75% adoption of one PB strategy 352 (when assuming the average or above average mitigation potential of all PB strategies) and one 353 ABS strategy (when assuming the average or above average mitigation potential of all ABS 354 strategies), 2) The simultaneous at least 50% adoption of the most effective PB and ABS 355 strategy, and 3) The at least 75% adoption of the most effective ABS strategy. By 2050, Europe 356 could only meet the 1.5°C target by the simultaneous 100% adoption of the most effective PB 357 and ABS strategies (Fig. S4C).

358

While technically possible, even with transformative agri-food sector actions that remove adoption barriers for the simultaneous 100% adoption of the most effective PB and ABS strategies identified in this study is unlikely. Consequently, the identified strategies to reduce enteric  $CH_4$ emissions must be enacted together with other measures to decrease  $CH_4$  emissions. For example, strategies to reduce  $CH_4$  emissions from manure handling or pre- or post-farmgate measures, such as the reduction of food waste and a shift to a more plant-based diets<sup>11</sup> when per capita protein consumption is high.

366

Combining two or more strategies to mitigate enteric  $CH_4$  can increase or decrease the efficacy of the strategies. However, most likely the combination of two ore more strategies will give a greater reduction, than when only one is used. In this study, it was assumed that the combination of strategies would resuld in an additive mitigation effect, as this was observed when lipids were combined with tannins<sup>66</sup>, 3-NOP<sup>67, 68</sup>, or nitrates<sup>69</sup>. However, more studies are needed to evaluated the effect of combining two or more strategies, as combinations of multiple mitigation strategies are likely needed to sufficiently mitigate  $CH_4$  to limit globular warming to 1.5°C.

374

| 375 | Although one of the identified mitigation scenarios was suited to decrease global enteric $CH_4$  |
|-----|---|
| 376 | emissions to limit global warming to 1.5°C by 2030 but not 2050, the 1.5°C target is unlikely to be   |
| 377 | achieved, because 100% of the producers would need to adopt it. While none of the mitigation  |
| 378 | scenarios would allow Africa to meet the 1.5°C target, multiple scenarios that did not require a  |
| 379 | 100% adoption would allow Europe to reach the 1.5°C target. The reason for this is that Africa  |
| 380 | had a greater projected BAU increase in enteric $CH_4$ emissions compared with Europe (87 vs.   |
| 381 | 11%) between 2012 and 2030, as a result of projected increases in human population (56 vs. 4%)  |
| 382 | and per capita demand for red meat and milk protein (18 vs. 5%) resulting in a greater absolute   |
| 383 | increase in demand of red meat and milk protein (84 vs. 9%). In addition, Africa compared with  |
| 384 | Europe has an overall higher $CH_4I_M$ (104 and 19 kg $CO_2$ equivalents kg milk protein <sup>-1</sup> ,                                      |
| 385 | respectively) and $CH_4I_G$ (198 and 46 kg $CO_2$ equivalents kg red meat protein <sup>-1</sup> ), which leads to                             |
| 386 | proportionally greater increases in enteric $CH_4$ for red meat and milk protein produced in Africa   |
| 387 | compared to Europe. Similar reasons led to the observed differences between 2012 and 2050.  |
| 388 |   |
| 389 | Even though Africa may not be able to meet the 1.5°C target, the projected BAU per capita red   |
| 390 | meat and milk protein demand in 2030 will still be 51% and 78% smaller than that of Europe (3.4   |
| 391 | vs. 6.9 g red meat protein capita <sup>-1</sup> day <sup>-1</sup> and 4.3 vs. 19.9 g of milk protein capita <sup>-1</sup> day <sup>-1</sup> , |
| 392 | respectively). Despite this large disparity in annual animal protein consumption, annual BAU per  |
| 393 | capita enteric $CH_4$ emissions for red meat and milk consumed in Africa was 111 and 8% greater   |
| 394 | than that in Europe in 2012 (245 vs. 116 kg $CO_2$ equivalents capitiia <sup>-1</sup> year <sup>-1</sup> and 144 vs. 134 kg                   |
| 395 | $CO_2$ equivalents capita <sup>-1</sup> head year <sup>-1</sup> , respectively) and 161 and 25% greater than that in Europe                   |
|     |   |

in 2050 (303 vs. 116 kg CO<sub>2</sub> equivalents capita<sup>-1</sup> year<sup>-1</sup> and 163 vs. 130 kg CO<sub>2</sub> equivalents capita<sup>-1</sup> year<sup>-1</sup>, respectively). This shows the need and opportunity to decrease CH<sub>4</sub>I in Africa and other LMIC where CH<sub>4</sub>I is high. In Europe and other HIC, where CH<sub>4</sub>I and annual per capita enteric CH<sub>4</sub> emissions associated with red meat and milk protein consumption are low but red meat and milk demand are high, emissions might be reduced by shifting demand to plant-based

401 alternatives<sup>11</sup>. In addition, red meat and milk exports from HIC to LMIC could help to reduce

402 enteric CH<sub>4</sub> emissions to meet the 1.5°C target. However, these exports often do not reach food403 insecure regions where the money to buy food is limited or unavailable and increases in local
404 production are more likely to meet the demand and recommended levels of dietary protein intake.
405

406 Future research needs to 1) develop novel mitigation strategies especially for pasture-based 407 systems (less than half of the identified strategies were relevant for pasture systems), 2) increase 408 the understanding of the mitigation potential of combinations of enteric fermentation mitigation 409 strategies, 3) investigate the mitigation effect of identified strategies on emissions of growing and 410 non-lactating cattle (only half of the identified strategies had sufficient data available to evaluate 411  $CH_4I_G$ ), 4) estimate offsets of  $CH_4$  mitigation by increases in GHG emissions elsewhere in the 412 supply chain including in longer supply chains characterized by international trade, and 5) identify 413 the barriers to wide-scale adoption of effective mitigation strategies in HIC and LMIC.

414

#### 415 Conclusion

416 This comprehensive meta-analysis identified in a quantitative and comparative manner three 417 effective PB and five effective ABS strategies. The three PB strategies decreased product-based 418 CH₄ emissions by on average 12% (ranging from 9 to 17%) and increased animal production by a 419 median of 17% (ranging from 9 to 162%). The five ABS strategies reduced product-based  $CH_4$ 420 emissions by an average of 17% (ranging from 12 to 32%) and daily CH₄ emissions by an 421 average of 21% (ranging from 12 to 35%). The 100% adoption of only one of the PB or ABS 422 strategies at a time, cannot sufficiently decrease global enteric CH<sub>4</sub> emissions from agriculture by 423 2030 or 2050 to achieve the 1.5°C target. However, the simultaneous 100% adoption of the most 424 effective PB and ABS strategy can sufficiently decrease global enteric CH₄ emissions to achieve 425 the 1.5°C target by 2030 but not 2050. Adoption barriers to the identified strategies are likely to 426 prohibit them from reaching their full technical potential. Thus, to ensure meeting the 1.5°C 427 climate target, it will be crucial that adoption barriers are identified and removed, and the 428 identified strategies are implemented. This also needs to be done for strategies that remove

emissions from the supply and demand site in the agricultural sector. Further, the mitigation effect of the simultaneous implementation of more than two of the identified strategies should be studied. At a regional level, projected autonomous increases in enteric  $CH_4$  emissions may prevent meeting the 1.5°C target in studied mitigation scenarios in LMIC, such as for Africa. The projected increases in enteric  $CH_4$  in HIC, such as Europe, are relatively small. Multiple studied scenarios may allow HIC to meet the 1.5°C target by 2030 and one scenario will also do so for the 2050 target.

436

#### 437 Materials and Methods

438 Literature Search and Classification of Mitigation Strategies. The database for this meta-439 analysis was compiled using data obtained by searching the databases of the Commonwealth 440 Agricultural Bureau International (CABI), the EBSCO Discovery Service, and the Web of Science. 441 Publications from 1964 through 2016 were searched using CABI and EBSCO Discovery Service 442 with the search terms 'rumen' AND 'methane' and an additional four searches were completed in 443 the EBSCO Discovery Service using the term 'rumen' in combination with 'methane', 'energy 444 partitioning', 'energy metabolism', or 'energy balance'. Publications from 2017 through 2018 were 445 searched using CABI and Web of Science databases. Seven searches were conducted with the 446 search term 'methane' in combination with 'beef', 'cattle', 'dairy', 'goat', 'sheep', 'rumen', or 447 'ruminant' and three searches with the search term 'rumen' in combination with 'energy balance', 448 'energy metabolism', or 'energy partitioning'. Publications listed in an independently developed database supported by the AnimalChange project, MitiGate<sup>17</sup>, were merged with the database 449 450 created in the current analysis.

The abstracts of the publications found in the search were reviewed, and based on the abstract content, publications were selected for further consideration if they included *in vivo* measurement of enteric CH<sub>4</sub> emissions, a clearly defined treatment and control, and multiple replications (at least four or more animals in continuous design experiments, crossover design experiments, etc.). Publications were excluded if they were not from peer-reviewed literature or if they were not in English, French, German, Spanish or Portuguese. Furthermore, publications were excluded if

457 they were based on inappropriate study design (i.e., experimental period ≤ 10 days) or

458 measurement technique (e.g. the 'sniffer technique' that is based on  $CH_4$ -to- $CO_2$  ratio of exhaled 459 breath<sup>70,71</sup>).

460 The completed database consisted of 650 publications. From these, only the publications that

had a treatment that could be assigned to one of three main mitigation categories, as described

462 below, and reported statistical variance for at least one of the CH<sub>4</sub> emissions emission metrics

463 (e.g. LSD, RSD, or SE of the mean) were included in the final analysis. WebPlotDigitizer

464 (https://automeris.io/WebPlotDigitizer/; accessed 30 October 2019) was used to determine

absolute values for a total of nine metrics in seven publications where data were reported as

466 figures.

467 The data were classified into three main mitigation categories: (1) animal and feed management, 468 (2) diet formulation, and (3) rumen manipulation, each of which was then further classified into up 469 to five subcategories (Table S2). Only the mitigation strategies that each had at least two 470 publications for at least one CH<sub>4</sub> emission metric and two of the remaining CH<sub>4</sub> emission or 471 animal metrics were analyzed within a main category. Treatment effects were assessed relative 472 to their respective control values for all responses, therefore, closely related variables and 473 variables with different units were included in the analysis. For example, CH<sub>4</sub>I<sub>M</sub> included daily CH<sub>4</sub> 474 emissions per kg of milk and milk corrected for fixed energy, fat and protein, or milk solids (all 475 milk non-water components combined) content as well as milk solids yield. Similarly, for CH<sub>4</sub>I<sub>G</sub>, 476 both weight gain and carcass gain were used. Metrics for feed intake included intakes of dry 477 matter, gross energy, organic matter, and intake expressed per unit of body weight or metabolic 478 body weight. Digestibility (of fiber) metrics included only apparent digestibility of neutral detergent 479 fiber. Where multiple treatments of a common treatment type were present within an experiment, 480 the treatment means were averaged, and their respective errors pooled, so that each experiment 481 produced a single "Treatment" and "Control" pair of response means and SDs. 482 The final dataset analyzed in the present study included data from 430 peer-reviewed 483 publications, of which 66% were of cattle, 31% of small ruminants (sheep and goats) and 3% of 484 other ruminant species (buffalo, deer, and yak). The complete list of references used in the

485 current analysis is given in Table S1 and the database can be found on

486 www.datacommons.psu.edu under the link

487 ttps://www.datacommons.psu.edu/commonswizard/MetadataDisplay.aspx?Dataset=6333 and the 488 DOI 10.26208/6em7-k817. The majority of the publications reported daily CH<sub>4</sub> emissions (92%), 489 feed intake (84%), and  $CH_4Y$  (71%), but less than half of the publications reported weight gain for 490 all animal types (growing, lactating, and other adult animals) (49%),  $Y_m$  (48%), fiber digestibility 491 (41%), milk yield (29%),  $CH_4I_M$  (21%), or  $CH_4I_G$  (7%) (Fig. S5). The final analysis only included 492 weight gain data for growing animals (106 publications), which led to the exclusion of the weight 493 gain data of half of the publications (104) that reported weight gain data for lactating and other 494 adult animals.

495

496 Statistical Analysis. A mixed model meta-analysis weighted by inverse variance was carried out 497 considering treatment mean comparisons within the publications as a random effect. Analyses 498 were run across all ruminant species (cattle, buffalo, deer, goat, sheep, and yak) and included 499 main mitigation strategies and their respective subcategories as potential moderator fixed effects. 500 Analyses were conducted separately for each of the nine response variables (daily  $CH_4$ ,  $CH_4Y$ , 501  $Y_m$ , CH<sub>4</sub>I<sub>G</sub>, CH<sub>4</sub>I<sub>M</sub>, feed intake, weight gain for growing animals, milk yield, and fiber digestibility) 502 using a log ratio of means, namely log(Treatment/Control), in order to standardize treatment 503 effects across multiple measures, species, and outcomes, as well as to allow the expression of treatment differences as relative percentages<sup>72,73</sup>. Weight gain for growing animals when 504 505 consuming tanniferous plants, however, was assessed based on a standardized relative 506 difference, [(Treatment-Control)/SE<sub>Diff</sub>], due to the presence of negative growth rate responses in two treatment mean comparisons<sup>73</sup>. Computations were carried out using Comprehensive Meta-507 508 Analysis (V. 3.3.070; Biostat, Englewood, NJ). All analyses were adjusted for multiple comparisons using a step-down Bonferroni procedure to reduce the risk of Type I error<sup>74</sup> (SAS, V. 509 510 9.4; SAS Inst. Inc, Cary, NC). The effect of a mitigation strategy was considered significant for 511 adjusted P < 0.05 and  $0.05 \le$  adjusted  $P \le 0.10$  was considered as a trend.

512

#### 513 Estimation of the potential for identified strategies to decrease methane emissions

The potential of the identified strategies to decrease global, LMIC (e.g. countries in the African Region), and HIC (e.g. countries in the European Region) enteric  $CH_4$  emissions between 2012 and 2030 and between 2012 and 2050 was estimated using three mitigation scenarios. In the mitigation scenarios, identified measures to mitigate enteric  $CH_4$  from the current analysis (Fig. 2) were applied to demand projections under a BAU scenario. Further, a sensitivity analysis for

519 100%, 75%, 50%, and 25% adoption rate of mitigation measures was performed.

520 The BAU scenario was defined by the FAO<sup>75</sup> as a continuation of historical trends of food

521 preferences and inclusion of current initiatives to address SDG targets. Annual demands for

522 protein from red meat (bovine meat, mutton, and goat meat) and milk for 2012, 2030, and 2050

523 were projected by using published per capita demand projections by Henchion et al. (2021)<sup>64</sup> and

524 human population projections by FAO<sup>65</sup>. Consistent with the demand projections by Henchion et

al. (2021)<sup>64</sup> projections were classified into the six regions defined by the World Health

526 Organization (WHO; African Region, Region of the Americas, South-East Asia Region, European

527 Region, Eastern Mediterranean Region, and Western Pacific Region)<sup>76</sup>. The regional production

528 of red meat and dairy protein by production system (feedlot, grassland, and mixed) reported by

529 GLEAM<sup>5</sup> for 2010 was applied to demand projections. As some of the regional classifications in

530 GLEAM differed from the WHO regions, best judgment was used to match GLEAM regions to

531 WHO regions. The countries/regions included in each WHO region in our analysis for demand

532 projections, population projection, and GLEAM are listed in Table S4. Further, intensities for

533 enteric CH<sub>4</sub> emissions (enteric CH<sub>4</sub> per kg of red meat or milk protein) by animal production

534 system (feedlot, grassland, and mixed) reported by GLEAM for 2010 were multiplied by projected

animal protein demand by animal production system to estimate enteric CH<sub>4</sub> emissions for each

536 system. For this, the underlying assumption was that demand will be met by increased production

537 in each region.

538 The three mitigation scenarios were: 1) Adoption of one PB strategy (increasing feeding level,

539 decreasing grass maturity, or decreasing dietary forage-to-concentrate ratio), 2) Adoption of one

ABS strategy (the inclusion of CH₄ inhibitors, tanniferous forages, electron sinks, oils or fats, or
oilseeds), and 3) Simultaneous adoption of one PB and one ABS.

542 For a 100% adoption rate of one PB strategy, the identified average (average of all mitigation 543 potentials of strategies applicable to a production system), minimum and maximum (strategies 544 with lowest and highest mitigation potential applicable to a production system, respectively) 545 reductions of CH<sub>4</sub>I for a production system were used to adjust the emission intensities reported 546 by GLEAM<sup>4</sup> for red meat and dairy protein for each of the projected years. When there were no 547 data for the  $CH_4I_6$  reduction potential of a strategy, it was assumed that the minimum reduction 548 potential was 0%, the maximum reduction potential was the one identified for CH<sub>4</sub>I<sub>M</sub>, and the 549 average reduction potential was the average of the minimum and maximum reduction potential. 550 For a 100% adoption rate of one ABS strategy, the identified average, minimum, and maximum 551 reductions of daily CH<sub>4</sub> emission for a production system were used to adjust the projected 552 annual CH<sub>4</sub> emissions for all red meat and dairy protein of a given productions system of the 553 projected years. For a 100% adoption rate of one PB strategy and one ABS strategy, the 554 reduction for the adoption of one PB strategy was first projected, and afterward, the adoption of 555 one ABS strategy was projected. Similar calculations were done for the other three assumed 556 adoption rates (75%, 50%, and 25%).

557

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766 Figures

767

Figure 1. Studied enteric methane mitigation strategies. For a complete list of strategies, seeTable S2.

770

**Figure 2.** Effective mitigation strategies and their effect on methane (CH<sub>4</sub>) emissions (A) and

animal performance metrics (B).  $CH_4I_M = CH_4$  emission intensity for milk (CH<sub>4</sub> g per kg of milk);

773  $CH_4I_G = CH_4$  emission intensity for weight gain (g  $CH_4$  per kg of weight gain for growing animals);

Daily  $CH_4$  = daily  $CH_4$  emissions (g animal<sup>-1</sup> day<sup>-1</sup>); Intake = dry matter intake (kg d<sup>-1</sup>); Digestibility

= apparent digestibility of neutral detergent fiber (%); Milk = milk yield (kg  $d^{-1}$ ); Gain = average

daily gain (kg d<sup>-1</sup>); when numeric values are shown a significant effect was observed (adjusted P

777 < 0.05) and no effect when adjusted  $P \ge 0.05$ .

778

**Figure 3.** Projected change in enteric methane (CH<sub>4</sub>) emissions between 2012 and 2030 without

780 mitigation strategy under business as usual (BAU) and modeled mitigation scenarios for enteric

781 CH<sub>4</sub> emission changes globally (A), in the African region (B), and in the European region (C).

782 Error bars represent the average mitigation effect of the least and most effective mitigation

strategy. Numbers in squares indicate the percentage of change from BAU.



| I          | MITIGATION STRATEGY                                  | POTENTIAL I          | EMISSIONS RED  | UCTION       | RELEVANT PROD | OUCTION SYSTEM |   |
|------------|--|----------------------|--|--------------|---------------|----------------|---|
| ised<br>ns | INCREASING FEEDING LEVEL                             | CH4IM<br>CH4Ig       | -17%<br>No Data  |              | -             | *              |   |
| oduct-Ba   | 2 DECREASING GRASS MATURITY                          | CH4IM<br>CH4IG       | -13%<br>No Data  |              | -             | *              |   |
| 2~         | B DECREASING DIETARY FORAGE-TO-<br>Concentrate Ratio | CH4IM<br>CH4IG       | -9%<br>-9%   |              | -             |                |   |
|            | D  |                      |  |              |               |                | = |
| IIS        | CH4INHIBITORS  | CH4IM -3<br>CH4Ig No | 2%   Daily CH4     Data   CH4Y                         | -35%<br>-34% |               |                |   |
| uctio      | 2 TANNIFEROUS FORAGES                                | CH4IM -1<br>CH4IG N  | 8% Daily CH <sub>4</sub><br>Data CH <sub>4</sub> Y     | -12%<br>-10% | -             | *              |   |
| e Red      | ELECTRON SINKS                                       | CH4IM -1<br>CH4IG -1 | 3%         Daily CH4           2%         CH4Y         | -17%<br>-15% | -             |                |   |
| solut      | OILS & FATS  | CH4IM -1<br>CH4IG -2 | 2% Daily CH <sub>4</sub><br>2% CH <sub>4</sub> Y       | -19%<br>-15% | -             |                |   |
| 8          | OILSEEDS     Lactatiog animals only                  | CH4IM -1<br>CH4IG N  | 2% Daily CH <sub>4</sub><br>o Effect CH <sub>4</sub> Y | -20%<br>-14% | -             |                |   |

Production system



FEEDLOT & MIXED SYSTEMS



|                      |  | <b>Relative Treatment Effect on Animal Performance</b> |   |  |  |
|----------------------|--|--|---|--|--|
|                      | MITIGATION STRATEGY  | INTAKE   | DIGESTIBILITY                                 | MILK                                       | GAIN   |
| -Base<br>tions       | 1 INCREASING FEEDING LEVEL   | +58%   | -7%   | +17%                                       | +162%  |
| oduct                | <b>EXAMPLE 2</b> DECREASING GRASS MATURITY   | No Effect  | +15%  | +9%  | No Data  |
| ~~                   | BECREASING DIETARY FORAGE-TO-<br>Concentrate Ratio   | +9%  | No Effect                                     | +17%                                       | +21%   |
|                      |  |  |   |  |  |
|                      |  |  |   |  |  |
| L su                 | CH₄ INHIBITORS   | No Effect  | No Effect                                     | No Effect                                  | No Effect  |
| luctions 7           | <ol> <li>CH₄ INHIBITORS</li> <li>CH₄ INHIBITORS</li> <li>TANNIFEROUS FORAGES</li> </ol>                          | No Effect<br>No Effect                                 | No Effect                                     | No Effect<br>No Effect                     | No Effect<br>No Effect                           |
| te Reductions        | <ol> <li>CH₄ INHIBITORS</li> <li>TANNIFEROUS FORAGES</li> <li>ELECTRON SINKS</li> </ol>                          | No Effect No Effect -2%                                | No Effect<br>-7%<br>No Effect                 | No Effect<br>No Effect<br>+3%              | No Effect<br>No Effect<br>No Effect              |
| bsolute Reductions 7 | <ol> <li>CH₄ INHIBITORS</li> <li>TANNIFEROUS FORAGES</li> <li>ELECTRON SINKS</li> <li>OILS &amp; FATS</li> </ol> | No Effect       No Effect       -2%       -6%          | No Effect       -7%       No Effect       -4% | No Effect<br>No Effect<br>+3%<br>No Effect | No Effect<br>No Effect<br>No Effect<br>No Effect |



#### A Projected change in global emissions between 2012 and 2030 under different scenarios

#### B Projected change in African emissions between 2012 and 2030 under different scenarios





#### C Projected change in European emissions between 2012 and 2030 under different scenarios