

Practical strategies to mitigate ruminant greenhouse gas emissions

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

KAUST <https://orcid.org/0000-0002-7503-995X>

Mark Tester

Agriculture King Abdullah University of Science and Technology

Kyle Lauersen

KAUST

Analysis

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Abstract

Livestock contributes to 14.5 percent of global greenhouse gas emissions, with ruminants being the largest contributor through enteric methane emissions. Although several strategies are available to mitigate livestock methane, no consensus exists on which methods are the most effective. Here, we projected by 2050 the impact of the most pragmatic strategies to reduce enteric methane, modelling cattle emissions. The projection shows that supplementing ruminant feed with anti-methanogenic seaweed and converting grassland into silvopasture offer the greatest potential to reduce emissions. A synergic combination of strategies can aid Europe and most of Asia to reach ruminant carbon neutrality by 2035 and 2038, respectively. However, global cattle CO₂-eq emissions will be reduced by no more than 34 percent by 2050, remaining far above the carbon neutrality target. Mitigation strategies alone are insufficient to lower emissions, and reducing the demand for ruminant products is also necessary – particularly in Africa and Western Asia.

Main

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

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

Several GHG mitigation strategies are available for ruminant enteric methane, and their feasibility varies with the geographical distribution of natural and economic resources^{2,7,11}. Although some strategies are already in place, implementation of others lags behind despite their strong data-backed mitigation potential¹⁴⁻¹⁶. This delay is due in part to the economic inequality that impedes widespread research on ruminants. Such research requires long experimental timescales and a holistic understanding of their implications on ruminant subjects, the environment and human health.

Here, we use cattle to model ruminant CO₂-eq emissions and project the mitigation effect of existing strategies to improve animal productivity and grassland-management. Among the available mechanisms

to reduce ruminant GHG emissions, we focus on replacing regular animals with low-methane genotypes, grassland conversion to silvopasture, and methods to inhibit methane production in the rumen. Our projection indicates that global suppression of enteric methane emissions is not possible between by 2050, but mitigation can drastically reduce emission intensity (Figure 1). The projection is based on historical data from 1990 to 2017 from global cattle stocks, enteric methane CO₂-equivalent (CO₂-eq) emissions, and CO₂ emission from ruminant grasslands by area. Data come from the Statistical Database of the Food and Agriculture Organization of the United Nations (FAOSTAT), and exclude GHG emissions from other livestock life-cycle steps.

Breeding genetically advantageous ruminants

Microbial communities ferment plant biomass in the rumen¹⁷. In this process, hydrogen and CO₂ can be converted into nutrients by beneficial bacteria, or into methane by methanogenic archaea¹⁸. Methane production uses 2-12 percent of the gross dietary energy and represents a substantial metabolic lost to the ruminant^{19,20}. Some animals have genetic traits that can reduce enteric methane emissions by favouring beneficial microbial communities²¹ or increasing animal productivity per feed unit^{20,22}. Replacing regular with more efficient ruminants (low-methane genotypes) is a strategy that benefits both the environment and the ruminant economy^{19,20}.

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

In labour-intensive and less economically successful systems, as are found in Eastern Africa, ruminant breeds are selected for their adaptation to the environment (sparse grassland, heat, local diseases) rather than for their productivity^{34,38-41}. While efforts have been made to increase productivity by crossbreeding local with foreign breeds, most attempts lack scientific rigour and ignore the limitations of the foreign animals to adapt in the new environments^{38,41,42}. Community or farm-based breeding is a rapid alternative to centralised national or regional breeding strategies, nevertheless few farms – often located in developed countries, can afford comprehensive research facilities for selection of low-methane ruminants^{32,41,43,44}. Although individual farms or independent funding sources (e.g. African Dairy Genetics Gain Program⁴⁵) can finance local breeding, extensive ruminant replacement with efficient breeds requires long-term commitments from governments⁴⁶.

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

Improving feeding practices

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

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

Conversion to silvopasture

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

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

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

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

Other strategies focus on inhibiting methane production rather than eliminating the methanogens. Examples include probiotics, digestibility enhancers and chemical or natural supplements that alter

methanogenesis^{18,66,70,87}. Probiotics are a promising method for methane reduction where beneficial fungi and bacteria compete against methanogens for hydrogen sources to form propionate^{18,112}. Contrary to methane released to the environment, propionate is metabolised, favouring glucogenesis and increasing animal production^{18,113,114}. Available studies analysing the effect of probiotics on enteric methane production show contradictory results, and further research on probiotic strains is needed^{63,112,115-117}.

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

Naturally occurring halogenated compounds present a lower environmental risk to reduce rumen emissions¹³⁰. Plankton and seaweed produce BMC and bromoform to protect against predators and harmful hydrogen peroxides in the cells^{134,135}. Bromoform does not bioaccumulate in the food chain and is not classifiable as a human carcinogen¹³⁶⁻¹³⁸. It has been shown, for example, that after two years of daily gavage ingestion (<200 mg/kg), bromoform displayed little carcinogenicity in rats (0.5-4%; n=50)¹³⁹. Supplementing ruminant feed with bromoform-rich seaweed inhibits methanogen growth, consequently promoting propionate production¹⁴⁰. Seaweed of the genus *Asparagopsis* added in 0.2 to 3 percent to a grass diet can reduce methane emissions up to 98 percent in cattle and sheep^{55,141,142}. The use of bromoform-rich seaweed as an anti-methanogenic strategy also increases animal productivity in weight gain without affecting animal health or meat quality¹⁴¹. *Asparagopsis* is traditionally used in the Hawaiian cuisine without affecting human health¹⁴³.

Before slaughter, intermediate and mature cattle feed on high-quality fodder supplemented with nutrients to increase final animal product⁵⁶. Based on an average lifespan of 420 days for beef cattle⁵⁶, we

estimate that 11 kg of anti-methanogenic *Asparagopsis* can be supplemented on fodder during 36 percent of the animal lifespan (see Methods). Considering a mitigation effect of 98 percent reduction of enteric methane per animal¹⁴¹, seaweed at 2 percent feed supplement can reduce 320 Tg of CO₂-eq emissions from cattle – almost half of the current global enteric methane emissions. Overall, 35.6 percent fewer emissions will be generated compared to a business-as-usual scenario (Figure 2). Widespread commercialisation of seaweed as a feed supplement can be available as early as 2022⁵⁵.

Feasibility and mitigation impact

There is no single solution to reduce GHG emissions, and a synergic combination of mitigation methods is required to slow rates of ruminant enteric methane emissions (Figure 3). Although mitigation feasibility depends on economic and environmental resources by region, the focus should be on the strategies with immediate implementation potential. Due to differential research and technological maturity of the strategies described above, heterogeneous implementation could yield immediate benefits, as some of the most effective mitigation strategies already exist, but are not yet deployed at scale.

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

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

Worldwide conversion of 1.2 million hectares of grassland into silvopasture would have a net carbon sequestration balance of 0.34 Tg CO₂ captured after the first year of conversion. From 2045 onward, silvopasture carbon storage potential would reach a plateau, capturing 102.3 Tg CO₂ annually (Supplementary Table 2). Such carbon capture is equivalent to 13 percent of current global cattle CO₂-eq emission. Immediate conversion to silvopasture, and supplementation of anti-methanogenic seaweed in feed, could mitigate up to 46 percent of the annual cattle CO₂-eq emissions – avoiding 9,082 Tg CO₂-eq emissions between 2020 to 2050.

A reduction in cattle demand is also necessary

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

Methods

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

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<p>Breeding genetically advantageous ruminants</p>

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generated compared to a business-as-usual scenario (Figure 2). Widespread commercialisation of seaweed as a feed supplement can be available as early as 2022⁵⁵.

Feasibility and mitigation impact

There is no single solution to reduce GHG emissions, and a synergic combination of mitigation methods is required to slow rates of ruminant enteric methane emissions (Figure 3). Although mitigation feasibility depends on economic and environmental resources by region, the focus should be on the strategies with immediate implementation potential. Due to differential research and technological maturity of the strategies described above, heterogeneous implementation could yield immediate benefits, as some of the most effective mitigation strategies already exist, but are not yet deployed at scale.

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

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

Worldwide conversion of 1.2 million hectares of grassland into silvopasture would have a net carbon sequestration balance of 0.34 Tg CO₂ captured after the first year of conversion. From 2045 onward, silvopasture carbon storage potential would reach a plateau, capturing 102.3 Tg CO₂ annually (Supplementary Table 2). Such carbon capture is equivalent to 13 percent of current global cattle CO₂-eq emission. Immediate conversion to silvopasture, and supplementation of anti-methanogenic seaweed in feed, could mitigate up to 46 percent of the annual cattle CO₂-eq emissions – avoiding 9,082 Tg CO₂-eq emissions between 2020 to 2050.

A reduction in cattle demand is also necessary

Our analysis assumes no trend changes in the increasing demand for cattle consumption. Modelling mitigation strategies for enteric methane emissions shows that carbon neutrality by 2050 is possible only if there is a slowdown of the growth rate of cattle consumption. Changes in per capita meat consumption in Europe and Central to Eastern Asia, combined with policy mitigation efforts, lower current ruminant GHG emissions¹⁰. Mitigation strategies in those regions can sharpen this trend, potentially reaching carbon neutrality by 2035 and 2038, respectively (Figure 2). Nevertheless, the demand for ruminant products in developing countries will rise continuously due to population growth and increasing

per capita meat purchasing power⁹. Without mitigation, global enteric methane emissions will increase steadily – particularly in Africa, Southern and Western Asia (Figure 2). Implementation of mitigation strategies can reduce emissions intensity, returning to pre-1990 levels of ruminant methane emissions, but this is only a 34% reduction over 2017 emissions level (Figure 2). However, our results indicate that mitigation strategies alone are insufficient to achieve low enteric methane emissions, and a reduction of the demand for animal products is also necessary. *Sustainable* production of livestock cattle at a global scale does not seem possible, and further strategies such as alternative meat production (for example, cultured meat) are necessary.

Declarations

Data availability

All data used in this study are publicly available in the FAOSTAT database (<http://www.fao.org/faostat/en/#data>). Projection of enteric methane emissions and silvopasture carbon balance using EX-ACT estimations are available in the Supplementary Table 2.

Code availability

FAO EX-Ante Carbon-balance Tool is available at <http://www.fao.org/in-action/epic/ex-act-tool/suite-of-tools/ex-act/en/>.

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References

- 1 Rogelj, J. *et al.* Mitigation pathways compatible with 1.5° C in the context of sustainable development. . *IPCC Special Report on Global Warming of 1.5° C* (2018).
- 2 Gerber, P. J. *et al.* *Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities*. (Food and Agriculture Organization of the United Nations (FAO), 2013).
- 3 Kirschke, S. *et al.* Three decades of global methane sources and sinks. *Nature Geoscience***6**, 813-823, doi:10.1038/ngeo1955 (2013).
- 4 Moss, A. R., Jouany, J.-P. & Newbold, J. Methane production by ruminants: its contribution to global warming. *Annales de zootechnie***49**, 231-253 (2000).
- 5 Finneran, E. *et al.* Simulation modelling of the cost of producing and utilising feeds for ruminants on Irish farms. *Journal of Farm Management***14**, 95-116 (2010).

- 6 Faurès, J. M. *et al.* Climate-smart agriculture. Sourcebook. *FAO, Rome***557** (2013).
- 7 FAO. *World Livestock: Transforming the livestock sector through the Sustainable Development Goals*. 222 (Food and Agriculture Organization of the United Nations (FAO), 2018).
- 8 United Nations & Department of Economic Social Affairs, P. D. (United Nations New York, NY, 2019).
- 9 McLeod, A. *World livestock 2011-livestock in food security*. (Food and Agriculture Organization of the United Nations (FAO), 2011).
- 10 Alexandratos, N. & Bruinsma, J. World agriculture towards 2030/2050: the 2012 revision. (2012).
- 11 Rojas-Downing, M. M., Nejadhashemi, A. P., Harrigan, T. & Woznicki, S. A. Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management***16**, 145-163, doi:<https://doi.org/10.1016/j.crm.2017.02.001> (2017).
- 12 FAO. *Why is enteric methane important?*, <<http://www.fao.org/in-action/enteric-methane/background/why-is-enteric-methane-important/en/>> (2019).
- 13 FAO & NZAGRC. *Reducing enteric methane for improving food security and livelihoods. Project Highlights 2015–2017*. 18 (Food and Agriculture Organization of the United Nations (FAO), 2019).
- 14 Cottle, D., Nolan, J. & Wiedemann, S. Ruminant enteric methane mitigation: A review. *Animal Production Science***51**, 491-514, doi:10.1071/AN10163 (2011).
- 15 Patra, A. K. Enteric methane mitigation technologies for ruminant livestock: a synthesis of current research and future directions. *Environmental Monitoring and Assessment***184**, 1929-1952 (2012).
- 16 Boadi, D., Benchaar, C., Chiquette, J. & Massé, D. Mitigation strategies to reduce enteric methane emissions from dairy cows: update review. *Canadian Journal of Animal Science***84**, 319-335 (2004).
- 17 FAO. *What is enteric methane?*, <<http://www.fao.org/in-action/enteric-methane/background/what-is-enteric-methane/en/>> (2019).
- 18 McAllister, T. A. & Newbold, C. J. Redirecting rumen fermentation to reduce methanogenesis. *Australian Journal of Experimental Agriculture***48**, 7-13 (2008).
- 19 Johnson, D. E. & Ward, G. M. Estimates of animal methane emissions. *Environmental monitoring and assessment***42**, 133-141 (1996).
- 20 Hegarty, R. S. & McEwan, J. C. Genetic opportunities to reduce enteric methane emissions from ruminant livestock. 1-6 (2010).

- 21 Wallace, R. J. *et al.* A heritable subset of the core rumen microbiome dictates dairy cow productivity and emissions. *Science Advances***5**, eaav8391, doi:10.1126/sciadv.aav8391 (2019).
- 22 de Haas, Y. *et al.* Genetic parameters for predicted methane production and potential for reducing enteric emissions through genomic selection. *Journal of dairy science***94**, 6122-6134 (2011).
- 23 Hanotte, O., Dessie, T. & Kemp, S. Time to tap Africa's livestock genomes. *Science***328**, 1640, doi:10.1126/science.1186254 (2010).
- 24 ILRI. *Genomics Reference Resource for African Cattle*, <<https://data.ilri.org/portal/dataset/grfac>> (2019).
- 25 Banos, G., Coffey, M. P., Veerkamp, R. F., Berry, D. P. & Wall, E. Merging and characterising phenotypic data on conventional and rare traits from dairy cattle experimental resources in three countries. *animal***6**, 1040-1048, doi:10.1017/S1751731111002655 (2012).
- 26 Lund, M. S. *et al.* A common reference population from four European Holstein populations increases reliability of genomic predictions. *Genetics Selection Evolution***43**, 43, doi:10.1186/1297-9686-43-43 (2011).
- 27 de Haas, Y. & Lassen, J. METHAGENE-Towards large-scale methane measurements on individual ruminants for genetic evaluations. *EAAP-66th Annual Meeting 2015***21**, 90-90 (2015).
- 28 Mueller, J., Flores, E. & Gutierrez, G. Experiences with a large-scale sheep genetic improvement project in the Peruvian highlands. (2002).
- 29 Amaya, A., Martínez, R. & Cerón-Muñoz, M. Population structure and genetic diversity in Colombian Simmental cattle. *Tropical Animal Health and Production*, 1-7 (2019).
- 30 Walsh, D. & Cowley, R. Optimising beef business performance in northern Australia: what can 30 years of commercial innovation teach us? *The Rangeland Journal***38**, 291-305 (2016).
- 31 Alford, A. R. *et al.* The impact of breeding to reduce residual feed intake on enteric methane emissions from the Australian beef industry. *Australian Journal of Experimental Agriculture***46**, 813-820 (2006).
- 32 Garnsworthy, P. C. *et al.* Comparison of methods to measure methane for use in genetic evaluation of dairy cattle. *Animals***9**, 837 (2019).
- 33 de Haas, Y. *et al.* Improved ruminant genetics: Implementation guidance for policymakers and investors. (2016).
- 34 Bentley, D., Hegarty, R. S. & Alford, A. R. Managing livestock enterprises in Australia's extensive rangelands for greenhouse gas and environmental outcomes: a pastoral company perspective. *Australian*

*Journal of Experimental Agriculture***48**, 60-64 (2008).

- 35 Lassen, J. & Løvendahl, P. Heritability estimates for enteric methane emissions from Holstein cattle measured using noninvasive methods. *Journal of Dairy Science***99**, 1959-1967 (2016).
- 36 Hansen Axelsson, H. *et al.* Genomic selection using indicator traits to reduce the environmental impact of milk production. *Journal of Dairy Science***96**, 5306-5314, doi:<https://doi.org/10.3168/jds.2012-6041> (2013).
- 37 Maciel, I. C. d. F. *et al.* Could the breed composition improve performance and change the enteric methane emissions from beef cattle in a tropical intensive production system? *PLOS ONE***14**, e0220247, doi:10.1371/journal.pone.0220247 (2019).
- 38 Kosgey, I. S. & Okeyo, A. M. Genetic improvement of small ruminants in low-input, smallholder production systems: Technical and infrastructural issues. *Small Ruminant Research***70**, 76-88, doi:<https://doi.org/10.1016/j.smallrumres.2007.01.007> (2007).
- 39 Tibbo, M. Productivity and health of indigenous sheep breeds and crossbreds in central Ethiopian Highlands. (2006).
- 40 Lukuyu, M. N. *et al.* Farmers' Perceptions of Dairy Cattle Breeds, Breeding and Feeding Strategies: A Case of Smallholder Dairy Farmers in Western Kenya. *East African Agricultural and Forestry Journal***83**, 351-367, doi:10.1080/00128325.2019.1659215 (2019).
- 41 Philipsson, J., Rege, J. E. O., Zonabend König, E. & Okeyo Mwai, A. Sustainable breeding programmes for tropical low-and medium input farming systems. (2011).
- 42 Mueller, J. Programas de mejoramiento genético de pequeños rumiantes. *CD: III Seminario Sobre Mejoramiento Genético Ovino: Desafíos, Oportunidades y Perspectivas*, 23-25 (2008).
- 43 Haile, A. *et al.* Community-based sheep breeding programs generated substantial genetic gains and socioeconomic benefits. *animal*, 1-9, doi:10.1017/S1751731120000269 (2020).
- 44 Mueller, J. P. *et al.* Community-based livestock breeding programmes: essentials and examples. *Journal of Animal Breeding and Genetics***132**, 155-168, doi:<https://doi.org/10.1111/jbg.12136> (2015).
- 45 ILRI. *African Dairy Genetics Gain Program*, <<https://www.ilri.org/research/projects/african-dairy-genetic-gains>> (2016).
- 46 Haile, A. *et al.* Community-based breeding programmes are a viable solution for Ethiopian small ruminant genetic improvement but require public and private investments. *Journal of Animal Breeding and Genetics***136**, 319-328 (2019).

- 47 Wall, E., Simm, G. & Moran, D. Developing breeding schemes to assist mitigation of greenhouse gas emissions. *Animal***4**, 366-376 (2010).
- 48 Amole, T. A., Zijlstra, M., Descheemaeker, K., Ayantunde, A. A. & Duncan, A. J. Assessment of lifetime performance of small ruminants under different feeding systems. *anima***11**, 881-889 (2017).
- 49 Suybeng, B., Charmley, E., Gardiner, C. P., Malau-Aduli, B. S. & Malau-Aduli, A. E. O. Methane emissions and the use of *desmanthus* in beef cattle production in Northern Australia. *Animals***9**, 542 (2019).
- 50 Benchaar, C., Pomar, C. & Chiquette, J. Evaluation of dietary strategies to reduce methane production in ruminants: a modelling approach. *Canadian Journal of Animal Science***81**, 563-574 (2001).
- 51 Calle, Z. *et al.* A strategy for scaling-up intensive silvopastoral systems in Colombia. *Journal of sustainable forestry***32**, 677-693 (2013).
- 52 Gordon, A. M., Thevathasan, N. V., Mosquera-Losada, M. R., McAdam, J. & Rigueiro-Rodriguez, A. How much carbon can be stored in Canadian agroecosystems using a silvopastoral approach. *Silvopastoralism and sustainable land management*. CABI Publishing, Wallingford, UK, 210-218 (2005).
- 53 Vandermeulen, S., Ramírez-Restrepo, C. A., Beckers, Y., Claessens, H. & Bindelle, J. Agroforestry for ruminants: a review of trees and shrubs as fodder in silvopastoral temperate and tropical production systems. *Animal Production Science***58**, 767-777 (2018).
- 54 Haque, M. N. Dietary manipulation: a sustainable way to mitigate methane emissions from ruminants. *Journal of Animal Science and Technology***60**, 15, doi:10.1186/s40781-018-0175-7 (2018).
- 55 Tomkins, N. W. *et al.* Growth performance improvements in pasture and feedlot systems. 16/321,070 (2019).
- 56 CCA. *The Canadian Cattlemen's Association - Feedlot Operation*, <<https://www.cattle.ca/cca-resources/animal-care/feedlot-operation/>> (2020).
- 57 Wagner, J. J., Archibeque, S. L. & Feuz, D. M. The modern feedlot for finishing cattle. *Annu. Rev. Anim. Biosci.***2**, 535-554 (2014).
- 58 FAO. *Shaping the future of livestock – sustainably, responsibly, efficiently. The 10th Global Forum for Food and Agriculture (GFFA)*. 18 (Food and Agriculture Organization of the United Nations (FAO), 2018).
- 59 Rao, P. P. & Hall, A. J. Importance of crop residues in crop–livestock systems in India and farmers' perceptions of fodder quality in coarse cereals. *Field Crops Research***84**, 189-198 (2003).

- 60 Amata, I. A. The use of non-conventional feed resources (NCFR) for livestock feeding in the tropics: a review. *Journal of Global Biosciences***3**, 604-613 (2014).
- 61 Mirzaei-Aghsaghali, A. & Maheri-Sis, N. Nutritive value of some agro-industrial by-products for ruminants-A review. *World J. Zool***3**, 40-46 (2008).
- 62 Yanti, Y. & Yayota, M. Agricultural by-products as feed for ruminants in tropical area: nutritive value and mitigating methane emission. *Reviews in Agricultural Science***5**, 65-76 (2017).
- 63 Mohd Azlan, P. *et al.* *Aspergillus terreus* treated rice straw suppresses methane production and enhances feed digestibility in goats. *Tropical Animal Health and Production***50**, 565-571, doi:10.1007/s11250-017-1470-x (2018).
- 64 Sharma, D. D., Rangnekar, D. V. & Singh, M. in *Feeding of ruminants on fibrous crop residues* (eds Kiran Singh & J.B. Schiere) 486 (Indian Council of Agricultural Research, 1993).
- 65 Beauchemin, K. A., McGinn, S. M., Benchaar, C. & Holtshausen, L. Crushed sunflower, flax, or canola seeds in lactating dairy cow diets: Effects on methane production, rumen fermentation, and milk production. *Journal of dairy science***92**, 2118-2127 (2009).
- 66 Beauchemin, K. A., Colombatto, D., Morgavi, D. P. & Yang, W. Z. Use of exogenous fibrolytic enzymes to improve feed utilisation by ruminants. *Journal of Animal Science***81**, E37-E47 (2003).
- 67 Jose, S. & Dollinger, J. Silvopasture: a sustainable livestock production system. *Agroforestry Systems***93**, 1-9, doi:10.1007/s10457-019-00366-8 (2019).
- 68 Pagiola, S. *et al.* Paying for the environmental services of silvopastoral practices in Nicaragua. *Ecological Economics***64**, 374-385, doi:<https://doi.org/10.1016/j.ecolecon.2007.04.014> (2007).
- 69 Cieslak, A., Szumacher-Strabel, M., Stochmal, A. & Oleszek, W. Plant components with specific activities against rumen methanogens. *Animal***7**, 253-265 (2013).
- 70 Jouany, J. P. & Morgavi, D. P. Use of 'natural' products as alternatives to antibiotic feed additives in ruminant production. *Animal***1**, 1443-1466 (2007).
- 71 Wina, E. in *Dietary Phytochemicals and Microbes* 311-350 (Springer, 2012).
- 72 Mueller-Harvey, I. Unravelling the conundrum of tannins in animal nutrition and health. *Journal of the Science of Food and Agriculture***86**, 2010-2037, doi:10.1002/jsfa.2577 (2006).
- 73 Jayanegara, A., Leiber, F. & Kreuzer, M. Meta-analysis of the relationship between dietary tannin level and methane formation in ruminants from in vivo and in vitro experiments. *Journal of Animal Physiology and Animal Nutrition***96**, 365-375, doi:10.1111/j.1439-0396.2011.01172.x (2012).

- 74 Beauchemin, K. A., Kreuzer, M., O'mara, F. & McAllister, T. A. Nutritional management for enteric methane abatement: a review. *Australian Journal of Experimental Agriculture***48**, 21-27 (2008).
- 75 Hutchings, M. R., Athanasiadou, S., Kyriazakis, I. & Gordon, I. J. Can animals use foraging behaviour to combat parasites? *Proceedings of the Nutrition Society***62**, 361-370 (2003).
- 76 Ramírez-Restrepo, C. A., Barry, T. N., López-Villalobos, N., Kemp, P. D. & McNabb, W. C. Use of *Lotus corniculatus* containing condensed tannins to increase lamb and wool production under commercial dryland farming conditions without the use of anthelmintics. *Animal Feed Science and Technology***117**, 85-105 (2004).
- 77 Chizmar, S. *et al.* A Discounted Cash Flow and Capital Budgeting Analysis of Silvopastoral Systems in the Amazonas Region of Peru. *Land***9**, 353 (2020).
- 78 Jara-Rojas, R., Russy, S., Roco, L., Fleming-Muñoz, D. & Engler, A. Factors Affecting the Adoption of Agroforestry Practices: Insights from Silvopastoral Systems of Colombia. *Forests***11**, 648 (2020).
- 79 Dagang, A. B. K. & Nair, P. K. R. Silvopastoral research and adoption in Central America: recent findings and recommendations for future directions. *Agroforestry systems***59**, 149-155 (2003).
- 80 Orefice, J., Smith, R. G., Carroll, J., Asbjornsen, H. & Howard, T. Forage productivity and profitability in newly-established open pasture, silvopasture, and thinned forest production systems. *Agroforestry Systems***93**, 51-65, doi:10.1007/s10457-016-0052-7 (2019).
- 81 Díaz-Pereira, E., Romero-Díaz, A. & de Vente, J. Sustainable grazing land management to protect ecosystem services. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-020-09931-4 (2020).
- 82 McAllister, T. A. *et al.* in *Animal Agriculture* (eds Fuller W. Bazer, G. Cliff Lamb, & Guoyao Wu) 75-98 (Academic Press, 2020).
- 83 Hao, H. *et al.* Benefits and risks of antimicrobial use in food-producing animals. *Frontiers in Microbiology***5**, 288 (2014).
- 84 Motoyama, M. *et al.* Residues of pharmaceutical products in recycled organic manure produced from sewage sludge and solid waste from livestock and relationship to their fermentation level. *Chemosphere***84**, 432-438, doi:<https://doi.org/10.1016/j.chemosphere.2011.03.048> (2011).
- 85 Aidara-Kane, A. *et al.* World Health Organization (WHO) guidelines on use of medically important antimicrobials in food-producing animals. *Antimicrobial Resistance & Infection Control***7**, 7, doi:10.1186/s13756-017-0294-9 (2018).
- 86 Wu, Z. Antibiotic use and antibiotic resistance in food-producing animals in China. (2019).

- 87 European, U. Regulation (EC) No. 1831/2003 of the European Parliament and of the Council of 22 September 2003 on additives for use in animal nutrition. *Off J Eur Union***50** (2003).
- 88 European, U. (2005).
- 89 Administration, U. F. a. D. *FDA Releases Five-Year Plan for Supporting Antimicrobial Stewardship in Veterinary Settings*, <<https://www.fda.gov/animal-veterinary/cvm-updates/fda-releases-five-year-plan-supporting-antimicrobial-stewardship-veterinary-settings>> (2018).
- 90 Sinha, K. in *Times of India* (New Delhi, 2011).
- 91 Thacker, T. in *The Indian Express* (New Delhi, 2011).
- 92 Welk-Joerger, N. Regulating Rumensin: defining antibiotic feeds in the US in the wake of resistance. (2020).
- 93 Administration, U. F. a. D. Summary report on antimicrobials sold or distributed for use in food-producing animals. Washington, DC: US Department of Health and Human Services. (2018).
- 94 EMEA. *Monensin summary report, EMEA/CVMP/185123/2007-Final. European Medicines Agency, Veterinary Medicines and Inspections, Committee for Medicinal Products for Veterinary Use*, <https://www.ema.europa.eu/en/documents/mrl-report/monensin-cattle-including-dairy-cows-summary-report-committee-veterinary-medicinal-products_en.pdf> (2007).
- 95 Williams, Y. J. *et al.* A vaccine against rumen methanogens can alter the composition of archaeal populations. *Appl. Environ. Microbiol.***75**, 1860-1866 (2009).
- 96 Zhang, L. *et al.* Immunisation against Rumen Methanogenesis by Vaccination with a New Recombinant Protein. *PloS one***10**, e0140086-e0140086, doi:10.1371/journal.pone.0140086 (2015).
- 97 Wedlock, D. N. *et al.* Development of a vaccine to mitigate greenhouse gas emissions in agriculture: vaccination of sheep with methanogen fractions induces antibodies that block methane production in vitro. *New Zealand Veterinary Journal***58**, 29-36 (2010).
- 98 Cook, S. R. *et al.* Avian (IgY) anti-methanogen antibodies for reducing ruminal methane production: in vitro assessment of their effects. *Australian Journal of Experimental Agriculture***48**, 260-264 (2008).
- 99 Wright, A. D. G. *et al.* Reducing methane emissions in sheep by immunisation against rumen methanogens. *Vaccine***22**, 3976-3985, doi:<https://doi.org/10.1016/j.vaccine.2004.03.053> (2004).
- 100 Leahy, S. C. *et al.* The genome sequence of the rumen methanogen *Methanobrevibacter ruminantium* reveals new possibilities for controlling ruminant methane emissions. *PloS one***5** (2010).

- 101 Henderson, G. *et al.* Rumen microbial community composition varies with diet and host, but a core microbiome is found across a wide geographical range. *Scientific Reports***5**, 14567, doi:10.1038/srep14567 (2015).
- 102 Shi, W. *et al.* Methane yield phenotypes linked to differential gene expression in the sheep rumen microbiome. *Genome research***24**, 1517-1525 (2014).
- 103 Wright, A.-D. G. & Klieve, A. V. Does the complexity of the rumen microbial ecology preclude methane mitigation? *Animal Feed Science and Technology***166-167**, 248-253, doi:<https://doi.org/10.1016/j.anifeedsci.2011.04.015> (2011).
- 104 Klopfenstein, T. J., Purser, D. B. & Tyznik, W. J. Effects of Defaunation on Feed Digestibility, Rumen Metabolism and Blood Metabolites. *Journal of Animal Science***25**, 765-773, doi:10.2527/jas1966.253765x (1966).
- 105 Whitelaw, F. G., Eadie, J. M., Bruce, L. A. & Shand, W. J. Methane formation in faunated and ciliate-free cattle and its relationship with rumen volatile fatty acid proportions. *British Journal of Nutrition***52**, 261-275 (1984).
- 106 Mosoni, P., Martin, C., Forano, E. & Morgavi, D. P. Long-term defaunation increases the abundance of cellulolytic ruminococci and methanogens but does not affect the bacterial and methanogen diversity in the rumen of sheep. *Journal of Animal Science***89**, 783-791, doi:10.2527/jas.2010-2947 (2011).
- 107 Newbold, C. J., de la Fuente, G., Belanche, A., Ramos-Morales, E. & McEwan, N. R. The Role of Ciliate Protozoa in the Rumen. *Frontiers in microbiology***6**, 1313-1313, doi:10.3389/fmicb.2015.01313 (2015).
- 108 Park, T., Mao, H. & Yu, Z. Inhibition of Rumen Protozoa by Specific Inhibitors of Lysozyme and Peptidases in vitro. *Frontiers in Microbiology***10**, 2822 (2019).
- 109 Jouany, J. P., Demeyer, D. I. & Grain, J. Effect of defaunating the rumen. *Animal Feed Science and Technology***21**, 229-265 (1988).
- 110 Eugène, M., Archimède, H. & Sauvant, D. Quantitative meta-analysis on the effects of defaunation of the rumen on growth, intake and digestion in ruminants. *Livestock 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) (2004).
- 111 Hristov, A. N., Ivan, M., Neill, L. & McAllister, T. A. Evaluation of several potential bioactive agents for reducing protozoal activity in vitro. *Animal Feed Science and 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).
- 112 Jeyanathan, J., Martin, C. & Morgavi, D. P. The use of direct-fed microbials for mitigation of ruminant methane emissions: a review. *Animal***8**, 250-261, doi:10.1017/S1751731113002085 (2014).

- 113 Reichardt, N. *et al.* Phylogenetic distribution of three pathways for propionate production within the human gut microbiota. *The ISME Journal***8**, 1323-1335, doi:[10.1038/ismej.2014.14](https://doi.org/10.1038/ismej.2014.14) (2014).
- 114 Janssen, P. H. Influence of hydrogen on rumen methane formation and fermentation balances through microbial growth kinetics and fermentation thermodynamics. *Animal Feed Science and Technology***160**, 1-22, doi:<https://doi.org/10.1016/j.anifeedsci.2010.07.002> (2010).
- 115 Jeyanathan, J. *et al.* Bacterial direct-fed microbials fail to reduce methane emissions in primiparous lactating dairy cows. *Journal of Animal Science and Biotechnology***10**, 41, doi:[10.1186/s40104-019-0342-9](https://doi.org/10.1186/s40104-019-0342-9) (2019).
- 116 Philippeau, C. *et al.* Effects of bacterial direct-fed microbials on ruminal characteristics, methane emission, and milk fatty acid composition in cows fed high- or low-starch diets. *Journal of Dairy Science***100**, 2637-2650, doi:<https://doi.org/10.3168/jds.2016-11663> (2017).
- 117 Doto, S. P., Liu, J. X. & Wang, J. K. Effect of yeast culture and its combination with direct-fed microbials on growth performance and rumen fermentation of weaned lambs. *Tanzania Journal of Agricultural Sciences***16** (2017).
- 118 Patra, A. K. & Saxena, J. Dietary phytochemicals as rumen modifiers: a review of the effects on microbial populations. *Antonie van Leeuwenhoek***96**, 363-375, doi:[10.1007/s10482-009-9364-1](https://doi.org/10.1007/s10482-009-9364-1) (2009).
- 119 Beauchemin, K. A., McGinn, S. M. & Petit, H. V. Methane abatement strategies for cattle: Lipid supplementation of diets. *Canadian Journal of Animal Science***87**, 431-440, doi:[10.4141/CJAS07011](https://doi.org/10.4141/CJAS07011) (2007).
- 120 Bodas, R. *et al.* Manipulation of rumen fermentation and methane production with plant secondary metabolites. *Animal Feed Science and Technology***176**, 78-93, doi:<https://doi.org/10.1016/j.anifeedsci.2012.07.010> (2012).
- 121 Hart, K. J., Yáñez-Ruiz, D. R., Duval, S. M., McEwan, N. R. & Newbold, C. J. Plant extracts to manipulate rumen fermentation. *Animal Feed Science and Technology***147**, 8-35, doi:<https://doi.org/10.1016/j.anifeedsci.2007.09.007> (2008).
- 122 Hook, S. E., Wright, A.-D. G. & McBride, B. W. Methanogens: Methane Producers of the Rumen and Mitigation Strategies. *Archaea***2010**, 945785, doi:[10.1155/2010/945785](https://doi.org/10.1155/2010/945785) (2010).
- 123 Machmüller, A. & Kreuzer, M. Methane suppression by coconut oil and associated effects on nutrient and energy balance in sheep. *Canadian Journal of Animal Science***79**, 65-72 (1999).
- 124 Grainger, C., Williams, R., Clarke, T., Wright, A. D. G. & Eckard, R. J. Supplementation with whole cottonseed causes long-term reduction of methane emissions from lactating dairy cows offered a forage and cereal grain diet. *Journal of Dairy Science***93**, 2612-2619, doi:<https://doi.org/10.3168/jds.2009-2888> (2010).

- 125 Abecia, L. *et al.* Effect of bromochloromethane on methane emission, rumen fermentation pattern, milk yield, and fatty acid profile in lactating dairy goats. *Journal of Dairy Science***95**, 2027-2036, doi:<https://doi.org/10.3168/jds.2011-4831> (2012).
- 126 Yang, C., Rooke, J. A., Cabeza, I. & Wallace, R. J. Nitrate and Inhibition of Ruminal Methanogenesis: Microbial Ecology, Obstacles, and Opportunities for Lowering Methane Emissions from Ruminant Livestock. *Frontiers in microbiology***7**, 132-132, doi:10.3389/fmicb.2016.00132 (2016).
- 127 Kristjansson, J. K., Schönheit, P. & Thauer, R. K. Different K_s values for hydrogen of methanogenic bacteria and sulfate reducing bacteria: an explanation for the apparent inhibition of methanogenesis by sulfate. *Archives of Microbiology***131**, 278-282 (1982).
- 128 Mitsumori, M. *et al.* Responses in digestion, rumen fermentation and microbial populations to inhibition of methane formation by a halogenated methane analogue. *British Journal of Nutrition***108**, 482-491, doi:10.1017/S0007114511005794 (2012).
- 129 Stadtman, T. C. Vitamin B₁₂. *Science***171**, 859-867 (1971).
- 130 Tomkins, N. W., Colegate, S. M. & Hunter, R. A. A bromochloromethane formulation reduces enteric methanogenesis in cattle fed grain-based diets. *Animal Production Science***49**, 1053-1058 (2009).
- 131 Dittmann, M. T. *et al.* Influence of ruminal methane on digesta retention and digestive physiology in non-lactating dairy cattle. *British Journal of Nutrition***116**, 763-773 (2016).
- 132 Goel, G., Makkar, H. P. S. & Becker, K. Inhibition of methanogens by bromochloromethane: effects on microbial communities and rumen fermentation using batch and continuous fermentations. *British journal of nutrition***101**, 1484-1492 (2009).
- 133 UNEP. *The Montreal Protocol on Substances that Deplete the Ozone Layer - Article 2I: Bromochloromethane*, <<https://ozone.unep.org/treaties/montreal-protocol/articles/article-2i-bromochloromethane>> (2020).
- 134 Stemmler, I., Hense, I. & Quack, B. Marine sources of bromoform in the global open ocean-global patterns and emissions. *Biogeosciences (BG)***12**, 1967-1981 (2015).
- 135 Manley, S. L. Phylogenesis of halomethanes: A product of selection or a metabolic accident? *Biogeochemistry***60**, 163-180, doi:10.1023/A:1019859922489 (2002).
- 136 IARC & WHO. *IARC monographs on the evaluation of carcinogenic risk to humans. Re-evaluation of some organic chemicals, hydrazine and hydrogen peroxide*. Vol. 71 (World Health Organization and International Agency for Research on Cancer, 1999).
- 137 ATSDR. *Bromoform and dibromochloromethane*, <<https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=712&tid=128>> (2005).

- 138 Bove, G. E., Rogerson, P. A. & Vena, J. E. Case control study of the geographic variability of exposure to disinfectant byproducts and risk for rectal cancer. *International Journal of Health Geographics***6**, 18, doi:10.1186/1476-072X-6-18 (2007).
- 139 Melnick, R. L. NTP Toxicology and carcinogenesis studies of tribromomethane (bromoform)(CAS No. 75-25-2) in F344/N rats and B6C3f1 mice (gavage studies). Technical report series. (National Toxicology Program, Research Triangle Park, NC (USA), 1989).
- 140 Machado, L. *et al.* Dose-response effects of *Asparagopsis taxiformis* and *Oedogonium* sp. on in vitro fermentation and methane production. *Journal of Applied Phycology***28**, 1443-1452 (2016).
- 141 Kinley, R. D. *et al.* Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed. *Journal of Cleaner Production***259**, 120836, doi:<https://doi.org/10.1016/j.jclepro.2020.120836> (2020).
- 142 Li, X. *et al.* *Asparagopsis taxiformis* decreases enteric methane production from sheep. *Animal Production Science***58**, 681-688 (2018).
- 143 Gribble, G. W. The natural production of organobromine compounds. *Environmental Science and Pollution Research***7**, 37-49 (2000).
- 144 Duarte, C. M., Wu, J., Xiao, X., Bruhn, A. & Krause-Jensen, D. Can seaweed farming play a role in climate change mitigation and adaptation? *Frontiers in Marine Science***4**, 100 (2017).
- 145 Bernoux, M. *et al.* EX-Ante Carbon-balance Tool (EX-ACT) Technical Guidelines for Version 7. *EASYPol - On-line resource materials for policy making***Module 218** (2016).

Table

Table 1 | Sum of projected cattle-related emissions from 2020 to 2050, following a business-as-usual (BAS) and mitigation scenarios (TgCO₂ equivalent). Percentages indicate emissions reduced by the strategy. %*shows the reduction of emissions excluding the 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)

Figures

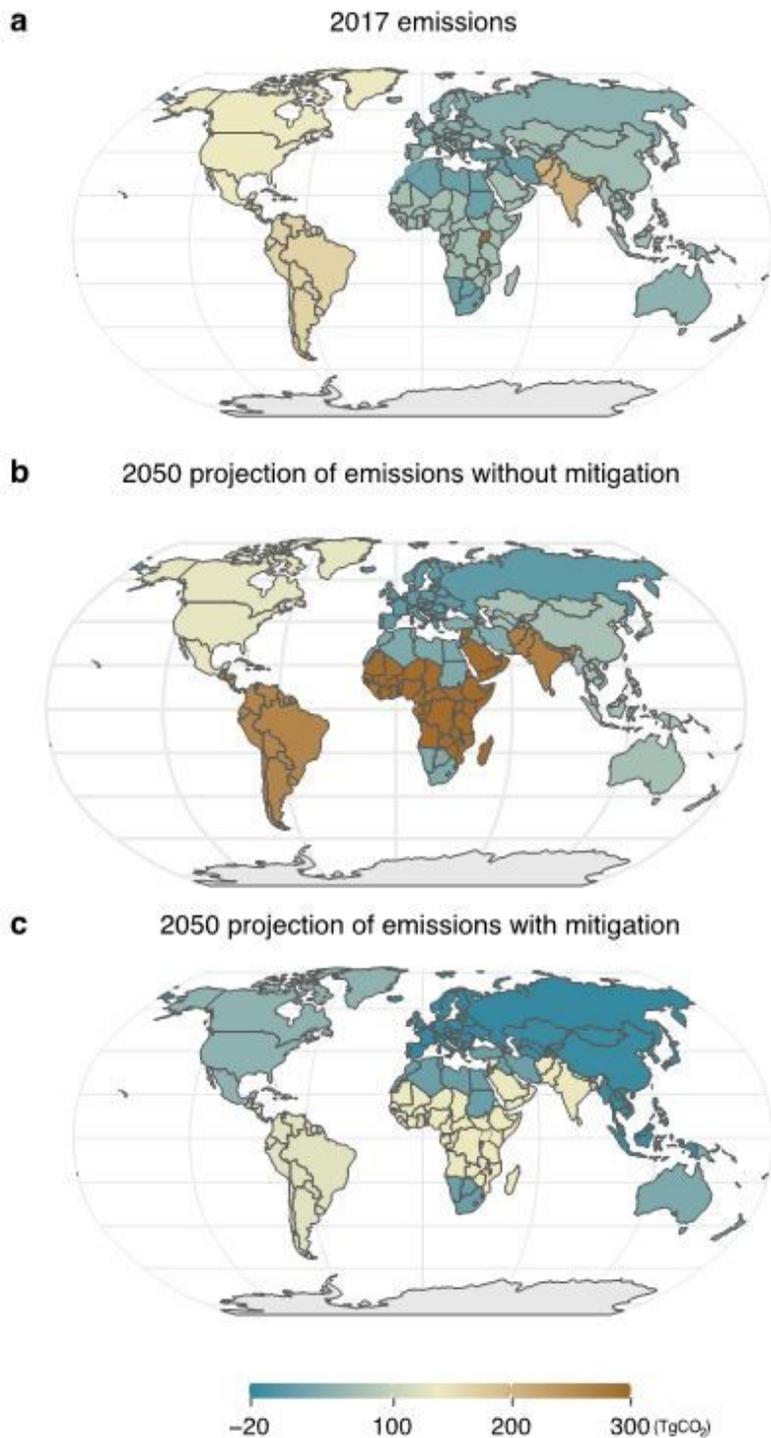


Figure 1

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.

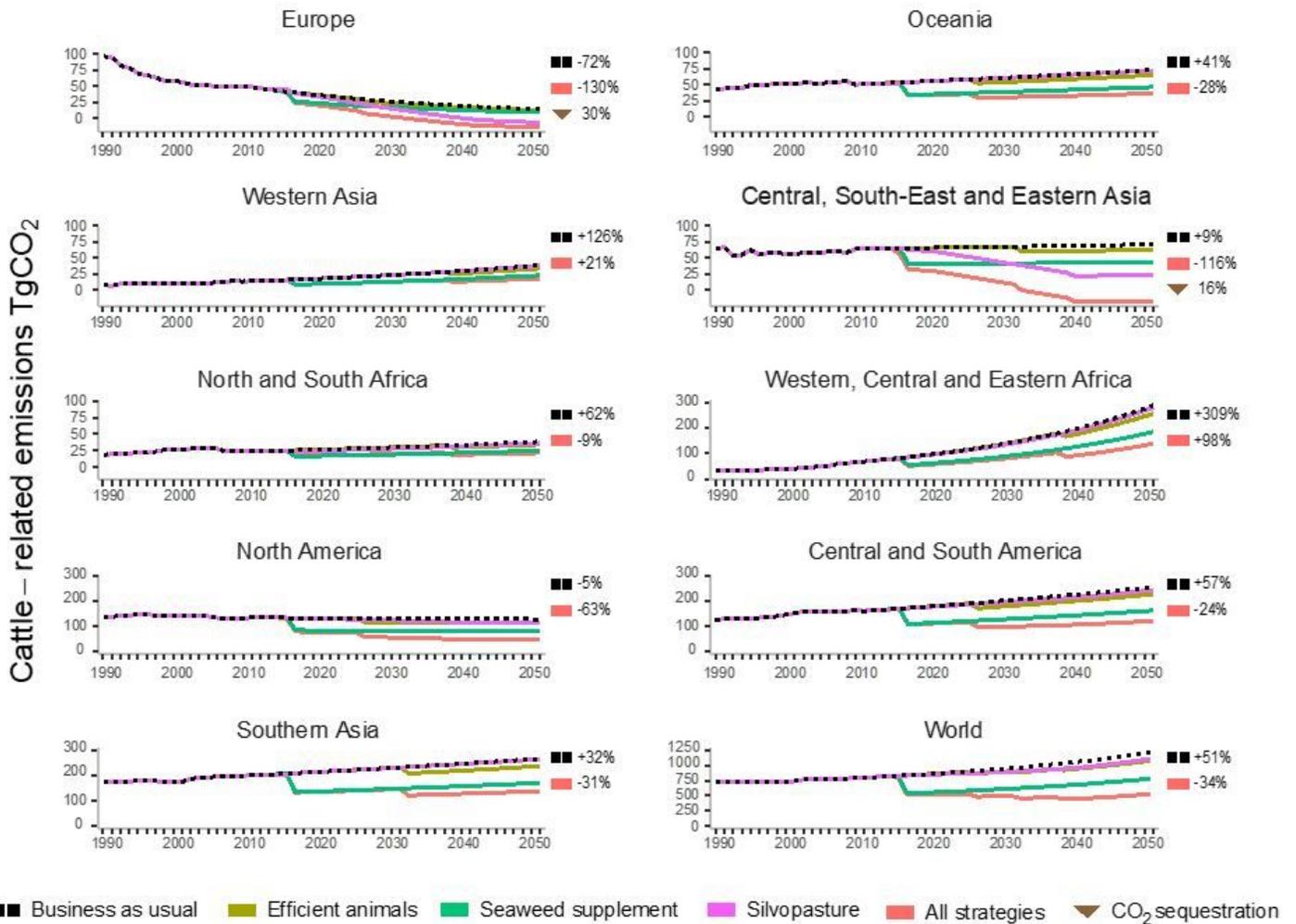


Figure 2

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.

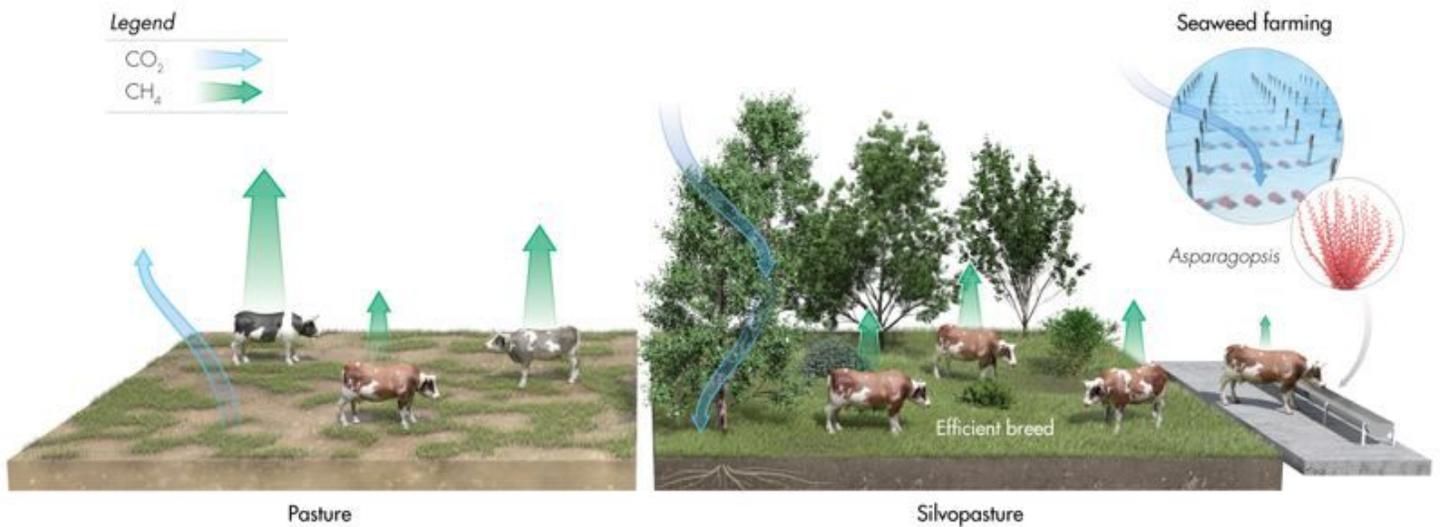


Figure 3

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.

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