Lowering the carbon footprint of food animals
The feed:microbiome:animal nexus and sustainability

Timmy: why do cows produce so much greenhouse gas? Is it possible to make them more environmentally friendly?

Photo by Elina Sazonova, courtesy of Pexels.com

Angela Schwarm[1], Live. H. Hagen[2], Sinéad Waters[3], Sharon A. Huws[4], Phillip B. Pope[1,2]

[1]Faculty of Biosciences, Norwegian University of Life Sciences, Norway
[2]Faculty of Biotechnology, Chemistry and Food Science, Norwegian University of Life Sciences, Norway
[3]Teagasc, Animal & Grassland Research and Innovation Centre, Ireland
[4]Institute for Global Food Security, School of Biological Sciences, Queen's University Belfast, UK

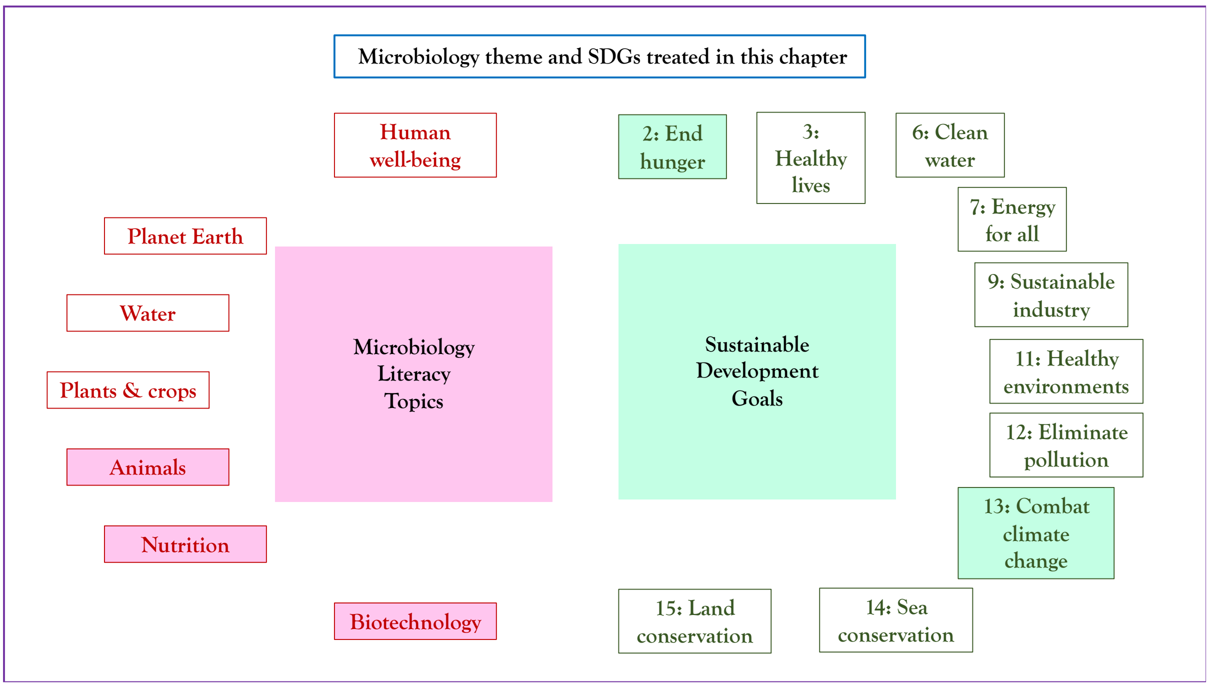
Lowering the carbon footprint of food animals

Storyline

In many parts of the world, eating meat, cheese, yoghurt or even ice cream is an everyday part of our life. The majority of these products actually come from domesticated cows, which are raised in farms all over the globe and collectively amount to approximately 1.5 billion animals[1]. While cow-based food products such as milk and meat are rich in protein and are commonly recommended as part of a balanced diet, producing them on a large scale causes many environmental problems. One of the biggest issues is that cows produce high levels of a greenhouse gas called methane when they digest their feed, which arises from the microbes in their specialized stomach otherwise known as a rumen. A further fascinating but complicated fact is that cows are totally dependant on their rumen microbes to break down the ingested feed and convert it into the energy that maintains their nutrition and health. Without commensal microbes, cows would die of starvation! Thus, if we are to reduce cows producing methane gas, which would make a huge difference in the sustainability of meat and dairy production, we must find a way that does it without negatively affecting the wellbeing of the animals themselves. Today, scientists are learning that there are many factors that can influence how a cow produces methane, ranging from the microbes in their rumen, the ingredients in the feed they eat, and who their parents were (i.e. their genetics). Furthermore, it seems likely that in order to solve this problem we need to study all three of these topics (feed:microbes:animal) at the same time!

The Microbiology and Societal Context

The microbiology: microbial digestion of feed; microbial conversion of plants to valuable nutrients for animal nutrition; symbiosis between gut microbiome and host animal; anti-methane feed ingredients; microbial greenhouse gas production. *Sustainability issues:* health; food and energy, economy and employment; environmental pollution; global warming.



Lowering the carbon footprint of food animals: the Microbiology

1. ***We need more food whilst using fewer resources.*** Our planet is filling up with people at a rapid pace. In fact, the human population is predicted to expand from approximately 7.8 billion today to nearly 10 billion over the next three decades. Such an increase in population means that we need to make more food, such as breads, grains, fresh fruits and vegetables as well as meat and dairy products. Scientists at the United Nations have previously calculated that to supply the world's predicted population in 2050, the amount of meat and dairy that is consumed today will have to increase by 76% and 63%, respectively (**Fig. 2**)[2]. This higher demand is expected to be largely driven by both population and prosperity growth in developing countries in Africa, Asia and the Americas (**Fig. 2**). However, resource constraints in many regions of the world, such as land and water, will restrict our ability to simply increase the number of farmed animals.

In addition to the availability of finite resources, we must consider the negative impacts that large industrial production of animals has on the environment, and the added consequences of simply increasing production of meat and dairy to meet population demands. One of the most publicized forms of pollution from the meat and dairy industry is its production of greenhouse gases, in particular methane. A greenhouse gas (GHG) absorbs and emits radiant energy and their accumulation in the earth's atmosphere warms the planet's surface. Methane as a greenhouse gas is 28 times more potent than carbon dioxide (CO_2), and it constitutes approximately 14% of the collective warming potential of the total atmospheric gases that are produced by human activity and contribute to climate change[3]. However, given the relative short lifetime of methane in the atmosphere (~12 years) compared to CO_2 (~30-95 years), faster impacts can be made to reduce man-made induced warming if we find strategies to limit its release into the atmosphere.

So how does a cow make methane? When a cow, sheep or goat eats grass or other plant material, the microbes in its stomach (rumen) digest the plant fibre into smaller molecules that can be used by the animal for energy[4]. This process also produces intermediate molecules that are of no nutritional benefit to the animal but are instead used by very specific group of microbes called methanogens, which convert them to methane gas[4]. The production of methane is a wasteful process for the animal, as methane cannot be used as energy source but instead is exhaled (via burping) results in a 10-12% energy loss.

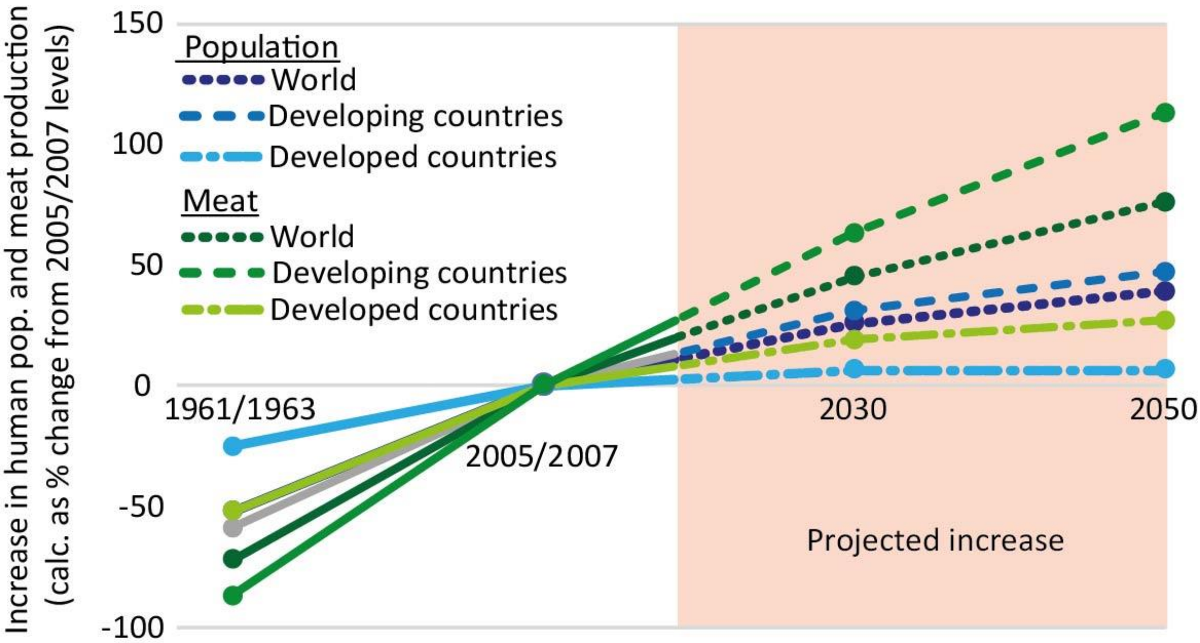


Figure 2. Estimate increases in population and agricultural production. In order to support the calorie intake for the projected ~10 billion people in 2050, it is estimated that annual world meat production would need to increase by some 76 percent from 2005/07 levels, consisting of a 113 percent increase in developing countries and a 27 percent increase in developed countries. Estimates are calculated as a percentage of records measured in 2005/2007[2]. Meat units were originally calculated as weight (tonnes).

2. ***In some parts of the world, animal husbandry or cattle ranching are of vital importance to society and/or nutrition.*** Currently in the western hemisphere, reducing our reliance on animal products and increasing the consumption of plant-based diets are increasingly being proposed as an alternative solution to both food insecurity and climate change. However, there are concerns that in many infertile or improvised regions of the world, removing farmed animals will be detrimental to the social welfare of farmers and the nutritional requirements of the general population[5]. Therefore, if we want to continue using animal products to sustain the global human population now and, in the future, we need to discover efficient and environmentally sustainable practices to ensure long-term expansion and security of the livestock agricultural sector.

It is widely accepted that the key to addressing this challenge is to optimize the intimate relationship between the environment (i.e. feed), the animal and their gut microbiota, the collection of microbes that play an integral role in digesting feedstuff into nutrients whilst producing greenhouse gases as a natural by-product **(Fig. 3)**[6]. However, although this topic has been on the political and scientific radar for decades, and despite the recent development of vital biotechnological tools, mitigation of GHG emissions by livestock still remains a challenge and is largely uncontrolled. Collectively this challenge addresses multiple microbiology literacy topics that focus on animals, nutrition and biotechnology, and relate to sustainable development goals (SDGs) 2 and 13: *end hunger*, and *climate change* **(Fig. 1)**.

3. ***Cows are able to digest grass because of the microbes in their gut.*** Important food animals such as cows, sheep and goats are similar in that they all have a rumen, a specialized compartment of their gastrointestinal system, specifically the largest of the four stomachs, that enables the animal to digest the grasses and grains they consume in their diet. Within the rumen,

there is a dense community of microbiota, which is collectively known as the **rumen microbiome** and amounts to approximately 500-1000 different populations of bacteria, archaea, protozoa, fungi and viruses. Together, the rumen microbiome cooperatively degrades complex plant fibers and polysaccharides in the animal's feed for their own energy needs. This connection between animal and microbiome is in fact a form of symbiosis as the rumen provides the microbiome ideal living conditions, such as a constant food supply and stable environmental condition (temperature, pH, etc.).

The degradative processes carried out by the rumen microbiome can be broken down into two key stages; hydrolysis and fermentation. Hydrolysis is the process of breaking different plant fibres (otherwise known as carbohydrates) into the building block sugar molecules that they are constituted from. Fermentation is the anaerobic (no oxygen) process of degrading organic nutrients such as sugar, to produce adenosine triphosphate (ATP), which essentially is the fuel that drives many different processes in living cells. Both hydrolysis and fermentation rely on fibrolytic microbes (**Fig. 3**) and in particular their enzymes which are the tools that actually perform these biological transformations. Fermentation also produces microbial "waste products", such as volatile fatty acids (VFAs), microbial proteins, and vitamins, which actually provide up to 70% of the nutrients that animals need for their own maintenance and growth. It also produces gases such as hydrogen (H_2) and carbon dioxide (CO_2). Excess levels of H_2 are actually detrimental to rumen fermentation, hence cows have co-evolved with methanogens, which are specialized H_2 consumers that convert H_2 and CO_2 to methane (CH_4), which is burped out by the animal (not farted!) in order to enable continued fermentation (**Fig. 3**). While it is the methanogens that produce methane, many different bacteria, fungi and protozoa ferment fibres and sugars into VFAs and H_2, meaning that tackling the methane problem requires scientists to consider not just methanogens but also the microbes that supply them with H_2 in the first place.

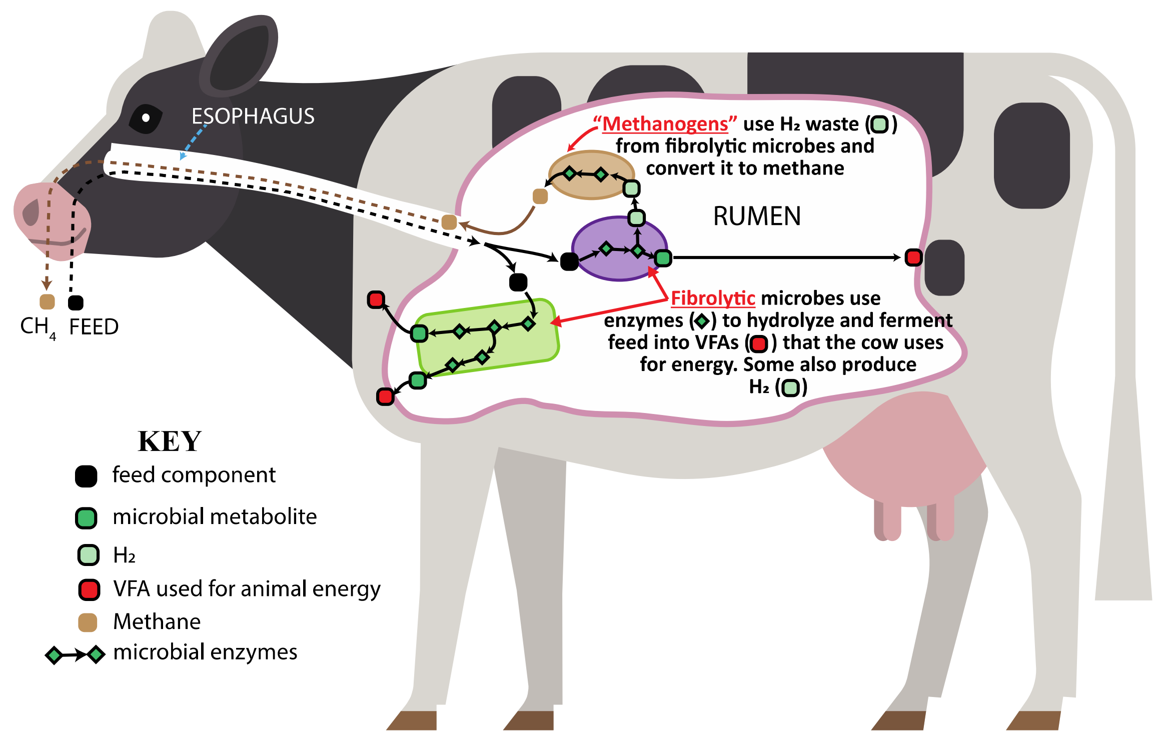


Figure 3. Summary of ruminant digestion performed by the rumen microbiome. In the rumen feed is converted by microbial enzymes into volatile fatty acids (VFAs) that the animal uses for

energy. These processes also produce hydrogen gas (H_2), which is converted to methane by methanogens and then emitted by the animal.

4. ***Anti-methanogenic feed ingredients: are there promising candidates?*** Alternative feed additives have long been used to interfere with microbial processes in the rumen, specifically with methane-producing methanogens[7]. Dietary supplementation to reduce enteric methane levels have included chemical compounds that bind ions (called ionophores), as well as natural products such as legumes, essential oils and fats. Chemical compounds produced from plants such as saponins (present in soapwort), tannins (present in leaves, buds, seeds and roots of many plants) have been used, as well as the supplementation of live bacteria into the diet (commonly referred to as probiotics)[7,8]. Unfortunately, many anti-methane treatments produce inconsistent results, are associated with high costs, are difficult to administer when animals are in the paddock eating grass, or actually decrease the conversion of feed into energy by the animal, which produces a measurable decline in animal productivity.

However, recently several new products have become available that show promise. Commercial supplements such as Bovaer[9], Agolin Ruminant[10] and Mootral[11] all claim to significantly reduce methane emissions from ruminants when added to their feed. New research has also shown that macroalgae can be used as an effective additive to livestock feeds with strong anti-methane potential. In particular, the bromoform-producing red algae such as *Asparagopsis taxiformis*, can substantially reduce methane emissions in the lab (in vitro) by greater than 80%, when less than 5% of algae is included in the feed[12,13]. Initial testing of the *Asparagopsis* genus with live cattle (in vivo) has shown that including 1% of algae in the animals diet can reduce methane emissions by up to 67%[14,15]. Whilst these results are encouraging, they are still preliminary and larger and long-term studies are needed to demonstrate the broader consequences related to animal production levels and wellbeing as well as large scale algae supply and cultivation.

5. ***The cow is a holistic system: rumen microbiome composition is associated with feed type, as well as the genetics of the host (animal).*** Over the years, scientists have shown that what the animal eats and the types of microbes in its gut can determine how fast it grows, how much milk it produces, how much methane it burps and how healthy it is. This two-way connection between diet and gut microbiome is actually very important in most mammalian herbivores (and us human omnivores); the type of food an animal eats has a big impact on what types of microbes live in its gut.

To make things even more complex, new research is revealing that it is not just the diet that shapes the gut microbiome of animals but that the parentage of the animal itself is also important. For example, scientists have discovered that there exist unique signatures in the human genome that are associated with certain microbes in the human gut. Moreover, possibly up to one-third of the microbes in the human gut are inherited from the mother. This microbiome heritability is not just limited to humans and has actually been shown to exist in ruminants such as cows and sheep[4,16,17]. This means that two groups of cows having different parents might be eating the exact same feed but, because of their family trees, they have different microbes in their gut, which digest their feed differently and hence affect how fast they grow or how much methane they burp.

6. ***The next step: bridging the feed-microbiome-host barrier.*** Animal production has traditionally been developed and improved by animal genetics and animal nutrition that target two "dimensions" of the animal, such as selecting a breed of an animal that is more resistant to

disease and more efficient to digest feed, OR a type, quality and proportion of feed ingredients that makes an animal grow faster or produce more or better milk. Now scientists have revealed a third dimension that has significant effects on the animal status – the microbiome, specifically their quantity (how many), quality (who is there), activity (what are they doing) and their interaction (synergism-antagonism). This means that while it is possible to use dietary strategies to affect the microbiome, such approaches may be further optimized by additionally accounting for the genetics of the cow ***and its*** gut microbiome.

It is now apparent to scientists that in order to optimize animal production further, they must first understand the higher dimensional cow "holobiont" (i.e. the cow and its microbes as one collective identity). To do this, scientists are proposing to study cows along the **feed-microbiome-animal** nexus. It is hoped that by doing this, they can produce more efficient and sustainable production of ruminants using a streamlined process that will: **(1) improve selection of animals whose genetics are responsible for inherent beneficial microbes, and (2) intelligently match diets with the types of microbes in their gut that are connected to the farmed breed type** (or vice versa). Given that the concept of the **feed-microbiome-animal** nexus is applicable to any animal system, it is envisaged that any new knowledge and approaches developed by scientists working with cows, sheep or goats will be transmissible to other important animals with microbial fermentation in agri- and aquaculture, such as pigs and fish, on a global scale.

Relevance for Sustainable Development Goals and Grand Challenges

Understanding the link between animals, their diet and their gut (rumen) microbiome relates to several SDGs (microbial aspects in italics), including

- **Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture** (end hunger and malnutrition, increase agricultural productivity). The UN urges society to ensure sustainable food production systems that are resilient and efficient and that help maintain ecosystems by 2030. Ruminant animals play a key role in global society as they convert plants that are indigestible by humans into edible meat and dairy products. Scientists hope that by better understanding how to influence animal production and wellbeing using the **feed-microbiome-animal** nexus we will be able to secure sustainable dairy and meat production that is accessible to the global population.
- **Goal 13. Take urgent action to combat climate change and its impacts** (reduce greenhouse gas emissions, mitigate consequences of global warming, develop early warning systems for global warming consequences, improve education about greenhouse gas production and global warming). Efficient fibre digestion is the niche of ruminants in human food production. In contrast, pigs compete with humans for the same feed resources, as they are both monogastrics. Ruminants such as cows, sheep and goats naturally produce methane gas as a result of the microbes that live in their gut and digest their (human-inedible) feedstuffs into absorbable nutrients and further into high-quality food for human consumption. Therefore, reducing enteric GHG emissions from ruminant animals whilst increasing the quantity and quality of productivity in order to meet the high-quality protein supply demands of an increasing global population is a critical challenge that faces the livestock industry. However, there is accumulating evidence that our understanding of the microbiome may soon improve to help agricultural industries to raise animals at large scale that are more efficient at utilizing their feed and also typically emit significantly less methane.

Potential Implications for Food Choice Decisions

1. ***Individual***
    a. Weighing up the various microbial and non-microbial factors and aligning them with personal convictions (do the health benefits or dietary preferences of consuming meat/dairy outweigh the general environmental considerations?)
    b. Proportion of animal to plant-based diets (climate footprint will be approximately proportional to food choices)?
    c. Reducing consumption of ruminant products (climate/environmental footprint will be approximately proportional to number)?
    d. Do I have the necessary dietary and nutritional information needed to substitute animal products?
    e. Do I have the necessary information concerning environmental impacts of the food I eat (both animal and plant based)?
    f. Non-microbial parameters: the vital role that conversion of indigestible plants to meat/dairy has in global regions without access to plant-based alternatives of equivalent nutritional benefit.

2. ***Community policies relating to animal production for food***
    a. Local environmental consequences of food choices.
    b. Costs associated with human health and nutrition.
    c. Non-microbial parameters: support of local businesses – farmers and associated agricultural industries.
    d. Education concerning the climate impact of foods (both animal and plant based)

3. ***National policies relating to animal production for food.***
    a. Healthcare economics of nutritional requirements and related diseases.
    b. Jobs associated with animal production.
    c. Environmental pollution from animal production (water and land).
    d. Greenhouse gas production and global warming.
    e. Consumer information about the climate impact of foods (both animal and plant based).
    f. Sequestration of agricultural land used for animal feed production that could otherwise be used for food production.

Pupil Participation

1. ***Class discussion of the issues associated with animal production***

2. ***Pupil stakeholder awareness***
    a. Animal production can have both positive and negative consequences for the SDGs. Which of these are most important to you personally/as a class?
    b. Can you think of anything that might be done to reduce the negative environmental consequences, especially in the food supply chain?
    c. Can you think of anything you might personally do to reduce the environmental footprint of your dietary choices?
    d. Do you know how much environmental impact your dietary choices have (both animal and plant based)?

3. ***Exercises** (could be made at any level, but these are probably secondary education level)*
   a. What is the environmental impact of your dietary choices? What information do you need to make this assessment? Where can you get this information from?
   b. In most western societies, many dietary options (both animal- and plant-based) of varying nutritional benefit are available to consumers. Is this the case in your country? What about developing nations?
   c. Animal food products (meat/dairy) are produced in large commercial facilities and by small stakeholders. What sustainable options are there for animal-based food products? How might you formulate a sustainable meat/dairy product and produce it for your city/town/region?
   d. Looking at the SDGs, how can we improve our food supply without having negative effects on the environment? What are the challenges and opportunities of A child-centric microbiology education framework? Create a sustainable national plan for food supply that covers nutritional requirements and their associated social, environmental and economic impacts.

The Evidence Base, Further Reading and Teaching Aids

1 Robinson, T. P. *et al.* Mapping the global distribution of livestock. *PLoS One* **9**, e96084 (2014).
2 Alexandratos, N. & Bruinsma, J. World Agriculture Towards 2030/2050: The 2012 Revision, FAO, Food and Agriculture Organization of the United Nations. (2012).
3 Gerber, P. J. *et al.* Tackling Climate Change Through Livestock – A Global Assessment of Emissions and Mitigation Opportunities. *Rome: Food and Agriculture Organization of the United Nations (FAO).* (2013).
4 Smith, P., Waters, S., Kenny, D. & Kelly, A. Rumen microbiome and methane emissions. *Tresearch* **14**, https://www.teagasc.ie/media/website/publications/2019/TResearch_Spring2019_RumenMicro_p20-21_proof.pdf (2019).
5 White, R. R. & Hall, M. B. Nutritional and greenhouse gas impacts of removing animals from US agriculture. *Proc. Natl Acad. Sci. USA* **114**, 10301-10308 (2017).
6 Huws, S. A. *et al.* Addressing Global Ruminant Agricultural Challenges Through Understanding the Rumen Microbiome: Past, Present, and Future. *Front. Microbiol.* **9**, 2161 (2018).
7 Patra, A. K. Enteric methane mitigation technologies for ruminant livestock: a synthesis of current research and future directions. *Environ. Monit. Assess.* **184**, 1929-1952 (2012).
8 Roque, B. M., Van Lingen, H. J., Vrancken, H. & Kebreab, E. Effect of Mootral-a garlic- and citrus-extract-based feed additive-on enteric methane emissions in feedlot cattle. *Transl. Anim. Sci.* **3**, 1383-1388 (2019).
9 DSM. (https://www.dsm.com/corporate/news/news-archive/2019/2019-09-30-dsm-takes-next-step-towards-implementation-of-its-methane-inhibitor-bovaer-in-the-netherlands.html).
10 Agolin. (https://www.agolin.ch/products/#ruminant).
11 Mootral. (https://www.mootral.com).
12 Kinley, R. D., de Nys, R., Vucko, M. J., Machado, L. & Tomkins, N. W. The red macroalgae Asparagopsis taxiformis is a potent natural antimethanogenic that reduces

methane production during in vitro fermentation with rumen fluid. *Anim. Prod. Sci.* **56**, 282-289 (2016).

13 Brooke, C. *et al.* Evaluation of the Potential of Two Common Pacific Coast Macroalgae for Mitigating Methane Emissions from Ruminants. *BioRxiv* **https://doi.org/10.1101/434480** (2018).

14 Kebreab, E. *https://ghginstitute.org/2018/07/18/seaweed-diet-for-burping-cows/#_ftn11* (2018).

15 Roque, B. M., Salwen, J. K., Kinley, R. & Kebreab, E. Inclusion of *Asparagopsis armata* in lactating dairy cows' diet reduces enteric methane emission by over 50 percent. *J. Clean. Prod.* **234**, 132-138 (2019).

16 Yirka, B. Researchers find a core cow microbiome dictates dairy cow productivity and emissions. *https://phys.org/news/2019-07-core-cow-microbiome-dictates-dairy.html* (2019).

17 Hansen, J. Methane from cow burps can be reduced by a two-front approach. *https://dca.au.dk/en/current-news/news/show/artikel/methan-fra-koboevser-kan-reduceres-via-to-fronter/* (2018).

Glossary

feed:microbiome:animal nexus: The biological connection between an animal, the food it eats and the microbes in its gut that converts it to nutrients.
fermentation: the extraction of energy from carbohydrates in the absence of oxygen, performed by microbes and their enzymes
fibre: dietary material usually derived from plants that are resistant to the action of digestive enzymes that are produced by the animal
fibrolytic bacteria: a group of microbes able to degrade complex plant fibres using enzymes
genetics: the study of genes, genetic variation and heredity in organisms.
holobiont: an animal and its microbes as one collective identity
hydrolysis: the chemical breakdown of a compound involving reaction with water
livestock: domesticated animals raised in agriculture to produce labor or products such as meat, eggs, milk, etc.
methane: a powerful greenhouse gas that is found naturally on earth and is produced by many geological and biological processes
methanogens: microbes that produce methane
rumen: the first stomach of a ruminant that partially digests feed by the actions of the rumen microbiome
ruminants: mammals that are able to acquire nutrients from plants by microbial fermentation that occurs within its specialized stomach
synergism: simultaneous activity of two or more biological entities (i.e. enzymes or organisms), resulting in a higher collective activity than the sum of the activities of the individual