Microbes of the Rumen

Farmer Jones: do you know why cows can eat grass and we can't?

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The Rumen

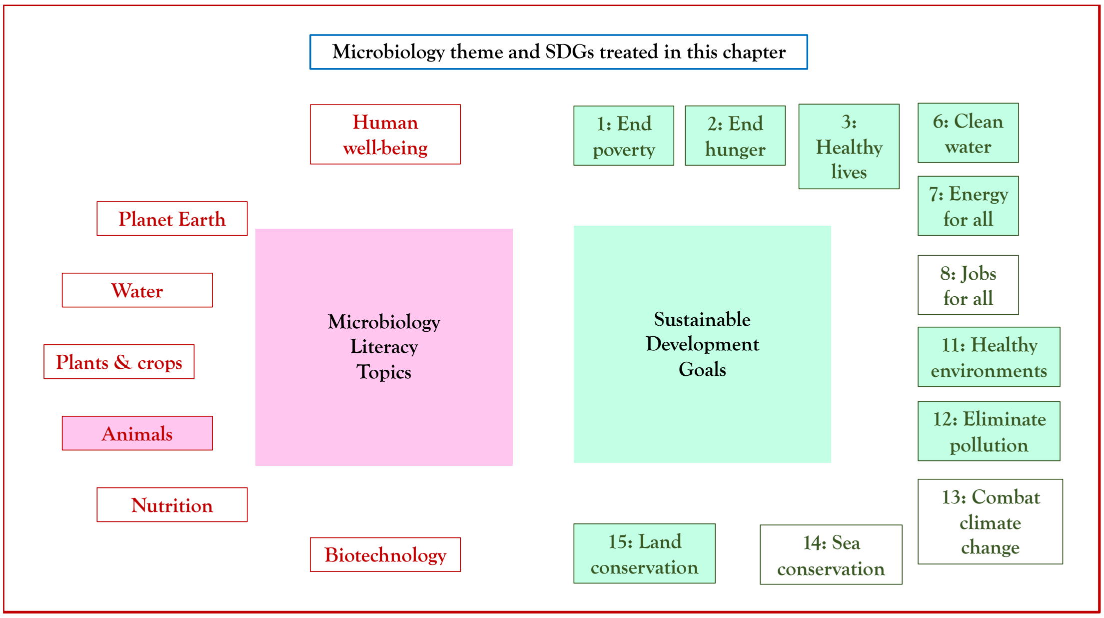
Storyline

Cattle, sheep, and goats belong to a class of herbivorous mammals that possess a gut structure that enables them to grow and produce milk while eating fibrous materials such as grass. The first stomach of these animals is a large sac called the reticulo-rumen, or rumen for short, and the animals are known as ruminants. Digestion in the rumen is carried out entirely by its resident microorganisms, which break down plant fibre to form volatile fatty acids (VFA). VFA are absorbed across the rumen wall, then transported in the blood to tissues and organs that use the VFA as a source of energy and to form glucose and protein, which support growth and milk production. The microorganisms pass down the digestive tract to be digested themselves, providing further nutrients to the host animal. Ruminants can therefore produce human-edible food from pastures and rough ground such as uplands. Indeed, ruminants produce, in meat and dairy products, the staple foodstuffs of many human societies worldwide. This benefit comes with a cost however. Ruminants have several environmental and health issues relating to Sustainable Development Goals. A natural end product of ruminal fermentation is methane. Methane is a potent greenhouse gas. Furthermore, ruminants produce a lot of urine and faeces rich in nitrogen. This can lead to pollution of the land and waterways. Ruminant meats and milk are highly nutritious, but there are concerns that overconsumption of these products by humans can lead to health problems.

The Microbiology and Societal Context

The microbiology: the ruminal microbiome; digestion of fibre in the rumen; formation of methane; nitrogen emissions; ruminal dysfunction; the ruminant gut and human infection; antimicrobial growth promoters.

Other societal context: ruminant products and human health/disease; global warming; land and groundwater pollution; ruminant-dependent societies; feeding the global human population; antibiotic resistance; water scarcity; biotechnology; fuel from animal wastes.



The Rumen: the Microbiology

1. ***The rumen contains huge numbers of diverse microorganisms.*** The rumen comprises up to 20% of the entire body weight of cattle and sheep. It is the first 'stomach', followed by the omasum, the abomasum, the small intestine and the large intestine. The biomass contained in the rumen is made up of ingested feedstuffs, such as grass, and a huge density and diverse array of microorganisms. The microbiome contains large microorganisms such as protozoa (also known as protists) and fungi, smaller ones like bacteria and archaea, and tiny viruses that infect the bacteria and probably also the other microorganisms. Together, they break down the large molecules that make up plant fibre – cellulose, hemicellulose and pectin mainly – to much smaller molecules, principally the volatile fatty acids (VFA). The VFA give the contents of the rumen a characteristic smell, a mixture of acetic, propionic and butyric acids as the main components. VFA are rapidly absorbed across the rumen wall to the bloodstream, where they are carried elsewhere in the body to be used for energy, sugar synthesis and protein synthesis. VFA are the main nutrients for growth and metabolism by the host animal. Abundant gas is produced, mainly CO_2 and methane (CH_4). Ruminants have evolved an anatomic mechanism to dispose of the gases via the mouth and to regurgitate the food for further chewing before swallowing it again. This helps break down the plant material physically, to expose greater surface areas to microbial attack. Fermenting the plant materials provides nutrients to the microorganisms, which grow very well even though oxygen is absent. Eventually, they flow through the omasum, where accompanying water is absorbed, then to the abomasum, which is a gastric stomach similar to the human one, except operating at a higher pH of 3 or 4. Digestion of the microorganisms in the abomasum provides further nutrients to the host.

2. ***Microorganisms in the rumen break down plant fibre.*** Pastures consist of plants such as grass which contain polymers that provide structural strength. Principal among these is cellulose, a polymer of glucose units joined by β-1,4 bonds. Starch, the main carbohydrate in bread and potatoes, is similarly a glucose polymer, but in starch the bonds are α-1,4 bonds. We and other mammals possess the enzymes necessary to break down the α-1,4 but not the β-1,4 bonds. Only microorganisms can break down the cellulose polymer. The microorganisms in the rumen do that on behalf of the host animal. It is perhaps surprising that it is only a small proportion of the total ruminal microbiota which are truly cellulolytic (cellulose digesters). The vast majority of the community are secondary digesters, further breaking down the products of the primary digesters to smaller products like the VFA. Digestion of plant fibre is a difficult process for even the best cellulolytic species, and they employ very complex enzyme systems to do so. Some protozoa (also known as protists) are cellulolytic, as are a few very important bacteria, and all anaerobic fungi appear to be cellulolytic. The fungi have extraordinarily active cellulolytic systems that could be exploited for use in biofuel production.

3. ***Methane is a natural consequence of anaerobic microbial activity.*** Because there is no oxygen in the rumen, bacteria, protozoa and fungi produce hydrogen and carbon dioxide rather than water and carbon dioxide as we do by respiration. Methane is formed in abundant quantities from the hydrogen and some of the carbon dioxide – up to 500 L per day in dairy

cows – by the rumen microbial community. It is the most ancient, in evolutionary terms, of microbes that carry out methanogenesis, namely the archaea. While methanogenesis is a metabolically elegant means of disposing of reducing equivalents where oxygen is not available, the methane produced by ruminants presents global environmental issues. It is a greenhouse gas (GHG), 28 times as potent as carbon dioxide, and the impact of methane emissions from ruminants has significant implications for climate change. As a rough indicator, ruminants have about the same impact on global warming as the airline industry. One cow emits the same GHG equivalents as a car's carbon dioxide emissions. Researchers are working on ways to lower ruminal methane emissions by dietary and genetic means. It seems from recent results that methane emissions can be predicted from the composition of the ruminal microbiome, which in turned depends on the genetics of the host animal. It may be possible, therefore, to undertake a breeding programme, guided by the ruminal microbiome composition, to generate ruminants that produce much less methane.

4. ***Nitrogen-rich urinary and faecal emissions.*** Because the rumen evolved to enable animals to accommodate and benefit from the slow process of fibre breakdown, this means that other components of ingested plant materials are exposed to microbial attack for longer than would be ideal. Protein is broken down many times more quickly than cellulose. The N of dietary protein is thus utilised wastefully, and much is excreted, mainly in urine. Nitrogen-rich excreta can result in polluted waterways and the production of nitrous oxide, a GHG about 10 times as potent as methane. Some research results have helped to mitigate the problem, but N emissions from cattle in particular remain a difficult environmental issue for ruminant livestock production.

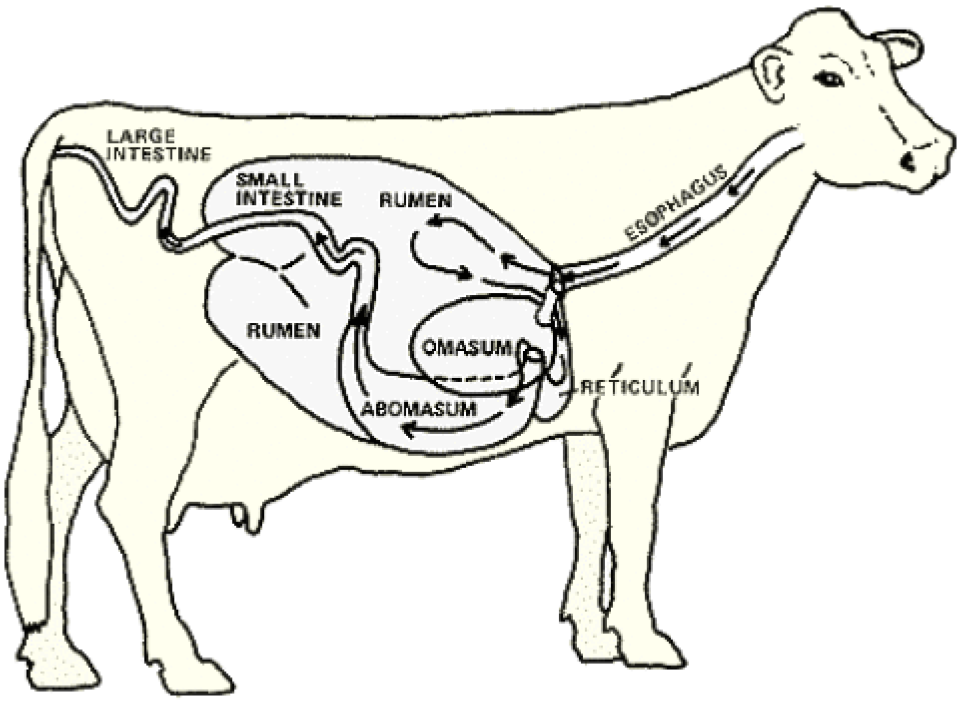


Fig. 1: The digestive tract of the adult cow

5. ***When the ruminal microbiome goes wrong.*** Ruminants sometimes suffer severe, life-threatening conditions that do not afflict other animals. One is ruminal acidosis, another,

bloat. Both occur as a result of the ruminal microbiome becoming abnormal and therefore dysfunctional. The acidity of the rumen is only loosely controlled, the acidity of the VFA normally being neutralised by buffering compounds in saliva. If acid production overwhelms salivary neutralisation, caused usually by overconsumption of readily digested feedstuffs, the pH falls. The majority of ruminal microorganisms are unable to grow at the lower pH. The ones that do grow produce lactic acid rather than VFA. As lactic acid is a stronger acid than VFA, the pH continues to fall, until only a handful of microbial species, which produce even more lactic acid, can survive. The low pH of the rumen causes systemic acidosis, often resulting in death. Bloat occurs when a stable foam forms in the rumen. The foam-stabilising material can come from the feed or sometimes from the microorganisms themselves. The gases resulting from microbial activity are unable to escape, pressure increases to levels that lead to the animal's death. Thus, the stability of the ruminal microbiome is relatively fragile and its disruption can be extremely serious for the health of the host animal.

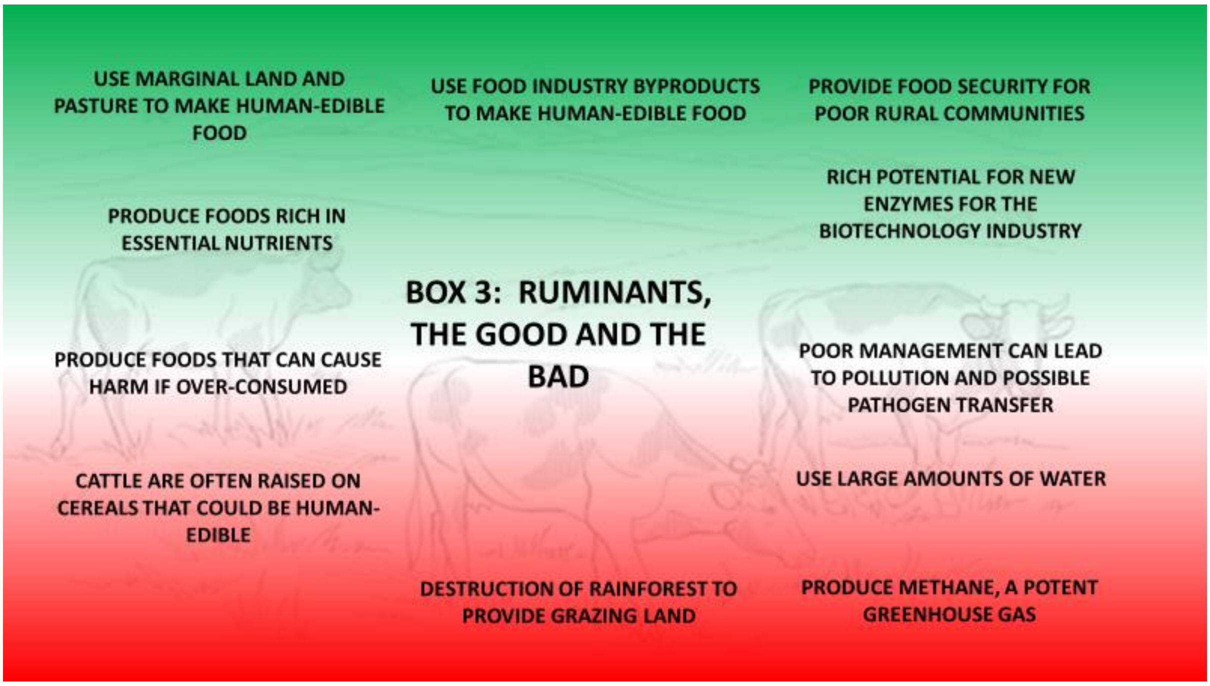
Some numbers concerning the rumen and ruminants

- There are about 10^{16} bacteria, 10^{14} archaea, 10^{11} protozoa and 10^{10} fungi in one cow rumen
- Estimates of diversity vary, but in terms of genera there are 100-300 bacteria, 5-10 archaea, 12-25 protozoa and 10-18 fungi
- The rumen of a dairy cow produces up to 5 kg of VFA and 0.4 kg of methane per day
- There are 3.5 billion ruminants on earth, of which 1 billion are cattle

6. ***How do other herbivorous animals manage?*** Many animal species other than ruminants consume diets rich in plant fibre. They employ a range of strategies to do so. The giant panda is an extreme example. It subsists entirely on a diet of poorly digestible bamboo. Perhaps one might imagine that giant panda might therefore have some highly efficient gut microorganisms to cope with this challenge, but in fact the opposite is true. The panda relies on a high throughput/low digestion strategy, whereby almost no cellulose digestion occurs and the animal only absorbs the small amount of soluble, digestible content of the bamboo. Horses consume roughly the same sorts of plant materials as ruminants, but instead of a rumen the horse has a hugely developed caecum at the beginning of the large intestine. The microorganisms that reside in the horse caecum are not the same as those we find in the rumen, but they are related and are similar in function. Crucially, the microbes formed as a result of caecal fermentation cannot be digested and their biomass used for nutrients as in ruminants, but those nutrients are lost in faeces.

7. ***Zoonotic diseases.*** The rumen effectively protects ruminant animals from digestive upsets that are common in other animals, because pathogenic bacteria are out-competed by the huge numbers of indigenous microorganisms. Nevertheless, cattle in particular can carry pathogenic bacteria which, although they do not cause disease in the host, can cause serious infections when transmitted to man, either by contact with faeces or by ingestion in products such as cheese. *Salmonella* and *Escherichia coli* O157:H7 are two of the most common agents of foodborne illness in humans. Both have been isolated from beef and dairy cattle through all stages of production, and both cause diarrhoea in humans, with *E. coli* O157:H7 often causing other serious problems as well. Shedding of the pathogens in faeces seems to be intermittent and can be difficult to detect. Ruminants are natural reservoirs for these bacteria and typically appear non-symptomatic while shedding these bacteria into the environment. *Escherichia coli* O157:H7 passes through the rumen and colonises the rectum of cattle. *Listeria monocytogenes* is not strictly speaking a zoonotic disease arising from cattle and sheep, as they can also become unwell from listeriosis, but it is thought that many animals carry *L. monocytogenes* asymptomatically. The pathogen will be excreted in faeces and can then be passed on to man, in whom severe, often fatal, disease occurs. *Listeria* infection is usually associated with the consumption of unpasteurised cheese, but it can be passed on via other foodstuffs as well.

8. ***Growth promoters and antibiotic resistance.*** Antibiotic resistance in human pathogens is one of the greatest health threats facing mankind. Even minor bacterial infections could result in severe disease if the antibiotics we now use no longer work. Ruminants are considered to be a major possible reservoir for antibiotic-resistant bacteria and genes. Antimicrobial compounds are used in ruminant production for two main purposes, therapeutically to kill infections and productively to enhance the efficiency of conversion of feeds to meat and milk. There is no doubt that worryingly large amounts of antibiotics are prescribed to treat disease in cattle mainly. The implications of these practices are dealt with elsewhere (xxx). Growth-promoting antimicrobials must be viewed in a completely different light, however. Although widely used, particularly in North America, compounds like monensin (an ionophore) have a completely different mechanism of action to the therapeutic antibiotics, and they do not lead to any form of transmissible antibiotic resistance. Instead they make the rumen microorganisms more productive in providing nutrients for the host animal, and at the same time lower methane emissions. Many nations, including those of the EU, have bowed to perceived consumer pressure and chosen to ban the use of growth-promoting antimicrobials without exception. There is a discussion to be had as to whether ionophores for ruminants could actually be considered as beneficial to the environment – they leave no residue, they lower the use of resources for livestock production, and they decrease the amount of greenhouse gases produced.



Relevance to Sustainable Development Goals and Grand Challenges

Ruminant livestock production impinges on many of the SDGs, both in positive and negative ways, including

- **Goal 1. End poverty in all its forms everywhere.** The ability that rumen microorganisms confer to cattle, sheep and goats in being able to eat materials that do not compete with human-edible food is a valuable resource in preventing poverty and hunger in many rural societies. Cattle hold a particularly central place in the socioecology of many of the poorest people on the planet. As well as being a source of food, cattle provide faecal material that, when dried in the sun, is used to make cooking fires and building materials, cattle are a tangible wealth resource.
- **Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture.** Many areas of the planet, such as permanent grasslands, would become uninhabitable without the food security that ruminant livestock bring. Meat and milk are highly nutritious, certainly in comparison with the plant foods available in the same environment. A more worrying trend is that many cattle are fed cereals like corn and barley which could be human-edible.
- **Goal 3. Ensure healthy lives and promote well-being for all at all ages.** Two opposing effectors come into play here. Ruminant-derived foods are rich in minerals, vitamins and protein; they also contain health-promoting conjugated linoleic acid (CLA), which is not found in other foodstuffs. These health-positive properties have to be offset against well documented damaging effects of red meat and dairy consumption however. Although the latter are largely problems associated with overconsumption, they cannot be ignored in the overall health context. Then as well we must consider human infections that originate from ruminant livestock. *Salmonella*, *E. coli* O157:H7 and *L. monocytogenes* have been mentioned, but others include cryptosporidiosis, giardiasis, leptospirosis and ringworm.

- **Goal 6. Ensure availability and sustainable management of water and sanitation for all.** Ruminant excreta frequently cause disposal problems, and all too frequently lead to contamination of waterways. While more careful management can minimise these problems, the demand of cattle for large amounts of water drains resource from the human population. These problems together mean that cattle production has a highly negative impact on water resources for mankind.
- **Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all.** If cattle wastes can be harvested and processed in an anaerobic digester, on-farm energy use can become more self-contained and sustainable. Ironically, anaerobic digesters produce methane too, and it is the methane that fuels electricity generation. Anaerobic digesters also lower the problems associated with getting rid of animal wastes. The implications for future biofuel consumption are much bigger, however. The enzymes that are so valuable in enabling ruminal microorganisms to digest plant fibre potentially also have a huge role in biofuel production.
- **Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable.** The proximity of ruminants to human settlements is primarily a rural issue, with safety predominantly being reflected in health issues, see Goal 3, above.
- **Goal 13. Take urgent action to combat climate change and its impacts.** There are no positives that can be taken from ruminant livestock production in relation to climate change. Methane emissions from rumen fermentation contribute a small but significant amount to greenhouse gas production, and nitrous oxide release from excreta is also problematic, given the potency of nitrous oxide as a greenhouse gas. The latter can be minimised by good waste management, but the former remains a difficult issue. There are signs that new feed additives or breeding strategies can lower methane emissions, but it is unlikely that they will eliminate the emissions. The other major impact of ruminant livestock production is the clearing of rainforests, particularly in the Amazon basin, to provide grazing land for cattle. Rainforests are vital for the health of the planet, absorbing carbon dioxide and producing oxygen. Only political and economic levers can halt this tragedy.
- **Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.** Once again, there is a conflict between food production and environmental health. Ruminants, usually sheep and goats but also wild ruminants like deer, remain the only means of harvesting human-edible food from some landscapes. Cattle also convert grassland to human-edible food. Many of these landscapes could, however, alternatively support forestry, either by planned plantations or by allowing native forests to return. There are 400,000 red deer in Scotland. The deer eat saplings that would otherwise allow native forest to regenerate.

Potential Implications for Decisions

1. ***Individual***

a. Deciding to eat less red meat and dairy products, or to become vegetarian or vegan. Some health benefits might ensue, if careful attention is paid to nutritional requirements. Environmental benefit is more compelling.

b. Should we encourage others to follow the vegetarian/vegan route?

2. ***Community policies***

a. Local environmental consequences of ruminant livestock production – waste disposal, safety, smell.

b. Farming as a community service, providing fresh, nutritious food to local communities.

3. ***National policies relating to ruminants***

a. Should there be a carbon (greenhouse gas) tax on ruminant livestock production? Or would incentivisation of farmers to change livestock management to lower emissions work better?

b. Possible levying of an environment tax for consumers buying red meat and milk.

c. Improved information transfer from research to farmers regarding animal and feeding management to lower greenhouse gas emissions.

d. Supporting farmers to improve waste management in order to lower emissions.

e. Investment in scientific research to understand rumen methane emissions better and to find ways of mitigating those emissions.

f. Review the environmental benefits of growth-promoting antimicrobial feed additives.

g. Control wild deer populations.

Pupil Participation

1. *Class discussion*

a. How many ruminant-derived food products can you name?

b. How many ruminant-derived non-food products can you name?

c. What ruminant-derived foods have you eaten in the last two days?

d. Could you eat less meat?

e. Would you like to be vegetarian?

f. Would you like to be vegan? What's the difference?

2. *Pupil stakeholder awareness*

a. How will climate change affect your life?

b. How will climate change affect people in Bangladesh?

c. How will climate change affect people in sub-Saharan Africa?

d. How could we help farmers?

e. If we could only eat foods produced within 10 km of our home, what would they be? What would you miss most?

3. *Exercises*

a. Methane is 28 times as potent a greenhouse gas as carbon dioxide. Is a cow or a car more damaging to the atmosphere? (A cow produces 500 L of methane per day, a car might travel 15,000 km in a year, emitting 120 g of CO_2 per km).

b. What options are there for making cattle produce less methane?

c. Which of man's activities produces most methane?
d. Which of man's activities produce most greenhouse gas?

The Evidence Base, Further Reading and Teaching Aids

Bach SJ, McAllister TA, Veira DM et al (2002).Transmission and control of *Escherichia coli* O157:H7 – a review. Can J Anim Sci 82:475–490.
Henderson, G., F. Cox, S. Ganesh, A. Jonker, W. Young, and P. H. Janssen. 2015. Rumen microbial community composition varies with diet and host, but a core microbiome is found across a wide geographical range. Sci. Rep. 5:14567.
R.E. Hungate (1966). The rumen and its microbes. Academic Press, New York.
A.K. Puniya et al. (eds.) (2015), Rumen Microbiology:From Evolution to Revolution, DOI 10.1007/978-81-322-2401-3_1.
Seshadri, R., Leahy, S., Attwood, G. et al. Cultivation and sequencing of rumen microbiome members from the Hungate1000 Collection. Nat Biotechnol 36, 359–367 (2018). https://doi.org/10.1038/nbt.4110
H. Steinfeld, P. Gerber, T. Wassenaar, V. Caste, M. Rosales, C. de Haan C, 'Livestock's Long Shadow.' (FAO, Rome, 2006).
Tapio, I., T. J. Snelling, et al. 2017. The ruminal microbiome associated with methane emissions from ruminant livestock. J Anim Sci. Biotechnol. 8:7.
Wallace, R. J., G. Sasson, et al. 2019. A heritable subset of the core rumen microbiome dictates dairy cow productivity and emissions. Sci. Adv. 5:eaav8391.

Fig. 1 is reproduced from the University of Minnesota Extension Program at https://extension.umn.edu/dairy-nutrition/ruminant-digestive-system.