

Practical strategies to mitigate ruminant greenhouse gas emissions

Alejandra Ortega (✉ alejandra.ortega@kaust.edu.sa)

King Abdullah University of Science and Technology <https://orcid.org/0000-0002-7503-995X>

Mark Tester

King Abdullah University of Science and Technology <https://orcid.org/0000-0002-5085-8801>

Kyle Lauersen

King Abdullah University of Science and Technology

Article

Keywords: greenhouse gas emissions, livestock, mitigation

Posted Date: February 4th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-179004/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

1 Practical strategies to mitigate ruminant greenhouse gas emissions

2
3 Alejandra Ortega^{1*}, Mark A. Tester² and Kyle Lauersen¹

4
5 ^{1.} Biological and Environmental Sciences and Engineering Division (BESE), King Abdullah
6 University of Science and Technology, Thuwal, Kingdom of Saudi Arabia

7 ^{2.} Center for Desert Agriculture, Biological and Environmental Sciences and
8 Engineering Division (BESE), King Abdullah University of Science and Technology, Thuwal,
9 Kingdom of Saudi Arabia

10 11 **Abstract**

12 Livestock contributes to 14.5 percent of global greenhouse gas emissions, with ruminants
13 being the largest contributor through enteric methane emissions. Although several mitigation
14 strategies are available to reduce livestock methane, no consensus exists on which methods are
15 the most effective. Here, the mitigation impact of the most pragmatic strategies to reduce
16 enteric methane has been projected to 2050, using cattle emissions as a model. The projection
17 shows that supplementing ruminant feed with anti-methanogenic seaweed and converting
18 grassland into silvopasture offer the greatest potential to reduce emissions. With a synergic
19 combination of strategies, the livestock sector in Europe and most of Asia can reach carbon
20 neutrality by 2035 and 2038, respectively. However, global cattle CO₂-eq emissions will be
21 reduced by no more than 34 percent by 2050, remaining far above the carbon neutrality target.

22 Mitigation strategies alone are insufficient to lower emissions, and reducing the demand for
23 ruminant products is also necessary – particularly in Africa and Western Asia.

24

25 **Main**

26 A key target to minimise the impact of the climate crisis on global ecosystems and human
27 economies is to reach carbon neutrality by 2050¹. For this, reductions to near-zero emissions of
28 carbon dioxide (CO₂) and non-CO₂ greenhouse gas (GHG) are necessary¹. The livestock sector,
29 which accounts for 14.5 percent of total anthropogenic emissions, generates methane – one of
30 the most potent GHGs and a significant driver of climate change^{2,3}. Archaea communities in the
31 rumen of cattle, sheep, goats, and other ruminants produce methane during enteric
32 fermentation, in an amount equivalent to 4.6 gigatonnes of CO₂ emissions annually^{2,4}. Livestock
33 husbandry additionally impacts natural resources during animal feed production, grassland use
34 and the life-cycle of animal products⁵⁻⁷.

35 With the human population projected to increase from its current 7.8 to 9.7 billion by 2050,
36 and the global demand for animal products expected to double over the same period,
37 reductions of livestock GHG emissions remain defiant to mitigation goals⁸⁻¹⁰. If GHG emission
38 rates continue their rapid growth, the current climate crisis will be exacerbated². Execution of
39 strategies to reduce GHG emissions is needed now to balance demands on food security and
40 environmental preservation^{7,11-13}.

41 Several GHG mitigation strategies are available for ruminant enteric methane, and their
42 feasibility varies with the geographical distribution of natural and economic resources^{2,7,11}.

43 Although some strategies are already in place, implementation of others lags behind despite

44 their strong data-backed mitigation potential¹⁴⁻¹⁶. This delay is due in part to the economic
45 inequality that impedes widespread research on ruminants. Such research requires long
46 experimental timescales and a holistic understanding of their implications on ruminant
47 subjects, the environment and human health.

48 Here, we use cattle to model ruminant CO₂-eq emissions and project the mitigation effect of
49 existing strategies to improve animal productivity and grassland-management. Among the
50 available mechanisms to reduce ruminant GHG emissions, we focus on replacing regular
51 animals with low-methane genotypes, grassland conversion to silvopasture, and methods to
52 inhibit methane production in the rumen. Our projection indicates that global suppression of
53 enteric methane emissions is not possible between by 2050, but mitigation can drastically
54 reduce emission intensity (Figure 1). The projection is based on historical data from 1990 to
55 2017 from global cattle stocks, enteric methane CO₂-equivalent (CO₂-eq) emissions, and CO₂
56 emission from ruminant grasslands by area. Data come from the Statistical Database of the
57 Food and Agriculture Organization of the United Nations (FAOSTAT), and exclude GHG
58 emissions from other livestock life-cycle steps.

59

60 **Breeding genetically advantageous ruminants**

61 Microbial communities ferment plant biomass in the rumen¹⁷. In this process, hydrogen and
62 CO₂ can be converted into nutrients by beneficial bacteria, or into methane by methanogenic
63 archaea¹⁸. Methane production uses 2-12 percent of the gross dietary energy and represents a
64 substantial metabolic lost to the ruminant^{19,20}. Some animals have genetic traits that can
65 reduce enteric methane emissions by favouring beneficial microbial communities²¹ or

66 increasing animal productivity per feed unit^{20,22}. Replacing regular with more efficient
67 ruminants (low-methane genotypes) is a strategy that benefits both the environment and the
68 ruminant economy^{19,20}.

69 Programs to gather ruminant genetic resources and promote selective breeding are already in
70 place worldwide, from single-country programs in Australia and Latin America to multinational
71 programs in Africa and Europe²³⁻²⁸. Nevertheless, ruminant breeding is a slow and expensive
72 process that can take decades before establishing a particular genotype²⁹⁻³². Moreover,
73 breeding must consider region-specific factors, as breeding developments suitable for one
74 region will likely not be implementable worldwide^{22,33}. Capital-intensive husbandry systems
75 have been successfully breeding beneficial genetic traits. For instance, in the Australian
76 Northern Territory, replacing foreign English Shorthorn cattle with a locally adapted breed
77 improved animal productivity, mitigating 43 percent of methane emission per tonne
78 liveweight^{30,34}. Similar capital-intensive breeding projects funded by national initiatives are in
79 place in other regions such as Europe and South America^{29,35-37}.

80 In labour-intensive and less economically successful systems, as are found in Eastern Africa,
81 ruminant breeds are selected for their adaptation to the environment (sparse grassland, heat,
82 local diseases) rather than for their productivity^{34,38-41}. While efforts have been made to
83 increase productivity by crossbreeding local with foreign breeds, most attempts lack scientific
84 rigour and ignore the limitations of the foreign animals to adapt in the new environments^{38,41,42}.
85 Community or farm-based breeding is a rapid alternative to centralised national or regional
86 breeding strategies, nevertheless few farms – often located in developed countries, can afford
87 comprehensive research facilities for selection of low-methane ruminants^{32,41,43,44}. Although

88 individual farms or independent funding sources (e.g. African Dairy Genetics Gain Program⁴⁵)
89 can finance local breeding, extensive ruminant replacement with efficient breeds requires long-
90 term commitments from governments⁴⁶.

91 Complex genetic interactions limit extrapolation from local breeding advances as a global
92 mitigation strategy of enteric methane emissions^{22,33,47}. For cattle, the available breeding
93 mitigation potential reduces only 11 percent methane per efficient animal²². Taking an
94 optimistic projection of current cattle breeding developments, we estimate that Europe,
95 Oceania and the Americas can successfully introduce locally selected breeds by 2030. Most of
96 Asia will reach this goal by 2035, and Western Asia and Africa by 2040 (Figure 2). As the
97 execution of such measures will take at least a decade, current research efforts to select low-
98 methane breeds could mitigate only 6.6 percent of global enteric methane emissions between
99 2020 and 2050 (Table 1 and Figure 2).

100

101 **Improving feeding practices**

102 Improvements in production practices and favouring quality feed can substantially reduce
103 GHG emissions from ruminant feed production^{6,48-53}. Ruminant diets range from free-grazing on
104 low-nutritional pasture to stall-feeding on horticulture produce of higher nutritional quality<sup>5,48-
105 50,54</sup>. The preference of one feeding practice over another depends on environmental and
106 economic feasibility and the physiological state of the animal⁵⁵. For instance, beef cattle
107 farming in temperate climates synchronises animal reproduction to pasture seasonality,
108 allowing calves to feed on grass; in contrast, intermediate and mature animals are fed on high-
109 quality fodder to gain weight before slaughter⁵⁵⁻⁵⁷.

110 Quality feed has a higher protein content and requires minimal fermentation, resulting in
111 higher animal productivity and lower intensity of methane emissions^{49,50,54}. Nevertheless,
112 ruminant feed production strongly impacts the environment, promoting degradation of natural
113 carbon sinks^{2,6,58}. A common practice to overcome feed production limitations is recycling
114 molasses, straws and grains otherwise discarded⁵⁹⁻⁶¹. However, such agricultural by-products
115 are highly fibrous, require longer fermentation and foment methane production^{54,59,61}. The
116 nutritional content can improve by degrading by-products cellulose before feeding ruminants;
117 however, this process increases feeding costs⁶²⁻⁶⁶.

118

119 **Conversion to silvopasture**

120 Adoption of more efficient land-use practices by converting pasture into silvopasture is
121 another strategy to overcome ruminant feed production limitations and mitigate GHG
122 emissions^{51,67,68}. Silvopasture introduces trees and shrubs within the pasture grassland,
123 securing quality feed all year round in tropical and subtropical latitudes^{53,67}. Leguminous, high-
124 quality grasses and other silvopastoral plants are rich in tannins and saponins – metabolites
125 that inhibit methanogenic populations in the rumen, improve nutrient absorption and reduce
126 methane emissions⁶⁹⁻⁷². Although these metabolites can induce toxicity from an overdose, *ad*
127 *libitum* foraging does not pose a risk of excessive dosing, as ruminants occasionally feed on
128 tannin-rich plants to reduce or prevent parasites^{70,73-76}. Finally, silvopasture provides additional
129 environmental benefits such as atmospheric CO₂ capture from increased plant biomass
130 production, soil recovery, water retention and increases in biodiversity^{51-53,67}.

131 The potential benefits of conversion to silvopasture vary among regions due to differences in
132 climate, humidity, and soil type (Supplementary Table 1). Tropical latitudes hold a potential
133 transformation of 45 to 85 percent of current ruminant grassland area, while 29 percent of the
134 global ruminant grassland could be converted into silvopasture. No conversion is effective in
135 arid regions in North Africa and the Middle East due to their climatic limitations. According to
136 our modelling of soil carbon stock changes using the FAO Ex-Ante Carbon-balance Tool (EX-
137 ACT), silvopasture systems can cut the GHG emissions related to ruminant grazing grassland
138 after the first year of conversion. Over a 30-year projection, silvopasture can capture globally
139 3.8 times more CO₂-eq than grassland without conversion (Table 1).

140 Although silvopasture has a higher return rate and net value than pasture, conversion requires
141 a large capital investment with a payback period of around four years⁷⁷. Government support
142 and incentive payments can motivate farmers to adopt silvopasture systems^{68,78,79}. Silvopasture
143 establishment and maintenance cost US\$3,129 ha⁻¹ over 30 years but generates revenue of
144 US\$7,165 ha⁻¹ (United States estimation from 2012; includes property taxes, forage and timber
145 revenue)⁸⁰. Besides, successful silvopasture conversion reduces husbandry labour costs,
146 increases animal productivity by introducing high-protein plants and shade value, diversifies
147 farm income sources, and provides invaluable ecosystem benefits^{51,68,81}.

148

149 **Inhibition of methanogenic communities in the rumen**

150 Removal of methanogenic communities in the rumen using antibiotics has been a common
151 strategy to reduce enteric methane emissions⁵⁴. However, this strategy is falling out of favour
152 due to significant concerns over antibiotic resistance, antibiotic contamination in the

153 environment, and the potential transfer of bioaccumulated compounds from animal products
154 to humans^{54,70,82-85}. Legislations worldwide ban antibiotics of importance for human health to
155 promote animal growth, restricting their use exclusively for veterinary purposes^{70,86-94}. In the
156 search for alternatives to inhibit enteric methanogens, vaccines could trigger ruminant immune
157 responses against certain strains of methanogens⁹⁵⁻¹⁰⁰. Since the core microbiome is inheritable
158 and methanogens seem highly conserved across ruminants, vaccines targeting dominant
159 methanogens could facilitate broad immunisation and potentially reduce enteric methane
160 emissions^{21,101-103}.

161 Methanogens attached to the cilia of enteric protozoa can be indirectly removed if protozoa
162 are removed from the rumen¹⁰⁴. Although protozoa removal can reduce up to 42 percent of
163 methane emissions in cattle¹⁰⁵, defaunation also disturbs beneficial microorganisms, impairing
164 digestion and animal performance¹⁰⁶⁻¹¹⁰. Despite being among the oldest proposed enteric
165 methane mitigation strategies, defaunation requires complex experimental procedures (i.e.
166 isolation of newborns, or fistulating adults) and no practical and sustainable method is
167 available^{104,107,108,111}.

168 Other strategies focus on inhibiting methane production rather than eliminating the
169 methanogens. Examples include probiotics, digestibility enhancers and chemical or natural
170 supplements that alter methanogenesis^{18,66,70,87}. Probiotics are a promising method for
171 methane reduction where beneficial fungi and bacteria compete against methanogens for
172 hydrogen sources to form propionate^{18,112}. Contrary to methane released to the environment,
173 propionate is metabolised, favouring gluconeogenesis and increasing animal production^{18,113,114}.

174 Available studies analysing the effect of probiotics on enteric methane production show
175 contradictory results, and further research on probiotic strains is needed^{63,112,115-117}.
176 Plant oils are natural additives that facilitate digestion, inhibit feed protein degradation,
177 reduce enteric microbial populations, and dehydrogenate ruminal fermentation
178 pathways^{54,70,74,118-121}. The capacity for enteric methane reduction depends on the type of plant
179 oil, the ratio of oil to feed, the diet, and the animal species^{54,74,119,122}. For instance, seven
180 percent of coconut oil added to a diet of hay and concentrate reduces up to 63 percent of
181 sheep methane emissions^{74,123}. Practical methane reductions by plant oil additives range
182 between 10-32 percent, as higher oil proportions affect feed intake, digestibility and animal
183 productivity^{65,74,119,124}. However, the extraction of plant oils is expensive, and other additives
184 can offer similar methane mitigation levels for a lower cost^{70,74}.

185 Widely used chemical additives (urea, nitrate, sulfate, halogenated compounds) can act as
186 high-potential electron acceptors, redirecting hydrogen to propionic fermentation and
187 disrupting methanogenesis^{54,114,125-128}. Halogenated compounds have strong anti-methanogenic
188 potential. Bromochloromethane (BCM) used as a feed additive interferes with cobalamin
189 (vitamin B12) – a hydrogen donor, disrupting with methane production¹²⁹. BMC exhibits low
190 toxicity risk, no bioaccumulation in animal tissue, and reduced up to 91 percent of ruminant
191 methane production^{125,128,130-132}. However, the Montreal Protocol restricts industrial production
192 of BCM due to a significant ozone-depletion potential¹³³.

193 Naturally occurring halogenated compounds present a lower environmental risk to reduce
194 rumen emissions¹³⁰. Plankton and seaweed produce BMC and bromoform to protect against
195 predators and harmful hydrogen peroxides in the cells^{134,135}. Bromoform does not

196 bioaccumulate in the food chain and is not classifiable as a human carcinogen¹³⁶⁻¹³⁸. It has been
197 shown, for example, that after two years of daily gavage ingestion (<200 mg/kg), bromoform
198 displayed little carcinogenicity in rats (0.5-4%; n=50)¹³⁹. Supplementing ruminant feed with
199 bromoform-rich seaweed inhibits methanogen growth, consequently promoting propionate
200 production¹⁴⁰. Seaweed of the genus *Asparagopsis* added in 0.2 to 3 percent to a grass diet can
201 reduce methane emissions up to 98 percent in cattle and sheep^{55,141,142}. The use of bromoform-
202 rich seaweed as an anti-methanogenic strategy also increases animal productivity in weight
203 gain without affecting animal health or meat quality¹⁴¹. *Asparagopsis* is traditionally used in the
204 Hawaiian cuisine without affecting human health¹⁴³.

205 Before slaughter, intermediate and mature cattle feed on high-quality fodder supplemented
206 with nutrients to increase final animal product⁵⁶. Based on an average lifespan of 420 days for
207 beef cattle⁵⁶, we estimate that 11 kg of anti-methanogenic *Asparagopsis* can be supplemented
208 on fodder during 36 percent of the animal lifespan (see Methods). Considering a mitigation
209 effect of 98 percent reduction of enteric methane per animal¹⁴¹, seaweed at 2 percent feed
210 supplement can reduce 320 Tg of CO₂-eq emissions from cattle – almost half of the current
211 global enteric methane emissions. Overall, 35.6 percent fewer emissions will be generated
212 compared to a business-as-usual scenario (Figure 2). Widespread commercialisation of seaweed
213 as a feed supplement can be available as early as 2022⁵⁵.

214

215 **Feasibility and mitigation impact**

216 There is no single solution to reduce GHG emissions, and a synergic combination of mitigation
217 methods is required to slow rates of ruminant enteric methane emissions (Figure 3). Although

218 mitigation feasibility depends on economic and environmental resources by region, the focus
219 should be on the strategies with immediate implementation potential. Due to differential
220 research and technological maturity of the strategies described above, heterogeneous
221 implementation could yield immediate benefits, as some of the most effective mitigation
222 strategies already exist, but are not yet deployed at scale.

223 Regional genetic research and breeding programs are necessary to select highly-productive
224 animals with lower methane-emission intensity^{20,47}. However, we show that in comparison to
225 feeding supplements and silvopasture conversion, breeding as a global strategy to mitigate
226 ruminant enteric methane emissions is not feasible in the short term and will not lead to a
227 significant mitigation impact. Based on existing developments, a global replacement of regular
228 cattle with low-methane animals will mitigate 1,943 Tg CO₂-eq emissions by 2050, representing
229 only a 6.6 percent reduction of the current rate of cattle emissions (Table 1 and Figure 2).

230 Our analyses indicate that using anti-methanogenic seaweed as a feed supplement and
231 silvopasture conversion hold the greatest impact on emissions reduction, providing benefits
232 that no other strategies permit. Seaweed and silvopasture plants not only disrupt enteric
233 methane production and convert atmospheric CO₂ into biomass, but offer sustainable
234 production pathways with much lower life-cycle emissions. Favouring seaweed and silvopasture
235 eases pressure on land and water resources, in addition to holding a carbon farming potential
236 to offset the emissions from ruminant husbandry (Figure 3)¹⁴⁴.

237 Worldwide conversion of 1.2 million hectares of grassland into silvopasture would have a net
238 carbon sequestration balance of 0.34 Tg CO₂ captured after the first year of conversion. From
239 2045 onward, silvopasture carbon storage potential would reach a plateau, capturing 102.3 Tg

240 CO₂ annually (Supplementary Table 2). Such carbon capture is equivalent to 13 percent of
241 current global cattle CO₂-eq emission. Immediate conversion to silvopasture, and
242 supplementation of anti-methanogenic seaweed in feed, could mitigate up to 46 percent of the
243 annual cattle CO₂-eq emissions – avoiding 9,082 Tg CO₂-eq emissions between 2020 to 2050.

244

245 **A reduction in cattle demand is also necessary**

246 Our analysis assumes no trend changes in the increasing demand for cattle consumption.
247 Modelling mitigation strategies for enteric methane emissions shows that carbon neutrality by
248 2050 is possible only if there is a slowdown of the growth rate of cattle consumption. Changes
249 in per capita meat consumption in Europe and Central to Eastern Asia, combined with policy
250 mitigation efforts, lower current ruminant GHG emissions¹⁰. Mitigation strategies in those
251 regions can sharpen this trend, potentially reaching carbon neutrality by 2035 and 2038,
252 respectively (Figure 2). Nevertheless, the demand for ruminant products in developing
253 countries will rise continuously due to population growth and increasing per capita meat
254 purchasing power⁹. Without mitigation, global enteric methane emissions will increase steadily
255 – particularly in Africa, Southern and Western Asia (Figure 2). Implementation of mitigation
256 strategies can reduce emissions intensity, returning to pre-1990 levels of ruminant methane
257 emissions, but this is only a 34% reduction over 2017 emissions level (Figure 2). However, our
258 results indicate that mitigation strategies alone are insufficient to achieve low enteric methane
259 emissions, and a reduction of the demand for animal products is also necessary. *Sustainable*
260 production of livestock cattle at a global scale does not seem possible, and further strategies
261 such as alternative meat production (for example, cultured meat) are necessary.

262

263 **Methods**

264 **Data source**

265 Historical data by country from 1990 to 2017 come from the FAOSTAT database of the Food
266 and Agriculture Organization of the United Nations (FAO,
267 <http://www.fao.org/faostat/en/#data>, accessed in June 2020). Data included carbon equivalent
268 (CO₂-eq) emissions from cattle enteric methane, cattle stocks (head and tonnes of production),
269 and carbon balance of ruminant grazing grassland by area. To facilitate carbon balance analyses
270 of silvopasture conversion, FAO data were grouped into nine regions based on similarities in soil
271 type and climate regime, following the global distribution of climate zones from the
272 Intergovernmental Panel on Climate Change (IPCC, Supplementary Table 1).

273

274 **Carbon balance from silvopasture conversion**

275 We used the Grassland Livestock module of the FAO EX-Ante Carbon-balance Tool (EX-ACT
276 version 8.5.6)¹⁴⁵ to analyse soil carbon stock balance. We estimated the potential global area to
277 be converted from pasture to silvopasture using the 2017 FAO data for grazing grassland with
278 organic soil area. We considered the rough regional percentage of area with a suitable IPCC
279 climate for growing silvopasture trees and shrubs. Proper conversion can be possible in regions
280 either with areas holding a tropical to warm temperate climate, moist to wet humidity and with
281 any soil type; or in areas holding a cool temperate and moist regime with a low activity clay soil
282 type (Supplementary Table 1). Using the area percentage and regional environmental
283 descriptors (Supplementary Table 1), we analysed the soil carbon stock balance for a 30-year

284 silvopasture projection allowing an implementation phase of five years. EX-ACT estimates,
285 among others, the carbon stock changes (Tg CO₂-eq) from land-based projects using IPCC Tier 1
286 methodology for GHG inventories¹⁴⁵. Projected soil carbon balance reflects the net emissions
287 differences between a business-as-usual scenario versus converting grassland into silvopasture.
288 *Moderately Degraded* and *Improved with inputs improvement* were selected as the initial and
289 final state of the project, respectively. Supplementary Table 1 reports descriptors of climate,
290 moisture regime and dominant soil type input in EX-ACT.

291

292 Supplement potential on cattle fodder

293 Environmental factors influence decision-making on whether to feed cattle by free-grazing on
294 pasture or in feedlots. We estimated that cattle feed on fodder during 36 percent of their
295 lifespan, for approximately 420 days⁵⁶. During the cow-calves operation, young animals graze
296 freely on pasture for nine months without supplement options; for the remaining five months
297 (150 days) before slaughtering, animals are intensively fattened up with a high-quality feed that
298 can be supplemented with bromoform-rich seaweed^{56,57}. Assuming that seaweed supplements
299 reduce 98 percent of enteric methane per animal¹⁴¹, the mitigation effect would account for an
300 annual reduction of 35.6% enteric emissions in the cattle sector.

301

302 Data analyses

303 The historical data from cattle enteric methane CO₂-eq and grassland CO₂ emissions were
304 used to project 2018-2050 emissions data in a business-as-usual scenario. First, we calculated
305 the historical trend averaging the moving trends from 1991-2017. Moving trends were obtained

306 with the formula $Trend_n = Year_n * 100 / Year_{n-1}$, where $Year_n$ indicates emissions in 1991.

307 Then, we projected annual emissions using the formula

308 $Year_{n+1} = Year_n * (Historical\ trend / 100)$, with $Year_{n+1}$ indicating emissions for 2018.

309 Based on the business-as-usual projections, we projected the mitigation effect for each

310 strategy. Using seaweed supplements, we mitigated 35.64 percent emissions starting in 2022.

311 Using efficient animals, we mitigated 11 percent beginning in 2030 in Europe, Oceania and the

312 Americas; in 2035 in Asia (excluding Western Asia); and in 2040 in Western Asia and Africa.

313 Emissions using a synergic combination of all the strategies were calculated summing up the

314 annual silvopasture carbon stock changes with the yearly mitigation of 35.64 or 46.64 percent

315 emissions, according to the year of implementation. All data are expressed in Tg CO₂-eq.

316

317 **Data availability**

318 All data used in this study are publicly available in the FAOSTAT database

319 (<http://www.fao.org/faostat/en/#data>). Projection of enteric methane emissions and

320 silvopasture carbon balance using EX-ACT estimations are available in the Supplementary Table

321 2.

322

323 **Acknowledgements**

324 This publication is based upon work supported by the King Abdullah University of Science and

325 Technology (KAUST).

326 **References**

- 327 1 Rogelj, J. *et al.* Mitigation pathways compatible with 1.5° C in the context of sustainable
328 development. . *IPCC Special Report on Global Warming of 1.5° C* (2018).
- 329 2 Gerber, P. J. *et al.* *Tackling climate change through livestock: a global assessment of*
330 *emissions and mitigation opportunities.* (Food and Agriculture Organization of the
331 United Nations (FAO), 2013).
- 332 3 Kirschke, S. *et al.* Three decades of global methane sources and sinks. *Nature Geoscience*
333 **6**, 813-823, doi:10.1038/ngeo1955 (2013).
- 334 4 Moss, A. R., Jouany, J.-P. & Newbold, J. Methane production by ruminants: its
335 contribution to global warming. *Annales de zootechnie* **49**, 231-253 (2000).
- 336 5 Finneran, E. *et al.* Simulation modelling of the cost of producing and utilising feeds for
337 ruminants on Irish farms. *Journal of Farm Management* **14**, 95-116 (2010).
- 338 6 Faurès, J. M. *et al.* Climate-smart agriculture. Sourcebook. *FAO, Rome* **557** (2013).
- 339 7 FAO. *World Livestock: Transforming the livestock sector through the Sustainable*
340 *Development Goals.* 222 (Food and Agriculture Organization of the United Nations
341 (FAO), 2018).
- 342 8 United Nations & Department of Economic Social Affairs, P. D. (United Nations New
343 York, NY, 2019).
- 344 9 McLeod, A. *World livestock 2011-livestock in food security.* (Food and Agriculture
345 Organization of the United Nations (FAO), 2011).
- 346 10 Alexandratos, N. & Bruinsma, J. World agriculture towards 2030/2050: the 2012
347 revision. (2012).
- 348 11 Rojas-Downing, M. M., Nejadhashemi, A. P., Harrigan, T. & Woznicki, S. A. Climate
349 change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*
350 **16**, 145-163, doi:<https://doi.org/10.1016/j.crm.2017.02.001> (2017).
- 351 12 FAO. *Why is enteric methane important?*, <[http://www.fao.org/in-action/enteric-](http://www.fao.org/in-action/enteric-methane/background/why-is-enteric-methane-important/en/)
352 [methane/background/why-is-enteric-methane-important/en/](http://www.fao.org/in-action/enteric-methane/background/why-is-enteric-methane-important/en/)> (2019).
- 353 13 FAO & NZAGRC. *Reducing enteric methane for improving food security and livelihoods.*
354 *Project Highlights 2015–2017.* 18 (Food and Agriculture Organization of the United
355 Nations (FAO), 2019).
- 356 14 Cottle, D., Nolan, J. & Wiedemann, S. Ruminant enteric methane mitigation: A review.
357 *Animal Production Science* **51**, 491-514, doi:10.1071/AN10163 (2011).
- 358 15 Patra, A. K. Enteric methane mitigation technologies for ruminant livestock: a synthesis
359 of current research and future directions. *Environmental Monitoring and Assessment*
360 **184**, 1929-1952 (2012).
- 361 16 Boadi, D., Benchaar, C., Chiquette, J. & Massé, D. Mitigation strategies to reduce enteric
362 methane emissions from dairy cows: update review. *Canadian Journal of Animal Science*
363 **84**, 319-335 (2004).
- 364 17 FAO. *What is enteric methane?*, <[http://www.fao.org/in-action/enteric-](http://www.fao.org/in-action/enteric-methane/background/what-is-enteric-methane/en/)
365 [methane/background/what-is-enteric-methane/en/](http://www.fao.org/in-action/enteric-methane/background/what-is-enteric-methane/en/)> (2019).
- 366 18 McAllister, T. A. & Newbold, C. J. Redirecting rumen fermentation to reduce
367 methanogenesis. *Australian Journal of Experimental Agriculture* **48**, 7-13 (2008).

368 19 Johnson, D. E. & Ward, G. M. Estimates of animal methane emissions. *Environmental*
369 *monitoring and assessment* **42**, 133-141 (1996).

370 20 Hegarty, R. S. & McEwan, J. C. Genetic opportunities to reduce enteric methane
371 emissions from ruminant livestock. 1-6 (2010).

372 21 Wallace, R. J. *et al.* A heritable subset of the core rumen microbiome dictates dairy cow
373 productivity and emissions. *Science Advances* **5**, eaav8391, doi:10.1126/sciadv.aav8391
374 (2019).

375 22 de Haas, Y. *et al.* Genetic parameters for predicted methane production and potential
376 for reducing enteric emissions through genomic selection. *Journal of dairy science* **94**,
377 6122-6134 (2011).

378 23 Hanotte, O., Dessie, T. & Kemp, S. Time to tap Africa's livestock genomes. *Science* **328**,
379 1640, doi:10.1126/science.1186254 (2010).

380 24 ILRI. *Genomics Reference Resource for African Cattle*,
381 <<https://data.ilri.org/portal/dataset/grrfac>> (2019).

382 25 Banos, G., Coffey, M. P., Veerkamp, R. F., Berry, D. P. & Wall, E. Merging and
383 characterising phenotypic data on conventional and rare traits from dairy cattle
384 experimental resources in three countries. *animal* **6**, 1040-1048,
385 doi:10.1017/S1751731111002655 (2012).

386 26 Lund, M. S. *et al.* A common reference population from four European Holstein
387 populations increases reliability of genomic predictions. *Genetics Selection Evolution* **43**,
388 43, doi:10.1186/1297-9686-43-43 (2011).

389 27 de Haas, Y. & Lassen, J. METHAGENE-Towards large-scale methane measurements on
390 individual ruminants for genetic evaluations. *EAAP-66th Annual Meeting 2015* **21**, 90-90
391 (2015).

392 28 Mueller, J., Flores, E. & Gutierrez, G. Experiences with a large-scale sheep genetic
393 improvement project in the Peruvian highlands. (2002).

394 29 Amaya, A., Martínez, R. & Cerón-Muñoz, M. Population structure and genetic diversity
395 in Colombian Simmental cattle. *Tropical Animal Health and Production*, 1-7 (2019).

396 30 Walsh, D. & Cowley, R. Optimising beef business performance in northern Australia:
397 what can 30 years of commercial innovation teach us? *The Rangeland Journal* **38**, 291-
398 305 (2016).

399 31 Alford, A. R. *et al.* The impact of breeding to reduce residual feed intake on enteric
400 methane emissions from the Australian beef industry. *Australian Journal of*
401 *Experimental Agriculture* **46**, 813-820 (2006).

402 32 Garnsworthy, P. C. *et al.* Comparison of methods to measure methane for use in genetic
403 evaluation of dairy cattle. *Animals* **9**, 837 (2019).

404 33 de Haas, Y. *et al.* Improved ruminant genetics: Implementation guidance for
405 policymakers and investors. (2016).

406 34 Bentley, D., Hegarty, R. S. & Alford, A. R. Managing livestock enterprises in Australia's
407 extensive rangelands for greenhouse gas and environmental outcomes: a pastoral
408 company perspective. *Australian Journal of Experimental Agriculture* **48**, 60-64 (2008).

409 35 Lassen, J. & Løvendahl, P. Heritability estimates for enteric methane emissions from
410 Holstein cattle measured using noninvasive methods. *Journal of Dairy Science* **99**, 1959-
411 1967 (2016).

412 36 Hansen Axelsson, H. *et al.* Genomic selection using indicator traits to reduce the
413 environmental impact of milk production. *Journal of Dairy Science* **96**, 5306-5314,
414 doi:<https://doi.org/10.3168/jds.2012-6041> (2013).

415 37 Maciel, I. C. d. F. *et al.* Could the breed composition improve performance and change
416 the enteric methane emissions from beef cattle in a tropical intensive production
417 system? *PLOS ONE* **14**, e0220247, doi:10.1371/journal.pone.0220247 (2019).

418 38 Kosgey, I. S. & Okeyo, A. M. Genetic improvement of small ruminants in low-input,
419 smallholder production systems: Technical and infrastructural issues. *Small Ruminant*
420 *Research* **70**, 76-88, doi:<https://doi.org/10.1016/j.smallrumres.2007.01.007> (2007).

421 39 Tibbo, M. Productivity and health of indigenous sheep breeds and crossbreds in central
422 Ethiopian Highlands. (2006).

423 40 Lukuyu, M. N. *et al.* Farmers' Perceptions of Dairy Cattle Breeds, Breeding and Feeding
424 Strategies: A Case of Smallholder Dairy Farmers in Western Kenya. *East African*
425 *Agricultural and Forestry Journal* **83**, 351-367, doi:10.1080/00128325.2019.1659215
426 (2019).

427 41 Philipsson, J., Rege, J. E. O., Zonabend König, E. & Okeyo Mwai, A. Sustainable breeding
428 programmes for tropical low-and medium input farming systems. (2011).

429 42 Mueller, J. Programas de mejoramiento genético de pequeños rumiantes. *CD: III*
430 *Seminario Sobre Mejoramiento Genético Ovino: Desafíos, Oportunidades y Perspectivas*,
431 23-25 (2008).

432 43 Haile, A. *et al.* Community-based sheep breeding programs generated substantial
433 genetic gains and socioeconomic benefits. *animal*, 1-9,
434 doi:10.1017/S1751731120000269 (2020).

435 44 Mueller, J. P. *et al.* Community-based livestock breeding programmes: essentials and
436 examples. *Journal of Animal Breeding and Genetics* **132**, 155-168,
437 doi:<https://doi.org/10.1111/jbg.12136> (2015).

438 45 ILRI. *African Dairy Genetics Gain Program*,
439 <<https://www.ilri.org/research/projects/african-dairy-genetic-gains>> (2016).

440 46 Haile, A. *et al.* Community-based breeding programmes are a viable solution for
441 Ethiopian small ruminant genetic improvement but require public and private
442 investments. *Journal of Animal Breeding and Genetics* **136**, 319-328 (2019).

443 47 Wall, E., Simm, G. & Moran, D. Developing breeding schemes to assist mitigation of
444 greenhouse gas emissions. *Animal* **4**, 366-376 (2010).

445 48 Amole, T. A., Zijlstra, M., Descheemaeker, K., Ayantunde, A. A. & Duncan, A. J.
446 Assessment of lifetime performance of small ruminants under different feeding systems.
447 *animal* **11**, 881-889 (2017).

448 49 Suybeng, B., Charmley, E., Gardiner, C. P., Malau-Aduli, B. S. & Malau-Aduli, A. E. O.
449 Methane emissions and the use of *desmanthus* in beef cattle production in Northern
450 Australia. *Animals* **9**, 542 (2019).

451 50 Benchaar, C., Pomar, C. & Chiquette, J. Evaluation of dietary strategies to reduce
452 methane production in ruminants: a modelling approach. *Canadian Journal of Animal*
453 *Science* **81**, 563-574 (2001).

454 51 Calle, Z. *et al.* A strategy for scaling-up intensive silvopastoral systems in Colombia.
455 *Journal of sustainable forestry* **32**, 677-693 (2013).

- 456 52 Gordon, A. M., Thevathasan, N. V., Mosquera-Losada, M. R., McAdam, J. & Rigueiro-
457 Rodriguez, A. How much carbon can be stored in Canadian agroecosystems using a
458 silvopastoral approach. *Silvopastoralism and sustainable land management*. CABI
459 Publishing, Wallingford, UK, 210-218 (2005).
- 460 53 Vandermeulen, S., Ramírez-Restrepo, C. A., Beckers, Y., Claessens, H. & Bindelle, J.
461 Agroforestry for ruminants: a review of trees and shrubs as fodder in silvopastoral
462 temperate and tropical production systems. *Animal Production Science* **58**, 767-777
463 (2018).
- 464 54 Haque, M. N. Dietary manipulation: a sustainable way to mitigate methane emissions
465 from ruminants. *Journal of Animal Science and Technology* **60**, 15, doi:10.1186/s40781-
466 018-0175-7 (2018).
- 467 55 Tomkins, N. W. *et al.* Growth performance improvements in pasture and feedlot
468 systems. 16/321,070 (2019).
- 469 56 CCA. *The Canadian Cattlemen's Association - Feedlot Operation*,
470 <<https://www.cattle.ca/cca-resources/animal-care/feedlot-operation/>> (2020).
- 471 57 Wagner, J. J., Archibeque, S. L. & Feuz, D. M. The modern feedlot for finishing cattle.
472 *Annu. Rev. Anim. Biosci.* **2**, 535-554 (2014).
- 473 58 FAO. *Shaping the future of livestock – sustainably, responsibly, efficiently. The 10th*
474 *Global Forum for Food and Agriculture (GFFA)*. 18 (Food and Agriculture Organization of
475 the United Nations (FAO), 2018).
- 476 59 Rao, P. P. & Hall, A. J. Importance of crop residues in crop–livestock systems in India and
477 farmers' perceptions of fodder quality in coarse cereals. *Field Crops Research* **84**, 189-
478 198 (2003).
- 479 60 Amata, I. A. The use of non-conventional feed resources (NCFR) for livestock feeding in
480 the tropics: a review. *Journal of Global Biosciences* **3**, 604-613 (2014).
- 481 61 Mirzaei-Aghsaghali, A. & Maheri-Sis, N. Nutritive value of some agro-industrial by-
482 products for ruminants-A review. *World J. Zool* **3**, 40-46 (2008).
- 483 62 Yanti, Y. & Yayota, M. Agricultural by-products as feed for ruminants in tropical area:
484 nutritive value and mitigating methane emission. *Reviews in Agricultural Science* **5**, 65-
485 76 (2017).
- 486 63 Mohd Azlan, P. *et al.* *Aspergillus terreus* treated rice straw suppresses methane
487 production and enhances feed digestibility in goats. *Tropical Animal Health and*
488 *Production* **50**, 565-571, doi:10.1007/s11250-017-1470-x (2018).
- 489 64 Sharma, D. D., Rangnekar, D. V. & Singh, M. in *Feeding of ruminants on fibrous crop*
490 *residues* (eds Kiran Singh & J.B. Schiere) 486 (Indian Council of Agricultural Research,
491 1993).
- 492 65 Beauchemin, K. A., McGinn, S. M., Benchaar, C. & Holtshausen, L. Crushed sunflower,
493 flax, or canola seeds in lactating dairy cow diets: Effects on methane production, rumen
494 fermentation, and milk production. *Journal of dairy science* **92**, 2118-2127 (2009).
- 495 66 Beauchemin, K. A., Colombatto, D., Morgavi, D. P. & Yang, W. Z. Use of exogenous
496 fibrolytic enzymes to improve feed utilisation by ruminants. *Journal of Animal Science*
497 **81**, E37-E47 (2003).
- 498 67 Jose, S. & Dollinger, J. Silvopasture: a sustainable livestock production system.
499 *Agroforestry Systems* **93**, 1-9, doi:10.1007/s10457-019-00366-8 (2019).

- 500 68 Pagiola, S. *et al.* Paying for the environmental services of silvopastoral practices in
501 Nicaragua. *Ecological Economics* **64**, 374-385,
502 doi:<https://doi.org/10.1016/j.ecolecon.2007.04.014> (2007).
- 503 69 Cieslak, A., Szumacher-Strabel, M., Stochmal, A. & Oleszek, W. Plant components with
504 specific activities against rumen methanogens. *Animal* **7**, 253-265 (2013).
- 505 70 Jouany, J. P. & Morgavi, D. P. Use of 'natural' products as alternatives to antibiotic feed
506 additives in ruminant production. *Animal* **1**, 1443-1466 (2007).
- 507 71 Wina, E. in *Dietary Phytochemicals and Microbes* 311-350 (Springer, 2012).
- 508 72 Mueller-Harvey, I. Unravelling the conundrum of tannins in animal nutrition and health.
509 *Journal of the Science of Food and Agriculture* **86**, 2010-2037, doi:10.1002/jsfa.2577
510 (2006).
- 511 73 Jayanegara, A., Leiber, F. & Kreuzer, M. Meta-analysis of the relationship between
512 dietary tannin level and methane formation in ruminants from in vivo and in vitro
513 experiments. *Journal of Animal Physiology and Animal Nutrition* **96**, 365-375,
514 doi:10.1111/j.1439-0396.2011.01172.x (2012).
- 515 74 Beauchemin, K. A., Kreuzer, M., O'mara, F. & McAllister, T. A. Nutritional management
516 for enteric methane abatement: a review. *Australian Journal of Experimental Agriculture*
517 **48**, 21-27 (2008).
- 518 75 Hutchings, M. R., Athanasiadou, S., Kyriazakis, I. & Gordon, I. J. Can animals use foraging
519 behaviour to combat parasites? *Proceedings of the Nutrition Society* **62**, 361-370 (2003).
- 520 76 Ramírez-Restrepo, C. A., Barry, T. N., López-Villalobos, N., Kemp, P. D. & McNabb, W. C.
521 Use of *Lotus corniculatus* containing condensed tannins to increase lamb and wool
522 production under commercial dryland farming conditions without the use of
523 anthelmintics. *Animal Feed Science and Technology* **117**, 85-105 (2004).
- 524 77 Chizmar, S. *et al.* A Discounted Cash Flow and Capital Budgeting Analysis of Silvopastoral
525 Systems in the Amazonas Region of Peru. *Land* **9**, 353 (2020).
- 526 78 Jara-Rojas, R., Russy, S., Roco, L., Fleming-Muñoz, D. & Engler, A. Factors Affecting the
527 Adoption of Agroforestry Practices: Insights from Silvopastoral Systems of Colombia.
528 *Forests* **11**, 648 (2020).
- 529 79 Dagang, A. B. K. & Nair, P. K. R. Silvopastoral research and adoption in Central America:
530 recent findings and recommendations for future directions. *Agroforestry systems* **59**,
531 149-155 (2003).
- 532 80 Orefice, J., Smith, R. G., Carroll, J., Asbjornsen, H. & Howard, T. Forage productivity and
533 profitability in newly-established open pasture, silvopasture, and thinned forest
534 production systems. *Agroforestry Systems* **93**, 51-65, doi:10.1007/s10457-016-0052-7
535 (2019).
- 536 81 Díaz-Pereira, E., Romero-Díaz, A. & de Vente, J. Sustainable grazing land management to
537 protect ecosystem services. *Mitigation and Adaptation Strategies for Global Change*,
538 doi:10.1007/s11027-020-09931-4 (2020).
- 539 82 McAllister, T. A. *et al.* in *Animal Agriculture* (eds Fuller W. Bazer, G. Cliff Lamb, &
540 Guoyao Wu) 75-98 (Academic Press, 2020).
- 541 83 Hao, H. *et al.* Benefits and risks of antimicrobial use in food-producing animals. *Frontiers*
542 *in Microbiology* **5**, 288 (2014).

543 84 Motoyama, M. *et al.* Residues of pharmaceutical products in recycled organic manure
544 produced from sewage sludge and solid waste from livestock and relationship to their
545 fermentation level. *Chemosphere* **84**, 432-438,
546 doi:<https://doi.org/10.1016/j.chemosphere.2011.03.048> (2011).

547 85 Aidara-Kane, A. *et al.* World Health Organization (WHO) guidelines on use of medically
548 important antimicrobials in food-producing animals. *Antimicrobial Resistance &*
549 *Infection Control* **7**, 7, doi:10.1186/s13756-017-0294-9 (2018).

550 86 Wu, Z. Antibiotic use and antibiotic resistance in food-producing animals in China.
551 (2019).

552 87 European, U. Regulation (EC) No. 1831/2003 of the European Parliament and of the
553 Council of 22 September 2003 on additives for use in animal nutrition. *Off J Eur Union* **50**
554 (2003).

555 88 European, U. (2005).

556 89 Administration, U. F. a. D. *FDA Releases Five-Year Plan for Supporting Antimicrobial*
557 *Stewardship in Veterinary Settings*, <[https://www.fda.gov/animal-veterinary/cvm-](https://www.fda.gov/animal-veterinary/cvm-updates/fda-releases-five-year-plan-supporting-antimicrobial-stewardship-veterinary-settings)
558 [updates/fda-releases-five-year-plan-supporting-antimicrobial-stewardship-veterinary-](https://www.fda.gov/animal-veterinary/cvm-updates/fda-releases-five-year-plan-supporting-antimicrobial-stewardship-veterinary-settings)
559 [settings](https://www.fda.gov/animal-veterinary/cvm-updates/fda-releases-five-year-plan-supporting-antimicrobial-stewardship-veterinary-settings)> (2018).

560 90 Sinha, K. in *Times of India* (New Delhi, 2011).

561 91 Thacker, T. in *The Indian Express* (New Delhi, 2011).

562 92 Welk-Joerger, N. Regulating Rumensin: defining antibiotic feeds in the US in the wake of
563 resistance. (2020).

564 93 Administration, U. F. a. D. Summary report on antimicrobials sold or distributed for use
565 in food-producing animals. Washington, DC: US Department of Health and Human
566 Services. (2018).

567 94 EMEA. *Monensin summary report, EMEA/CVMP/185123/2007-Final. European*
568 *Medicines Agency, Veterinary Medicines and Inspections, Committee for Medicinal*
569 *Products for Veterinary Use*, <[https://www.ema.europa.eu/en/documents/mrl-](https://www.ema.europa.eu/en/documents/mrl-report/monensin-cattle-including-dairy-cows-summary-report-committee-veterinary-medicinal-products_en.pdf)
570 [report/monensin-cattle-including-dairy-cows-summary-report-committee-veterinary-](https://www.ema.europa.eu/en/documents/mrl-report/monensin-cattle-including-dairy-cows-summary-report-committee-veterinary-medicinal-products_en.pdf)
571 [medicinal-products_en.pdf](https://www.ema.europa.eu/en/documents/mrl-report/monensin-cattle-including-dairy-cows-summary-report-committee-veterinary-medicinal-products_en.pdf)> (2007).

572 95 Williams, Y. J. *et al.* A vaccine against rumen methanogens can alter the composition of
573 archaeal populations. *Appl. Environ. Microbiol.* **75**, 1860-1866 (2009).

574 96 Zhang, L. *et al.* Immunisation against Rumen Methanogenesis by Vaccination with a New
575 Recombinant Protein. *PLoS one* **10**, e0140086-e0140086,
576 doi:10.1371/journal.pone.0140086 (2015).

577 97 Wedlock, D. N. *et al.* Development of a vaccine to mitigate greenhouse gas emissions in
578 agriculture: vaccination of sheep with methanogen fractions induces antibodies that
579 block methane production in vitro. *New Zealand Veterinary Journal* **58**, 29-36 (2010).

580 98 Cook, S. R. *et al.* Avian (IgY) anti-methanogen antibodies for reducing ruminal methane
581 production: in vitro assessment of their effects. *Australian Journal of Experimental*
582 *Agriculture* **48**, 260-264 (2008).

583 99 Wright, A. D. G. *et al.* Reducing methane emissions in sheep by immunisation against
584 rumen methanogens. *Vaccine* **22**, 3976-3985,
585 doi:<https://doi.org/10.1016/j.vaccine.2004.03.053> (2004).

586 100 Leahy, S. C. *et al.* The genome sequence of the rumen methanogen *Methanobrevibacter*
587 ruminantium reveals new possibilities for controlling ruminant methane emissions. *PLoS*
588 *one* **5** (2010).

589 101 Henderson, G. *et al.* Rumen microbial community composition varies with diet and host,
590 but a core microbiome is found across a wide geographical range. *Scientific Reports* **5**,
591 14567, doi:10.1038/srep14567 (2015).

592 102 Shi, W. *et al.* Methane yield phenotypes linked to differential gene expression in the
593 sheep rumen microbiome. *Genome research* **24**, 1517-1525 (2014).

594 103 Wright, A.-D. G. & Klieve, A. V. Does the complexity of the rumen microbial ecology
595 preclude methane mitigation? *Animal Feed Science and Technology* **166-167**, 248-253,
596 doi:<https://doi.org/10.1016/j.anifeedsci.2011.04.015> (2011).

597 104 Klopfenstein, T. J., Purser, D. B. & Tyznik, W. J. Effects of Defaunation on Feed
598 Digestibility, Rumen Metabolism and Blood Metabolites. *Journal of Animal Science* **25**,
599 765-773, doi:10.2527/jas1966.253765x (1966).

600 105 Whitelaw, F. G., Eadie, J. M., Bruce, L. A. & Shand, W. J. Methane formation in faunated
601 and ciliate-free cattle and its relationship with rumen volatile fatty acid proportions.
602 *British Journal of Nutrition* **52**, 261-275 (1984).

603 106 Mosoni, P., Martin, C., Forano, E. & Morgavi, D. P. Long-term defaunation increases the
604 abundance of cellulolytic ruminococci and methanogens but does not affect the
605 bacterial and methanogen diversity in the rumen of sheep. *Journal of Animal Science* **89**,
606 783-791, doi:10.2527/jas.2010-2947 (2011).

607 107 Newbold, C. J., de la Fuente, G., Belanche, A., Ramos-Morales, E. & McEwan, N. R. The
608 Role of Ciliate Protozoa in the Rumen. *Frontiers in microbiology* **6**, 1313-1313,
609 doi:10.3389/fmicb.2015.01313 (2015).

610 108 Park, T., Mao, H. & Yu, Z. Inhibition of Rumen Protozoa by Specific Inhibitors of
611 Lysozyme and Peptidases in vitro. *Frontiers in Microbiology* **10**, 2822 (2019).

612 109 Jouany, J. P., Demeyer, D. I. & Grain, J. Effect of defaunating the rumen. *Animal Feed*
613 *Science and Technology* **21**, 229-265 (1988).

614 110 Eugène, M., Archimède, H. & Sauvant, D. Quantitative meta-analysis on the effects of
615 defaunation of the rumen on growth, intake and digestion in ruminants. *Livestock*
616 *Production Science* **85**, 81-97, doi:[https://doi.org/10.1016/S0301-6226\(03\)00117-9](https://doi.org/10.1016/S0301-6226(03)00117-9)
617 (2004).

618 111 Hristov, A. N., Ivan, M., Neill, L. & McAllister, T. A. Evaluation of several potential
619 bioactive agents for reducing protozoal activity in vitro. *Animal Feed Science and*
620 *Technology* **105**, 163-184, doi:[https://doi.org/10.1016/S0377-8401\(03\)00060-9](https://doi.org/10.1016/S0377-8401(03)00060-9) (2003).

621 112 Jeyanathan, J., Martin, C. & Morgavi, D. P. The use of direct-fed microbials for mitigation
622 of ruminant methane emissions: a review. *Animal* **8**, 250-261,
623 doi:10.1017/S1751731113002085 (2014).

624 113 Reichardt, N. *et al.* Phylogenetic distribution of three pathways for propionate
625 production within the human gut microbiota. *The ISME Journal* **8**, 1323-1335,
626 doi:10.1038/ismej.2014.14 (2014).

627 114 Janssen, P. H. Influence of hydrogen on rumen methane formation and fermentation
628 balances through microbial growth kinetics and fermentation thermodynamics. *Animal*

629 *Feed Science and Technology* **160**, 1-22,
630 doi:<https://doi.org/10.1016/j.anifeedsci.2010.07.002> (2010).

631 115 Jeyanathan, J. *et al.* Bacterial direct-fed microbials fail to reduce methane emissions in
632 primiparous lactating dairy cows. *Journal of Animal Science and Biotechnology* **10**, 41,
633 doi:10.1186/s40104-019-0342-9 (2019).

634 116 Philippeau, C. *et al.* Effects of bacterial direct-fed microbials on ruminal characteristics,
635 methane emission, and milk fatty acid composition in cows fed high- or low-starch diets.
636 *Journal of Dairy Science* **100**, 2637-2650, doi:<https://doi.org/10.3168/jds.2016-11663>
637 (2017).

638 117 Doto, S. P., Liu, J. X. & Wang, J. K. Effect of yeast culture and its combination with direct-
639 fed microbials on growth performance and rumen fermentation of weaned lambs.
640 *Tanzania Journal of Agricultural Sciences* **16** (2017).

641 118 Patra, A. K. & Saxena, J. Dietary phytochemicals as rumen modifiers: a review of the
642 effects on microbial populations. *Antonie van Leeuwenhoek* **96**, 363-375,
643 doi:10.1007/s10482-009-9364-1 (2009).

644 119 Beauchemin, K. A., McGinn, S. M. & Petit, H. V. Methane abatement strategies for
645 cattle: Lipid supplementation of diets. *Canadian Journal of Animal Science* **87**, 431-440,
646 doi:10.4141/CJAS07011 (2007).

647 120 Bodas, R. *et al.* Manipulation of rumen fermentation and methane production with
648 plant secondary metabolites. *Animal Feed Science and Technology* **176**, 78-93,
649 doi:<https://doi.org/10.1016/j.anifeedsci.2012.07.010> (2012).

650 121 Hart, K. J., Yáñez-Ruiz, D. R., Duval, S. M., McEwan, N. R. & Newbold, C. J. Plant extracts
651 to manipulate rumen fermentation. *Animal Feed Science and Technology* **147**, 8-35,
652 doi:<https://doi.org/10.1016/j.anifeedsci.2007.09.007> (2008).

653 122 Hook, S. E., Wright, A.-D. G. & McBride, B. W. Methanogens: Methane Producers of the
654 Rumen and Mitigation Strategies. *Archaea* **2010**, 945785, doi:10.1155/2010/945785
655 (2010).

656 123 Machmüller, A. & Kreuzer, M. Methane suppression by coconut oil and associated
657 effects on nutrient and energy balance in sheep. *Canadian Journal of Animal Science* **79**,
658 65-72 (1999).

659 124 Grainger, C., Williams, R., Clarke, T., Wright, A. D. G. & Eckard, R. J. Supplementation
660 with whole cottonseed causes long-term reduction of methane emissions from lactating
661 dairy cows offered a forage and cereal grain diet. *Journal of Dairy Science* **93**, 2612-
662 2619, doi:<https://doi.org/10.3168/jds.2009-2888> (2010).

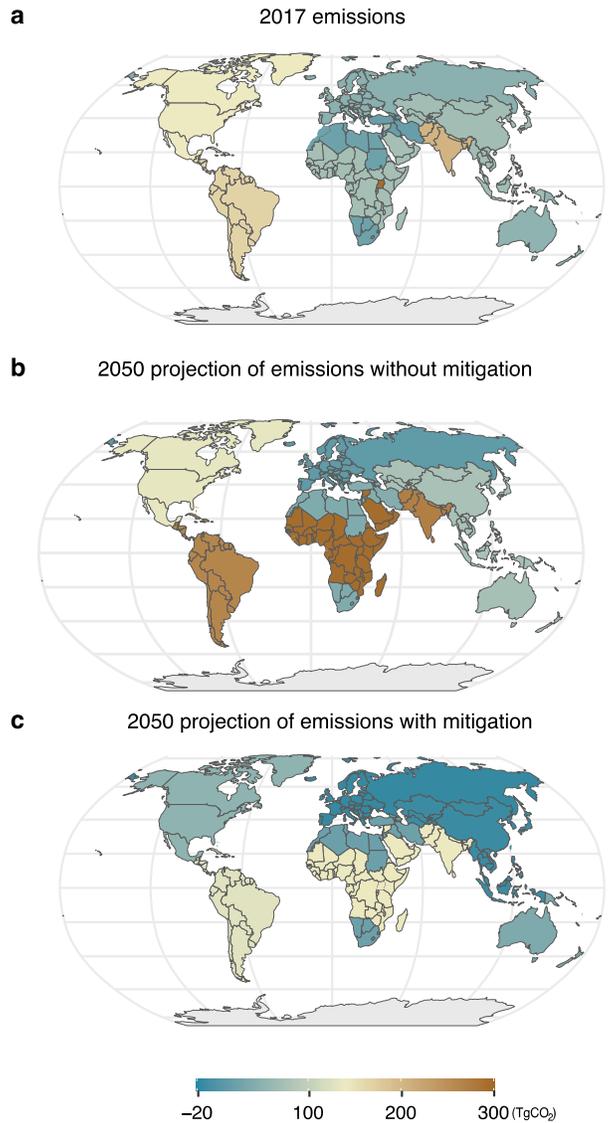
663 125 Abecia, L. *et al.* Effect of bromochloromethane on methane emission, rumen
664 fermentation pattern, milk yield, and fatty acid profile in lactating dairy goats. *Journal of*
665 *Dairy Science* **95**, 2027-2036, doi:<https://doi.org/10.3168/jds.2011-4831> (2012).

666 126 Yang, C., Rooke, J. A., Cabeza, I. & Wallace, R. J. Nitrate and Inhibition of Ruminant
667 Methanogenesis: Microbial Ecology, Obstacles, and Opportunities for Lowering
668 Methane Emissions from Ruminant Livestock. *Frontiers in microbiology* **7**, 132-132,
669 doi:10.3389/fmicb.2016.00132 (2016).

670 127 Kristjansson, J. K., Schönheit, P. & Thauer, R. K. Different K_s values for hydrogen of
671 methanogenic bacteria and sulfate reducing bacteria: an explanation for the apparent
672 inhibition of methanogenesis by sulfate. *Archives of Microbiology* **131**, 278-282 (1982).

673 128 Mitsumori, M. *et al.* Responses in digestion, rumen fermentation and microbial
674 populations to inhibition of methane formation by a halogenated methane analogue.
675 *British Journal of Nutrition* **108**, 482-491, doi:10.1017/S0007114511005794 (2012).
676 129 Stadtman, T. C. Vitamin B12. *Science* **171**, 859-867 (1971).
677 130 Tomkins, N. W., Colegate, S. M. & Hunter, R. A. A bromochloromethane formulation
678 reduces enteric methanogenesis in cattle fed grain-based diets. *Animal Production*
679 *Science* **49**, 1053-1058 (2009).
680 131 Dittmann, M. T. *et al.* Influence of ruminal methane on digesta retention and digestive
681 physiology in non-lactating dairy cattle. *British Journal of Nutrition* **116**, 763-773 (2016).
682 132 Goel, G., Makkar, H. P. S. & Becker, K. Inhibition of methanogens by
683 bromochloromethane: effects on microbial communities and rumen fermentation using
684 batch and continuous fermentations. *British journal of nutrition* **101**, 1484-1492 (2009).
685 133 UNEP. *The Montreal Protocol on Substances that Deplete the Ozone Layer - Article 2I:*
686 *Bromochloromethane*, <[https://ozone.unep.org/treaties/montreal-](https://ozone.unep.org/treaties/montreal-protocol/articles/article-2i-bromochloromethane)
687 [protocol/articles/article-2i-bromochloromethane](https://ozone.unep.org/treaties/montreal-protocol/articles/article-2i-bromochloromethane)> (2020).
688 134 Stemmler, I., Hense, I. & Quack, B. Marine sources of bromoform in the global open
689 ocean-global patterns and emissions. *Biogeosciences (BG)* **12**, 1967-1981 (2015).
690 135 Manley, S. L. Phytogenesis of halomethanes: A product of selection or a metabolic
691 accident? *Biogeochemistry* **60**, 163-180, doi:10.1023/A:1019859922489 (2002).
692 136 IARC & WHO. *IARC monographs on the evaluation of carcinogenic risk to humans. Re-*
693 *evaluation of some organic chemicals, hydrazine and hydrogen peroxide*. Vol. 71 (World
694 Health Organization and International Agency for Research on Cancer, 1999).
695 137 ATSDR. *Bromoform and dibromochloromethane*,
696 <<https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=712&tid=128>> (2005).
697 138 Bove, G. E., Rogerson, P. A. & Vena, J. E. Case control study of the geographic variability
698 of exposure to disinfectant byproducts and risk for rectal cancer. *International Journal of*
699 *Health Geographics* **6**, 18, doi:10.1186/1476-072X-6-18 (2007).
700 139 Melnick, R. L. NTP Toxicology and carcinogenesis studies of tribromomethane
701 (bromoform)(CAS No. 75-25-2) in F344/N rats and B6C3f1 mice (gavage studies).
702 Technical report series. (National Toxicology Program, Research Triangle Park, NC (USA),
703 1989).
704 140 Machado, L. *et al.* Dose-response effects of *Asparagopsis taxiformis* and *Oedogonium*
705 sp. on in vitro fermentation and methane production. *Journal of Applied Phycology* **28**,
706 1443-1452 (2016).
707 141 Kinley, R. D. *et al.* Mitigating the carbon footprint and improving productivity of
708 ruminant livestock agriculture using a red seaweed. *Journal of Cleaner Production* **259**,
709 120836, doi:<https://doi.org/10.1016/j.jclepro.2020.120836> (2020).
710 142 Li, X. *et al.* *Asparagopsis taxiformis* decreases enteric methane production from sheep.
711 *Animal Production Science* **58**, 681-688 (2018).
712 143 Gribble, G. W. The natural production of organobromine compounds. *Environmental*
713 *Science and Pollution Research* **7**, 37-49 (2000).
714 144 Duarte, C. M., Wu, J., Xiao, X., Bruhn, A. & Krause-Jensen, D. Can seaweed farming play a
715 role in climate change mitigation and adaptation? *Frontiers in Marine Science* **4**, 100
716 (2017).

717 145 Bernoux, M. *et al.* EX-Ante Carbon-balance Tool (EX-ACT) Technical Guidelines for
718 Version 7. *EASYPol - On-line resource materials for policy making* **Module 218** (2016).
719
720



722

723

724 **Figure 1** | Cattle-related enteric methane and CO₂ emissions from grassland grazing by country.

725 **a**, Current emissions. **b**, emission by 2050 in a business-as-usual scenario. **c**, 2050 projection of

726 emissions with a synergistic combination of the most practical mitigation strategies available:

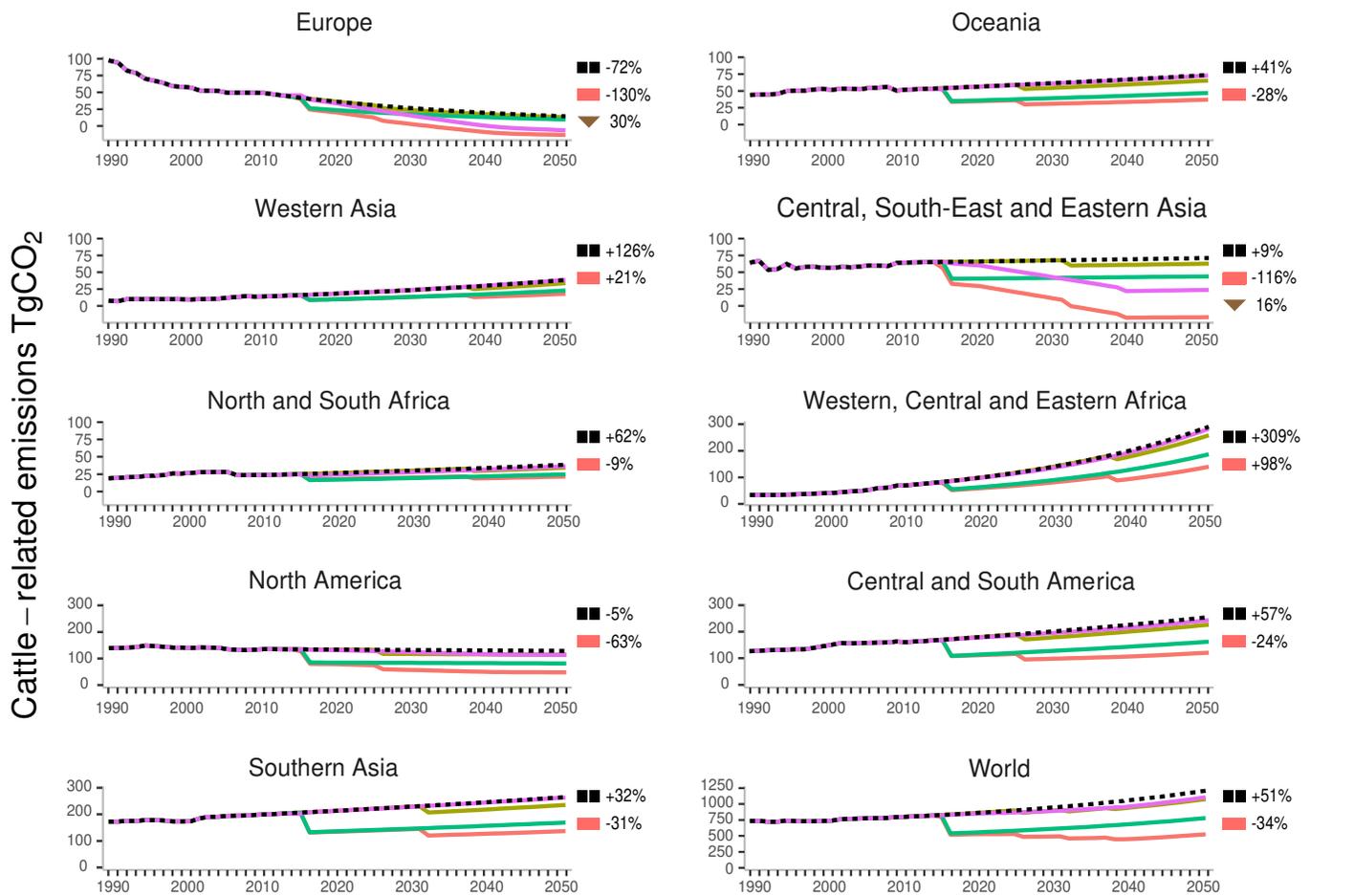
727 replacing regular breeds with genotypes for low-methane emissions, use of anti-methanogenic

728 seaweed as feed supplement, and grassland transition to silvopasture. Under a mitigation

729 scenario, Europe and most of Asia would reach carbon neutrality, in addition to offering carbon

730 sequestration in soil and plant biomass from silvopasture systems (negative values in the

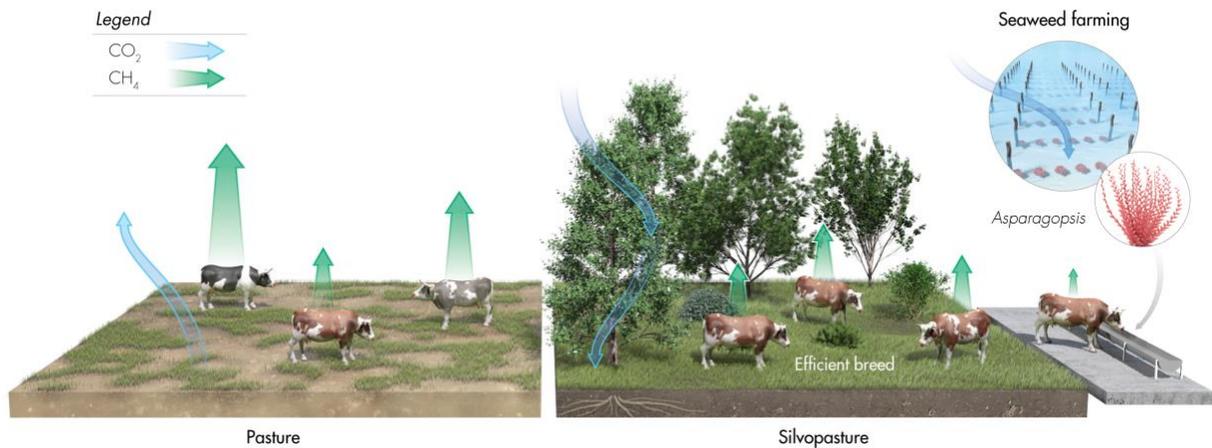
731 carbon stock balance; Tg CO₂ equivalent).



Business as usual
 Efficient animals
 Seaweed supplement
 Silvopasture
 All strategies
 CO₂ sequestration

732

733 **Figure 2 |** Global projection of 2020-2050 GHG emissions under a business-as-usual scenario
 734 and by implementing mitigation strategies, based on 1990-2017 data from enteric and
 735 grassland-use CO₂ equivalent emissions. Trendlines dip between 2017 and 2020 after
 736 silvopasture conversion, supplementing anti-methanogenic seaweed, replacing regular cattle
 737 with genetically efficient animals, and using a synergistic implementation of all these strategies.
 738 Differences between 2050 and 2017 emissions are shown for each region, under scenarios of
 739 business-as-usual and execution of all strategies. *Europe* and *Central, South-East and Eastern*
 740 *Asia* additionally project carbon sequestration potential (brown arrows). Note the difference of
 741 scale in the emission axes.



742

743 **Figure 3 |** Plausible mitigation effects of available strategies to reduce GHG emissions directly
 744 related to cattle. Planting silvopasture plants reduces the environmental impact of fodder
 745 production while increasing soil and biomass carbon sequestration. Additionally, replacing
 746 regular breeds with low-methane animals and feeding anti-methanogenic seaweed
 747 (*Asparagopsis*) to ruminants, can increase animal productivity and reduce methane emission
 748 intensity. Seaweed production via photosynthetic carbon capture offers significant potential for
 749 transforming atmospheric carbon dioxide into ruminant biomass.

750 **Table 1** | Sum of projected cattle-related emissions from 2020 to 2050, following a business-as-usual (BAS) and mitigation scenarios
751 (TgCO₂ equivalent). Percentages indicate emissions reduced by the strategy. %*shows the reduction of emissions excluding the
752 breeding strategy. N, North; S, South; C, Central; E, Eastern; W, Western; SE, South-East.

Region	Enteric emissions			Grassland emissions		Enteric + grassland emissions	
	BAS	Seaweed (%)	Breeding (%)	BAS	Silvopasture (%)	BAS	Synergic mitigation (%/*%)
Africa N/S	919	609 (33.8)	878 (4.5)	71	71 (0)	991	991 (35.6/31.4)
Africa C/E/W	4,929	3,230 (34.5)	4,651 (5.6)	238	-139 (158.6)	5,167	5,167 (45.6/40.2)
America N	4,026	2,687 (33.3)	3,728 (7.4)	210	-271 (228.7)	4,236	4,236 (50/43)
America C/S	6,620	4,387 (33.7)	6,094 (7.9)	35	-210 (707.5)	6,655	6,655 (45.2/37.2)
Asia C/SE/E	1,991	1,326 (33.4)	1,876 (5.8)	265	-847 (419.8)	2,256	2,256 (83.9/78.8)
Asia W	953	629 (34)	907 (4.9)	0	0 (0)	954	954 (38.9/34)
Asia S	7,352	4,883 (33.6)	6,908 (6)	56	-26 (146.2)	7,407	7,407 (40.4/34.4)
Europe	736	502 (31.7)	692 (5.9)	41	-371 (1006.3)	777	777 (88.7/83.1)
Oceania	1,922	1,275 (33.6)	1,771 (7.8)	52	-12 (123.5)	1,974	1,974 (43.7/36)
World	29,448	19,529 (33.7)	27,505 (6.6)	968	-1,804 (286.4)	30,415	30,415 (48.1/41.7)

753

Figures

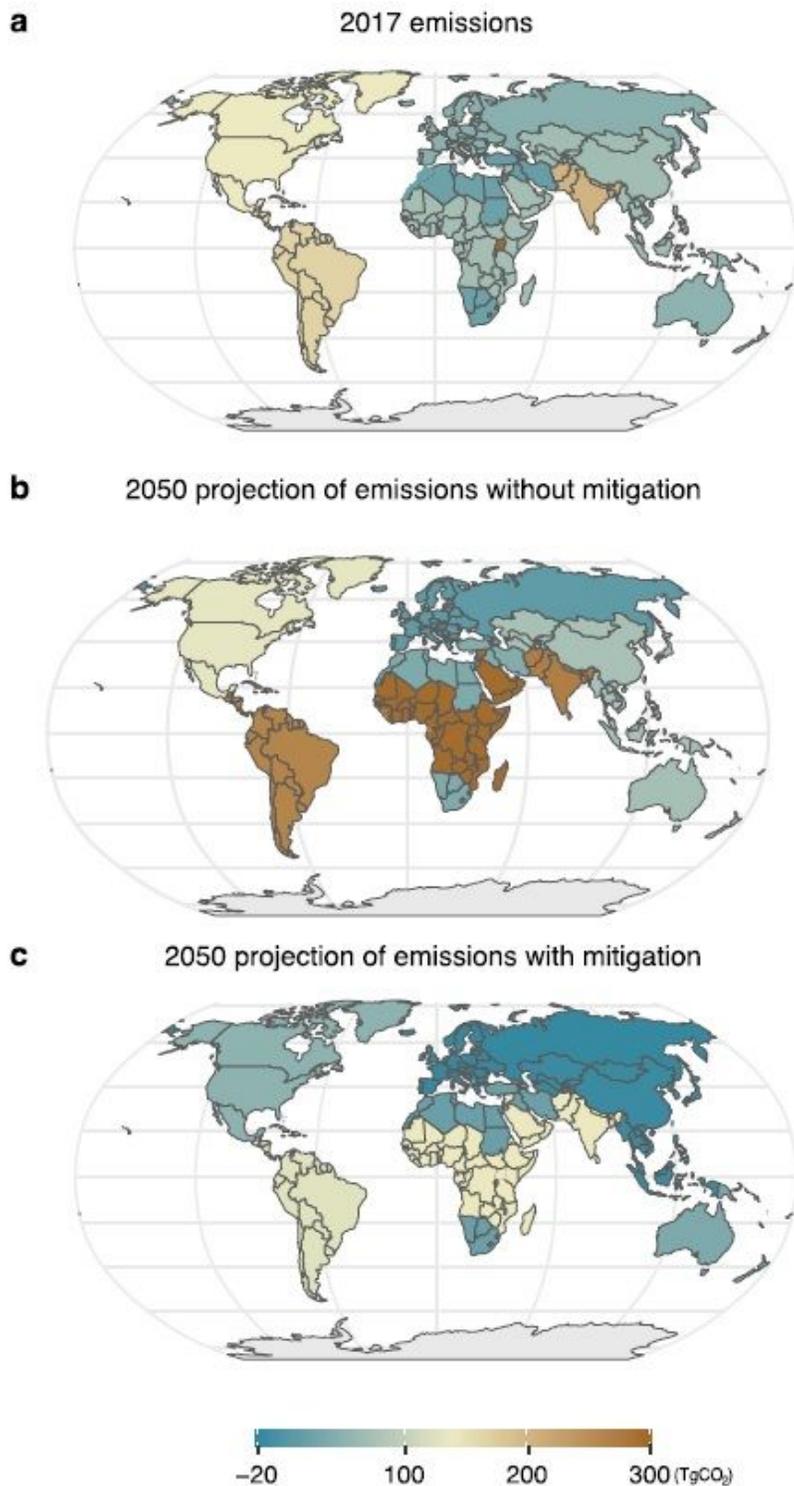


Figure 1

Cattle-related enteric methane and CO₂ emissions from grassland grazing by country. a, Current emissions. b, emission by 2050 in a business-as-usual scenario. c, 2050 projection of emissions with a synergistic combination of the most practical mitigation strategies available: replacing regular breeds

with genotypes for low-methane emissions, use of anti-methanogenic seaweed as feed supplement, and grassland transition to silvopasture. Under a mitigation scenario, Europe and most of Asia would reach carbon neutrality, in addition to offering carbon sequestration in soil and plant biomass from silvopasture systems (negative values in the carbon stock balance; Tg CO₂ equivalent). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

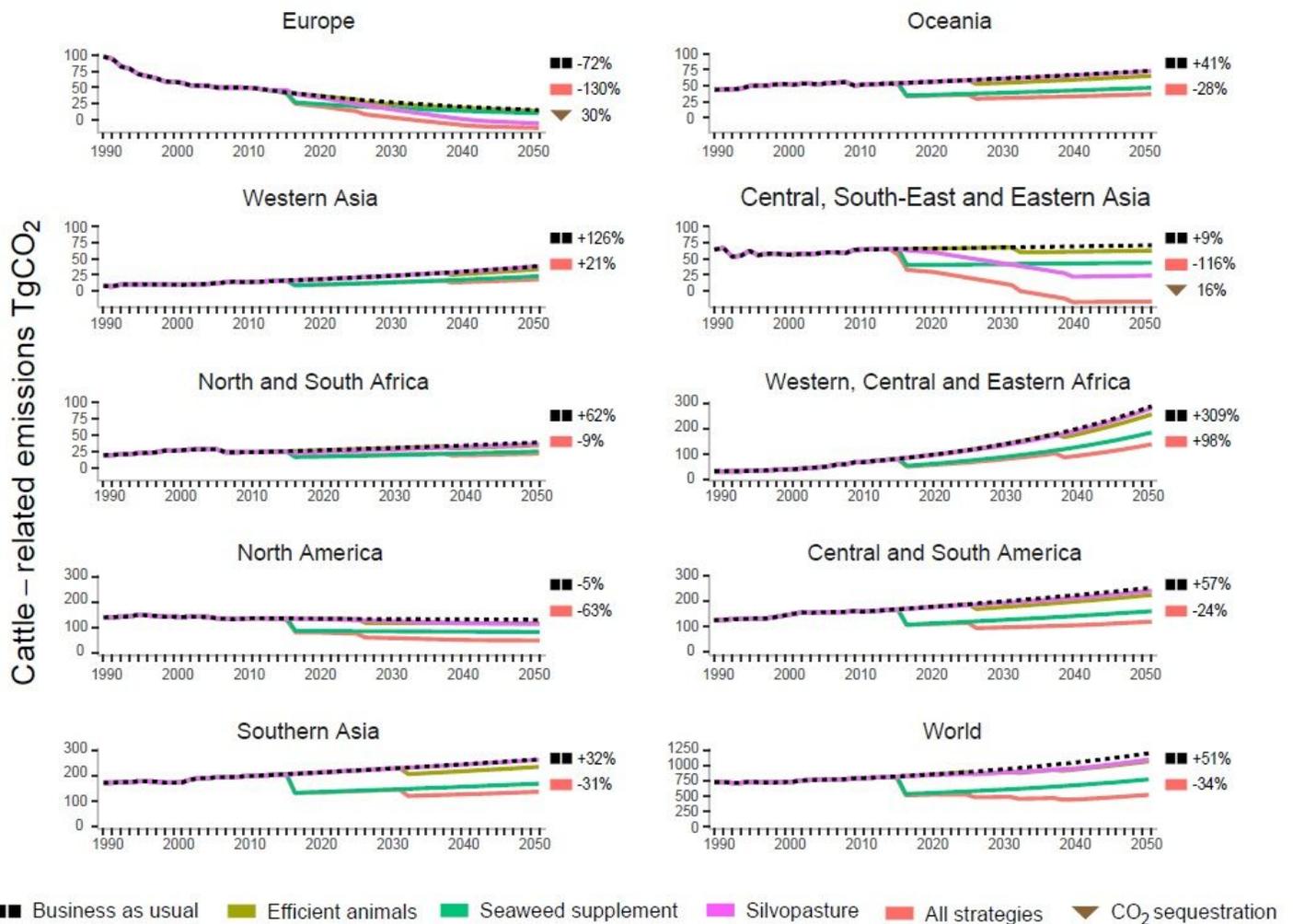


Figure 2

Global projection of 2020-2050 GHG emissions under a business-as-usual scenario and by implementing mitigation strategies, based on 1990-2017 data from enteric and grassland-use CO₂ equivalent emissions. Trendlines dip between 2017 and 2020 after silvopasture conversion, supplementing anti-methanogenic seaweed, replacing regular cattle with genetically efficient animals, and using a synergistic implementation of all these strategies. Differences between 2050 and 2017 emissions are shown for each region, under scenarios of business-as-usual and execution of all strategies. Europe and Central,

South-East and Eastern Asia additionally project carbon sequestration potential (brown arrows). Note the difference of scale in the emission axes.

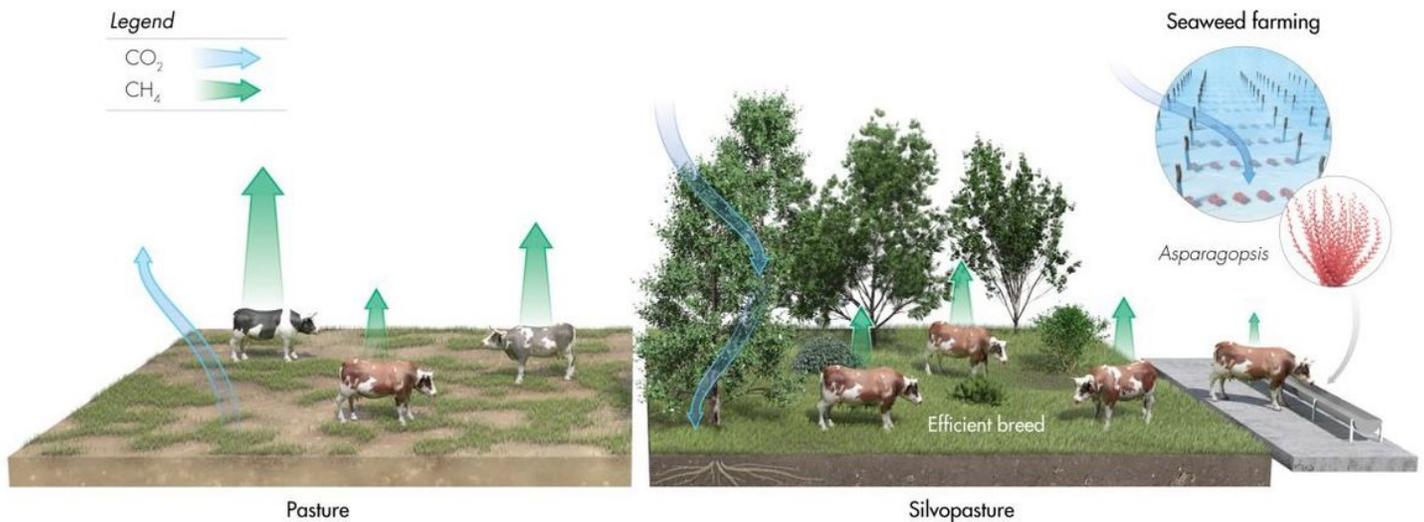


Figure 3

Plausible mitigation effects of available strategies to reduce GHG emissions directly related to cattle. Planting silvopasture plants reduces the environmental impact of fodder production while increasing soil and biomass carbon sequestration. Additionally, replacing regular breeds with low-methane animals and feeding anti-methanogenic seaweed (*Asparagopsis*) to ruminants, can increase animal productivity and reduce methane emission intensity. Seaweed production via photosynthetic carbon capture offers significant potential for transforming atmospheric carbon dioxide into ruminant biomass.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryInformation.xlsx](#)