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Building Block

Methane and the sustainability of ruminant livestock

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Contents

Why should you read this building block?

The environmental sustainability of our food production methods, and what kinds of agricultural systems might be compatible with keeping global warming below internationally agreed upon limits, are key topics for sustainable food systems research and policy.

Since the food system is an important emitter of three different greenhouse gases; carbon dioxide, methane and nitrous oxide; greater clarity as to their warming impacts and their consequent contribution to climate change is needed.

Introduction

The climate impacts of different greenhouse gas emissions are often expressed using shorthand emission metrics. However, because these metrics reduce the full physical complexities of different emissions to a simple comparison, they can sometimes fail to represent certain dynamics, and there can be considerable variation in how we report and think about different gases relative to each other using different metric concepts. These issues can in turn cause confusion and lend themselves to misinterpretations.

These observations are particularly true in the case of methane, the valuation of which differs significantly according to the metric used. Recently, this has become a notable topic in discussions over food system sustainability, since agriculture is a major source of human-generated methane emissions. How to think about methane features especially prominently in debates about whether ***ruminant*** production can be sustainable, and if so, what types of system should be preferred.

In this piece, we introduce the fundamental climate science, highlight some policy and practical considerations relating to different ways of thinking about emissions, and finally situate the discussion within the context of wider concerns about livestock production and sustainability. We cover these topics in the following sections:

1. Climate change: models, metrics and reality
2. The challenges in comparing different greenhouse gas emissions
3. The fundamental difference between GWP100 and GWP*
4. Carbon dioxide, methane, and stabilising global temperature
5. Food system methane emissions and climatic sustainability
6. Current and projected trends in ruminant methane
7. Ruminants and sustainability - the bigger picture

1. Climate change: models, metrics and reality

Our understanding of climate change is driven by Earth system science and observation, which essentially tracks the results of our uncontrolled multi-century experiment in increasing greenhouse gas concentrations in the atmosphere. Scientists have developed computer simulation models that try to capture the dynamics of how the Earth responds to greenhouse gases, and can be used to make predictions based on projections of future greenhouse gas emissions.

These models are of varying levels of complexity, from complete Earth system simulations requiring several days' worth of supercomputer power to run a single scenario; to reduced complexity versions that just capture the key dynamics highlighted by the full models. But as not everyone is familiar with climate models and their use, and for many purposes the full complexities are not always relevant or straightforward to incorporate, we also have even simpler ways of capturing potential effects of emissions of diverse ***GHGs*** on the climate using *emission metrics*.

GHG emission metrics are reporting measures that can be used to express, typically as a single number, a simplified representation of these more complex impacts on the global climate. To inform climate policy it was deemed useful to have a simple metric that can directly relate emissions of different gases to each other. This would result in a universal 'currency' of greenhouse gas emissions that could be used to help policy makers design emission reduction strategies and report progress across multiple GHGs.

A way to achieve this was presented in the first ***IPCC*** Assessment Report[1] with the ***Global Warming Potential*** (GWP). The GWP scales emissions of different gases according to the total amount that a one-off emission 'pulse' of a given gas changes the atmospheric energy balance ('***radiative forcing***' – which leads to global warming) over a specified time-horizon following the emission. As the main cause of anthropogenic global warming, CO_2 was set as the baseline against which other emissions are compared, and so the GWP '***carbon-dioxide equivalent***' (CO_2-e) became the basic currency for most GHG emissions. If CO_2 is assigned a value of 1, then all the other GHGs are assigned a number in relation to that 1.

While the GWP, and specifically, the 100-year variant (GWP100), has subsequently become the *de facto* 'standard' metric for reporting and comparing the impacts of different GHG emissions, some climate scientists have continued to highlight its limitations and have discussed alternative or complementary approaches to better capture the impacts different GHGs have on the climate[2,3]. The IPCC have consistently acknowledged the limitations of emission metrics, including the following summary in the most recent synthesis report: *"The choice of emission metric and time horizon depends on type of application and policy context; hence, no single metric is optimal for all policy goals. All metrics have shortcomings, and choices contain value judgments"*[4]. Recently, concerns over what the GWP100 can or cannot tell us have been raised in the context of agricultural sustainability, and whether we might need to rethink some assumptions about the climate impacts of agriculture, and especially of ruminant livestock[i].

We should note here that concepts of 'equivalent emissions,' while derived from physical climate science, are not generally used in physical climate science itself. The climate models mentioned above which are used to study and predict climate change are based either on emissions of individual gases with individual, distinct properties, or changes to total radiative forcing inferred from emission pathways.

This is important to keep in mind through the following discussion, as aspects of the debate suggest that some stakeholders conflate emission metrics with climate science. Some may mistakenly believe that new metrics completely overturn our understanding of atmospheric physics. They do not. Any confusion or disagreement over the role of different gases relates to how they are communicated and the implications for policy – the topic does not represent contention or uncertainty in the physical science of climate change or over the impacts of individual gases like methane.

[i] For this piece, we focus on ruminant livestock, as debates over the framing of methane have been especially prominent here, and we also seek to address a number of wider environmental sustainability concerns linked with ruminant production. The climate principles discussed below apply to any biogenic source of methane, however, and for food system sustainability could also be considered in the context of rice production and consumption, given that it is also a large contributor to anthropogenic methane emissions.

2. The challenges in comparing different greenhouse gas emissions

Because the conventional metrics (e.g. GWP) are based on 'equivalent' individual emissions – a direct scaling of different gases relative to CO_2 – some may assume that this is exactly how the emissions affect the temperature: that, for example, methane is the same as CO_2 except 28 times stronger (28 being the default 100-year global warming potential for methane from the IPCC 5th Assessment Report[5]). But methane does not contribute to climate change in a directly analogous way to CO_2.

Compared to CO_2, methane is a much more potent warming gas (per molecule in the atmosphere); but is also much shorter-lived. The figure below shows the warming contribution over time if we emit a one-off pulse emission of 1 Mt of CO_2, as compared with a 1Mt CO_2-equivalent amount, as defined using the GWP100, of methane (≈ 0.036 Mt CH_4) or nitrous oxide (≈ 0.0038 Mt N_2O).

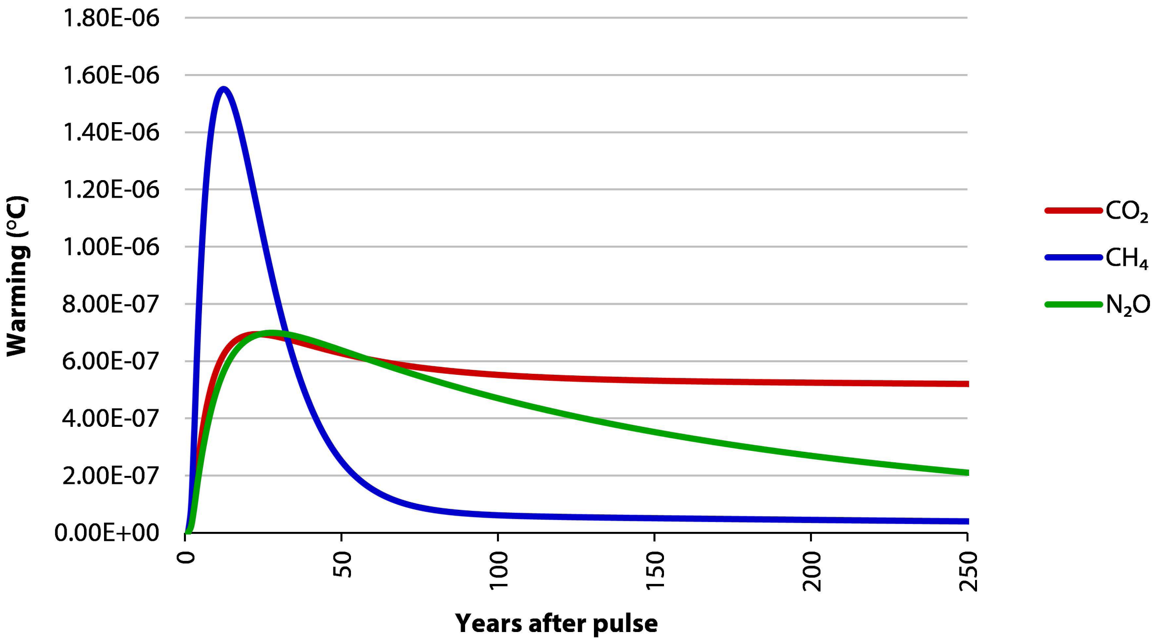

Figure 1. Global warming response to a one-off pulse emissions of 1Mt CO_2-equivalent of CO_2, CH_4 or N_2O, as defined using the 100-year Global Warming potential. Response functions and emission metric values as in the IPCC 5th Assessment Report (excluding climate-carbon cycle feedbacks). This figure reproduced with permission from the UK Committee on Climate Change report 'Land use: Policies for a Net Zero UK'

The methane emission initially causes a large increase in warming, but this is automatically undone over the next few decades as this methane breaks down (primarily into CO_2 – see footnote[ii]). The CO_2 emission has a much smaller warming effect over the first few decades, but it is only removed very slowly from the atmosphere (with a portion of any emissions persisting for millennia), and so its warming impact continues over the 250 years shown here, and well beyond. The nitrous oxide emission shows similar behaviour to CO_2 over the first 100 years before then also decaying more rapidly than CO_2. As its behaviour is sufficiently similar to CO_2 over immediately policy-relevant

[ii] A distinction emerges here between biogenic methane (methane from biological sources such as agriculture or wetlands) and fossil methane ('natural gas' leakage). For biogenic methane, this CO_2 resulting from methane breakdown does not represent an additional source of carbon in the atmosphere, while for fossil methane it does. For further information on the breakdown of methane, including this point, see section 3 of our explainer Agricultural Methane and its Role as a Greenhouse Gas

periods (at least the first century after an emission occurred), N_2O can be treated as more directly equivalent to CO_2 without running into the complications outlined below for methane, and so we do not elaborate further on the dynamics of N_2O emissions in this piece.

These temporal differences between the gases mean that we cannot fully capture or anticipate their contribution to global temperatures simply by using a single metric (such as the GWP100) to compare them.

This is a challenge even for individual, one-off emissions as illustrated above. So what happens if we keep emitting these gases year-on-year over many decades?

Given the uniquely long atmospheric lifespan of CO_2, to know how it has contributed to global temperature changes, it is necessary to consider the *total amount* of CO_2 emitted to date (the accumulating 'stock'). Because of its longevity, even stable CO_2 emissions will lead to ever-increasing CO_2 concentrations, and so to ever-increasing temperatures (see Fig 4 in our earlier Building Block on agricultural methane). This means that to stop ever-increasing CO_2-induced warming, CO_2 emissions must be brought down to net-zero (CO_2 emissions must cease or be balanced by CO_2 removals). Meanwhile, the short lifespan of methane means that its climate impacts are primarily dependent on the *ongoing emissions rate* (or 'flow'), that is, the extent to which one pulse of methane is replaced by another because, as illustrated above, the main impacts of a methane emission occur within the first few decades after its release. A constant rate of methane emissions will eventually contribute to the *maintenance* of an elevated concentration of methane in the atmosphere. Increases in the rate of methane emissions will lead to an increasing concentration of methane and contribute to further warming; reductions in emission rates will reduce methane concentrations and result in the temperature declining again from its existing elevated level - undoing some of the warming we already experience. For further illustration and explanation of these points, see our previous explainer, 'agricultural methane and its role as a greenhouse gas'.

To capture these dynamics, an alternative application of the Global Warming Potential has recently been proposed, termed ***GWP****[6,7]. The calculation underpinning GWP* primarily expresses the warming effects of *changes* in the emissions rate of methane as equivalent to a large pulse emission or removal of CO_2, rather than providing a snapshot of methane emissions at a single point in time (without reference to whether they are rising, falling or staying constant).

3. The fundamental difference between GWP100 and GWP*

Conventional application of the GWP acts as a single per-emission exchange rate by which different greenhouse gases are weighted in relation to CO_2. GWP* aims to report equivalent emissions based on whether sustained changes in the emission rates of short-lived gases would result in a similar warming contribution to an individual, one-off CO_2 emission[iii].

It is not, therefore, that GWP* can now provide a new, 'correct' valuation of how many tonnes of CO_2 each individual tonne of methane is worth. The aim of GWP* is instead to provide an alternative conceptual framework for representing how methane and CO_2 emission scenarios affect global temperatures. By choosing to undertake an activity that emits 1 tonne of methane, we *are* adding an amount of otherwise avoidable radiative forcing equivalent to 28 tonnes of CO_2 over the first 100

iii By treating methane in this way, GWP* can describe methane emissions within a 'cumulative carbon' framework. Each individual CO_2 emission adds a relatively uniform amount of additional, long-term warming, which will persist even when emissions cease. This means there is a time-independent, linear relationship between cumulative CO_2 emissions to date, and their contribution to global temperature increases[8]. GWP* can report methane emissions in a way that also conforms to this relationship[7,9].

years after its emission, as represented by the GWP100 of methane. But while CO_2 emissions *must* reach net-zero to stop temperature increasing, methane emissions can be sustained indefinitely (at some level below today's emissions) without temperatures increasing further. This is not conceptually possible if we imagine each individual emission of methane and CO_2 to be directly equivalent to each other as framed by the GWP100. That is why GWP* takes such a different approach. GWP* is based on the observation that the overall dynamics of how sustained emissions of different gases contribute to global temperature change cannot be represented by any simple means of weighting individual emissions. On the other hand, the design of GWP* also makes it very difficult to apply as a single, straightforward climate indicator (for example, as a carbon footprint label), in the way that GWP100 is commonly used, since the GWP*-based value of today's methane emissions would depend on the rate of methane emissions from that same entity or activity at some prior point in time.

Debates over the relative merits and appropriate uses of either metric are still playing out. Here, we instead discuss some of the bigger questions that are raised. What might thinking differently about the role of different gases – as could be revealed through climate modelling or GWP*, but is less apparent in how the GWP100 has been used - tell us about how food systems contribute to climate change, and about what types and systems of production could be climatically sustainable?

4. Carbon dioxide, methane, and stabilising the global temperature

All anthropogenic greenhouse gas emissions contribute to climate change. Any emitters – whether producing methane, CO_2, or other gases – thus play a role in our elevated temperatures. Reducing emissions of any greenhouse gas is beneficial, and all emitters have a responsibility to try and reduce their impacts. To have any chance of limiting warming to 1.5-2 °C above pre-industrial levels, we need to rapidly decrease emissions of all gases, and from all sectors[10]. This does not however mean that emission reductions of different gases play the same role in meeting these targets.

A halt as of today in CO_2 emissions would lead to no further increases in CO_2-induced warming, but stable elevated temperatures would persist for many centuries[11]. For methane, we could stabilise temperatures with some ongoing emissions (if emission rates gradually declined from today's levels). A halt on methane emissions would lead to a one-off decline in temperature. Stopping methane emissions entirely would reverse most of the warming that methane is currently responsible for, resulting in a one-off decline in global temperatures back down to a new baseline level (which would continue to increase back up again if CO_2 emissions were not stopped at the same time). So 'zero emission' targets for two different sectors, one emitting only carbon dioxide and one emitting only methane, would result in different contributions to climate change mitigation.

Because CO_2 acts cumulatively, reaching 'net zero' emissions is the ultimate requirement, but the speed with which we get there is also key. The sooner we start reducing CO_2 emissions, and the faster we reach net zero, the lesser the long-term warming we will have from CO_2 that has accumulated in the atmosphere. In principle, this means that escalating our efforts and getting to net zero CO_2 a few years earlier would permit a larger annual quantity of methane to be emitted *indefinitely* with the same consequences for global temperature, if that is what we want. Or put another way, for a given temperature cap, the faster we stop CO_2 emissions, the higher the rate of methane we are 'allowed' to continue emitting. Conversely, reducing methane emissions will 'allow' only a fixed, one-off quantity of extra CO_2 to be released. This does not avoid the need to bring CO_2 emissions to zero, but it can delay the point by which net-zero has to be achieved (because an extra quantity of permissible CO_2 translates to additional years of continued emissions).

But while some ongoing methane emissions may be able to give no *further* temperature increases from those emissions, maintaining these emissions into the future means they will continue to contribute to our elevated temperatures, and the resulting climate damages we will experience. And we are not yet on a route to rapid decarbonisation: fossil fuel emissions continue to increase year-on-year[12] - with the caveat that the current disruption caused by Covid-19 means that 2020 is likely to depart significantly from general trends. Most projections suggest that it is very unlikely we will be able to stop CO_2 emissions quickly enough that we can merely 'stabilise' the warming from methane at its current levels while also keeping to our 1.5-2°C targets[iv]. Significantly reducing methane emissions from livestock would increase the amount of total CO_2 that can be emitted while remaining under these temperature limits, and so may make them more attainable[13]. Integrated economic-climate models show how eliminating ruminant methane could therefore delay the rate at which a complete shift to clean energy is required, and so make this transition cheaper[14]. This also highlights some of the practical questions that might be raised in light of how this trade-off operates: "society may prefer a higher energy system transition cost to dietary change" (*ibid.*).

In the 1.5 degree pathways produced by global economic models as appraised in the IPCC Special Report on Warming of 1.5 degrees, global CO_2 emissions reach net zero by about 2050, while agricultural methane emissions are reduced by about 24-47% below 2010 levels by 2050[15]. Reducing CH_4 emissions by less than this amount would mean that global CO_2 emissions will have to decline even faster to meet this temperature objective, while reducing agricultural methane emissions by more could potentially delay – but not avoid – the date of net-zero CO_2 emissions by a few more years.

Would a wider appreciation of these points have implications for how we view the mitigation action required from different countries or industries that are responsible for different mixes of gases? **These are not issues that are introduced or solved through GHG emission metrics**; questions of how, how fast and by whom different emission reductions are made are embedded in broader moral or political considerations. These will involve thinking about, for example, the historical and future responsibility of different countries and sectors in contributing to current and future climate change; differing developmental needs between countries; how much long-term warming we can accept from different activities; the costs, feasibility and trade-offs incurred in different options; and who wins and who loses as a result of the decisions made. A better understanding of what different metrics can tell us (or what they cannot) may, however, help inform policy choices.

5. Food system methane emissions and climatic sustainability

If we overlook the dynamics described above, the main risk is that we might view different emission reductions as directly interchangeable, meaning that action to reduce methane emissions could potentially occur **at the expense of** action to reduce CO_2.

As it affects the food system, misunderstanding these dynamics can sometimes lead to unhelpful framings of the food (and specifically ruminant) problem.

5.1 Cows compared with cars

Media representations and some non-governmental organisation (NGO) advocacy around food emissions invoke comparisons between agriculture and fossil fuels, often describing cattle emissions

[iv] In addition, we need to keep some 'temperature space' for the removal of aerosol-induced cooling that is expected once we stop burning fossil fuels.

in terms of those of the transport sector. This may have helped draw attention to a topic by associating one activity widely appreciated to contribute to global warming (transport) with another less associated with the problem (agriculture and ruminant livestock). However, such comparisons have come in for criticism. Initially, this was because different accounting methods were applied to communicate emissions from either sector: typically a full ***life-cycle*** footprint was reported for livestock, but only exhaust/tailpipe emissions for transport[16].

More fundamentally, however, and as the discussion above has shown, the methane emissions from the ruminant sector and the CO_2 from the transport sector do not have directly equivalent impacts on the climate.

Transport is a major contributor to the problem of climate change via its current dependence on fossil fuels. As emphasised, the release of CO_2 into the atmosphere *has a permanent effect on global temperatures that will only stop getting worse once emissions stop, and can only be undone by actively removing past emissions*. Some level of ruminant methane, on the other hand, may be compatible with even strict warming targets. Methane's warming contribution is also not as irrevocable as that of CO_2 - the impacts of ruminant methane on the climate can rapidly change (up or down), based on animal numbers or production methods.

To be clear however, methane is by no means the only climate consideration for ruminants: they also contribute N_2O and CO_2, which both have cumulative effects. This is discussed further below.

The 'cows vs cars' framing might also misleadingly imply that we have an either-or choice. But if we are serious about keeping warming to 1.5-2°C, we need to rapidly curtail emissions from both agriculture and transport.

5.2 Intensive vs extensive animal production

Similar considerations may apply over whether to favour intensive or extensive ruminant production systems. ***Intensification*** of a ruminant system may reduce methane emissions per unit of food but will likely lock in greater use of fossil fuels for feed production and housing. From a broader strategic perspective, additional energy demand may make overall decarbonisation more difficult.

While extensive grazing systems might emit more methane per unit of food than intensive production systems, some of them will be less dependent on fossil fuels and fertiliser inputs (see section below on 'Ruminants and sustainability – the bigger picture' for some system comparisons'). That said, many Life Cycle Assessments tend to report emissions aggregated using the GWP100 CO_2e metric rather than reporting the gases separately, so there is not always the data available to confirm whether the balance of emissions really does substantially differ between alternative production systems[17].

Once again, however, our current situation means that this is not an either-or situation: we need to reduce overall climate impacts rapidly, and this will ultimately put a limit on emissions from both intensive and extensive systems. No production methods would be able to meet the ever-increasing global demand for ruminant products without significant environmental (including climate) damage. In either type of system, the increasing methane emissions that would result will contribute to continued increases in temperature (see below), with additional environmental impacts depending on the specific system. For intensive production, these negative effects will likely come in the form of feed-food competition, potentially greater energy use, and dependence on chemical inputs; for extensive production, contributions to ongoing land-use change and its associated carbon and ***biodiversity*** impacts (discussed later) may be the more significant considerations. There will be other social, ethical and economic differences between systems as well (see here for a fuller discussion).

6. Current and projected trends in ruminant methane

Unlike CO_2, long-term sustained methane emissions do not necessarily always contribute to *additional* warming; so in principle a sustained rate of methane from an activity such as ruminant production may be compatible with our 1.5-2°C temperature goals. However, three points need to be highlighted.

Firstly, stabilising methane-induced warming (and thus keeping methane emissions at or close to current rates of release) at *today's* levels is highly unlikely to allow us to keep to these climate targets since it will take up too much of the temperature 'space' (as described in further detail in section above on 'Carbon dioxide, methane, and stabilising the global temperature').

Secondly, even stabilising global ruminant methane emissions at today's levels would **require those of us in, for example, Europe, the Americas and Oceania who already eat much more than the global average to reduce our consumption, given the growth in the world's population and the rising demand for meat and dairy in developing regions that currently have much lower consumption per capita.**

The third point to note is that current trends indicate that stabilisation is in any case not on the cards. As figure 2 shows below, the projections are for an increase in ruminant production, and this translates into increases in methane (and other) emissions and, consequently, in extra warming (in reality, regardless whether reported using GWP100 or GWP*). So the ongoing trend of increased ruminant production is highly concerning, and failure to curtail the demand for ruminant products will make it harder, if not impossible, to meet the climate commitments set out in the Paris Agreement.

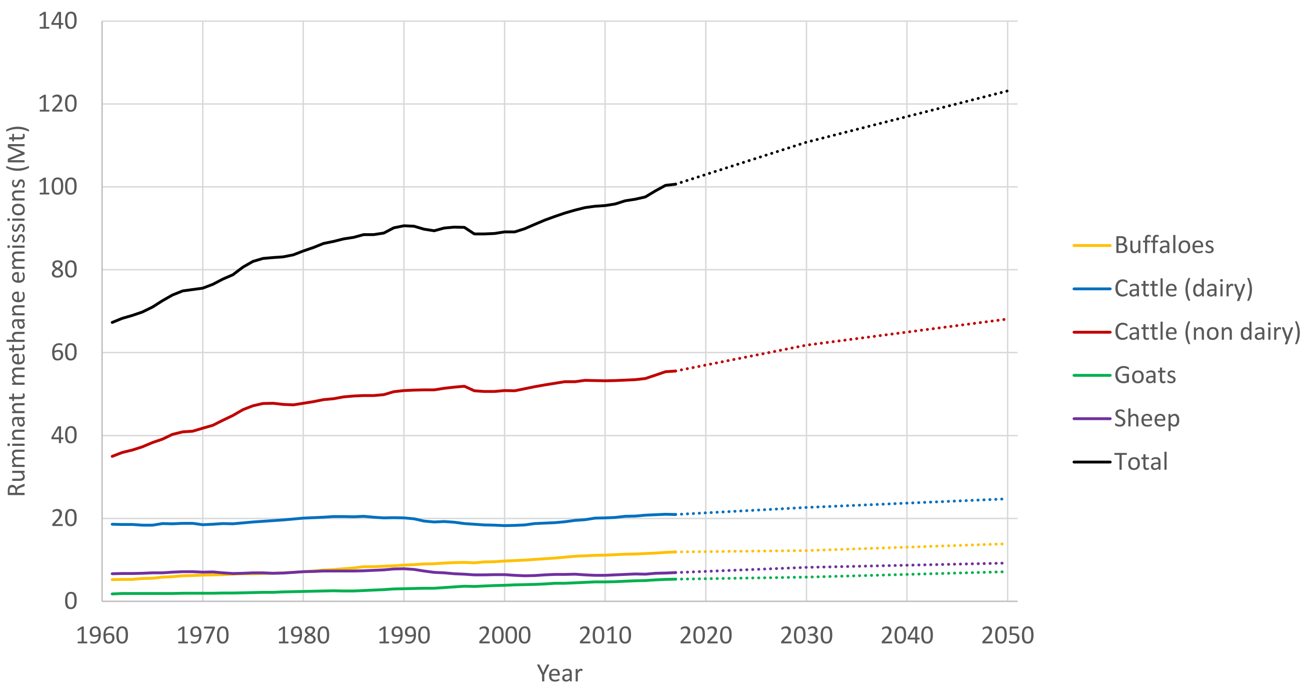

Figure 2. Trends and projections in methane emissions (from both enteric fermentation and manures) for major ruminant livestock. Data from FAOSTAT[18]

And it is still beneficial to decrease methane emissions, as emphasized above. Indeed, if GWP* is used, then climatic benefit of a sustained decrease of methane emissions is highlighted much more sharply than from GWP100.

7. Ruminants and sustainability – the bigger picture

When aggregated using the GWP100, the most widely accepted estimate suggests that globally, livestock production (including embedded feed production and land use change) contributes around 14.5% of annual greenhouse gas emissions, with methane accounting for about 44% of this - 39.1% of total livestock emissions from ***enteric fermentation*** methane alone[19]. The importance of methane is reflected in assessment of individual foods; ruminants are generally found to have the largest 'carbon footprints', with enteric methane a major contributor[20].

As a result, methane has dominated the argument over the environmental impacts of ruminants. The introduction of the new metric, GWP*, into the public discourse has caused a great deal of discussion within the food sustainability community. One of the key insights it provides – that ongoing methane emissions can be compatible with temperature stabilisation – has been used by some stakeholders to argue that ruminants, particularly those in grazing systems, are (variously) not a problem, or inherently less problematic than ***monogastric*** pigs and poultry.

We have demonstrated above why, despite this, we still cannot ignore ruminant methane. It is even more important to emphasise that a narrow focus on methane alone **can lead to the assumption that the ruminant 'problem' is synonymous with the methane 'problem'** (or non-problem), when in fact **ruminant systems can bring with them a range of other environmental (including climatic) and societal concerns.**

Leaving aside methane for a moment, ruminants are responsible for other climate changing emissions as well: nitrous oxide and carbon dioxide - from the animals' manure, feed and input production and from land-use change (including ***deforestation*** and the clearance of other vegetation for pasture or grain-feed production). Aggregated globally, total non-methane emissions from ruminants are still greater than emissions from monogastric livestock[21]. Even when scaling emissions per kg of protein we still see that ruminant production can have similar or greater emission intensities of CO_2 and N_2O, as shown in table 1.

That said, there is likely to be very considerable variation by specific production system and country, as indicated in table 2. The data here shows gas-specific footprints for typical conventional and ***organic*** UK meat production (data from Smith *et al.*, 2019[22]). Across both production methods, ruminant systems in the UK had lower CO_2 emissions per kg protein than monogastric systems, but greater emissions of N_2O. Combining these CO_2 and N_2O emissions using the 100-year global warming potential (which, as illustrated and discussed above, provides a more direct equivalence than for methane over important policy timeframes) suggests that the ruminants can still have a greater climate impact per kg protein produced than monogastric livestock, even without considering the role of methane. Relating back to the discussion of intensive and extensive production above, organic livestock systems in the UK tend to be extensive (in addition to meeting the other requirement for organic certification), while 'conventional' in the UK context will span a range of more extensive and intensive systems (noting that definitions of intensive and extensive are not always clear cut). The data from Smith *et al.*, 2019[22] suggest that organic production could provide lower emission footprints than conventional systems, and the lower CO_2 emissions for organic ruminant systems is particularly notable. However, it is important to highlight the authors' conclusion, particularly in light of the discussion below, that this emission reduction would be negated by the CO_2 generated by additional land-use change required if we wanted to maintain the same meat output. In addition, we note that here we only provide a selected overview of some UK system comparisons – the impacts of different production methods are highly variable and dependent on the specific management of individual systems, with large ranges in relative performance between organic and conventional systems across different indicators[23].

Table 1. Emissions (kg) of methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) from production of 1kg of protein from average Global and Western European cattle, sheep, pig and chicken production (aggregated across all types of production system). Data from the FAO Global Livestock Environmental Assessment Model (GLEAM)

Region	Animal Species	CH_4	CO_2	N_2O	CO_2 + N_2O (GWP100 CO_2e)
Global	Cattle	6.54	65	0.22	123.3
	Sheep	4.82	21	0.20	74
	Pigs	0.68	25	0.04	35.6
	Chicken	0.02	26	0.03	33.95
Western Europe	Cattle	2.59	26	0.12	57.8
	Sheep	2.50	20	0.09	43.85
	Pigs	0.46	27	0.04	37.6
	Chicken	0.02	24	0.02	29.3

Table 2. Emissions (kg) of methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) from production of 1kg of protein from organic and conventional cattle, sheep, pig and chicken in the UK. Based on data from Smith *et al.*, 2019[22] applying carcass weight to meat and meat to protein conversions from GLEAM for consistency with table 1 above (conversion factors from table 9.1 in the GLEAM 2.0 model description document).

System Type	Animal Species	CH_4	CO_2	N_2O	CO_2 + N_2O (GWP100 CO_2e)
Conventional	Cattle	1.67	15.32	0.12	47.12
	Sheep	3.57	11.55	0.11	40.7
	Pigs	0.22	16.89	0.04	27.49
	Chicken	0.02	21.52	0.04	32.12
Organic	Cattle	1.91	10.35	0.08	31.55
	Sheep	6.51	3.69	0.09	27.54
	Pigs	0.08	10.51	0.05	23.76
	Chicken	0.02	20.19	0.05	33.44

Even if ruminant production is not associated with ongoing land-use change for pasture or feed production (and at the moment these two processes *are* driving deforestation and hence CO_2 emissions), there is arguably a potential opportunity cost in not using this land for other climate mitigation purposes, including for carbon capture and/or bioenergy, or for other reasons such as ***biodiversity conservation***. Appraising the sequestration potential of land currently used by ruminants but which could be spared for other purposes is more difficult than it may first appear. It cannot automatically be assumed that land released from livestock will be used for something that has better consequences as regards climate and/or biodiversity, and the carbon fixed by any biological processes is also time-dependent and constrained by location-specific biophysical conditions (for further detail see the FCRN report *Grazed and Confused*). Nevertheless, potential non-agricultural uses of any spared land remain an important opportunity for climate change mitigation and other environmental aims, given political will. It is worth emphasising that **even if we had a 'separate basket' climate policy that treated methane differently to CO_2, land-use would likely prove the ultimate constraint on ruminant production,** since most models suggest we will require substantial additional land for ***carbon sequestration*** and bioenergy if we are to reach net-zero CO_2 emissions within a timeframe compatible with warming at 1.5-2 °C above pre-industrial temperatures.

The impacts of ruminant production also extend beyond climate change. The land-take of ruminants and the subsequent impact on biodiversity is the major concern here. While in certain specific contexts well managed grazing can help support conservation objectives and maintain biodiversity, the historical evidence and the aggregate picture clearly show that the expansion of ruminant production has occurred at the expense of native vegetation and has been a major cause of biodiversity loss[24,25]. In order to halt the decline in biodiversity it is imperative that we halt land expansion, especially in sensitive ecoregions.

Additionally, in many systems, fertilisers and pesticides are used to produce ruminant feed (both grass and grains) that can impact water quality and biodiversity, while other volatile compounds such as ammonia have air quality impacts.

On the other hand, there clearly is potential for some level of ruminant production within a climatically sustainable food production system. Well-managed ruminant systems might also be able to maintain soil carbon, or play a role in restoring degraded areas and, as noted above, maintaining biodiversity. Mixed rotations or agroforestry could integrate ruminants in systems that provide other important outputs, and some studies suggest that rearing ruminants on marginal lands and feeding them non-human digestible feedstuffs could contribute to a food supply with a potentially lower ***arable land*** footprint than an entirely animal-free food system, albeit with a higher *overall* land take[26].

Debates about the nutritional role of animal products are complex and contested, but for many in low income countries, where diets are lacking in diversity and largely grain or tuber based, access to animal source foods can provide essential sources of ***micronutrients*** (particularly for children and women of childbearing age). And of course, there is significant, widespread ruminant production in the first place because ruminant products have long made a major nutritional, culturally significant and widely-enjoyed contribution to our diets.

Beyond food provision and environmental concerns, livestock rearing can play an important social role and is a major economic contribution to the lives and ***livelihoods*** of some of the world's poorest communities. Animal husbandry is a way of life for large numbers of people across the world, and in many countries, landscapes and rural livelihoods are inextricably tied to livestock.

For some stakeholders these benefits serve to further justify the continuation of ruminant livestock production; for others they highlight the need to find alternative non-ruminant dependent ways of providing nutrition, and creating livelihoods and cultural value. Adding to the mix are complex and multi-layered concerns about animal ethics and welfare. These points further emphasise that a reductive focus on one issue – for example, the impact of methane – is only ever part of the story.

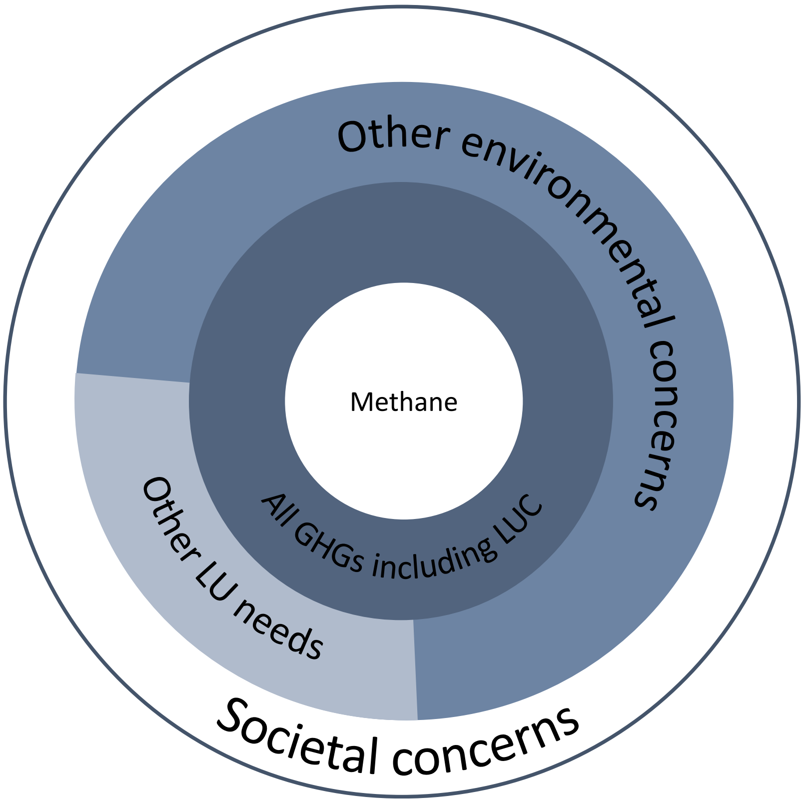

Figure 3: While methane has arguably dominated discussions about the environmental impacts of ruminants, the topic of methane sits within a broader context of different environmental, and ultimately societal, concerns. This includes greenhouse-gas (GHG) emissions from land-use change (LUC).

Conclusions

New ways of thinking about and reporting methane emissions may help us to better understand how different greenhouse gases contribute to global warming. A more nuanced perspective could even reveal a potential climatically sustainable space for ruminant production that may appear impossible under conventional ways of considering 'equivalence' between different emissions and net-zero emissions targets. But this climatic space is still limited, and not compatible with ever-increasing demand for ruminant products.

In short, the big picture conclusion from the last decade's research on dietary sustainability does not change. At current numbers and as currently produced, livestock, including but not only ruminant livestock, are and continue to be important contributors to the problem of climate change and to other environmental harms. Even if the methane emissions associated with their on-going consumption do not result in additional warming, high consuming countries and individuals occupy a disproportionately large climatic space. Reduced consumption of livestock products by these high consumers, as well as development and adoption of measures to reduce emissions from livestock production, could allow for global livestock production at potentially sustainable levels.

Glossary

Arable crops and arable land
Arable crops are those such as wheat and barley, which require good soil quality and a favourable climate to grow, and land amenable to the use of ploughing and harvesting machinery. Arable land is by definition land used to grow arable crops, in contrast to land used for fruit and vegetable crops and for pasture used to feed grazing animals.

Biodiversity
Biodiversity refers in the broadest sense to the variety and variability of living organisms in a particular area, or on earth in general. More specifically, the concept is used to denote different aspects of the variety and variability of life, e.g. the number of species in an area (species richness) or the size of species' populations (species abundance). Biodiversity is measured in different ways and at various scales from the genetic through to the landscape level.

Biodiversity conservation
Biodiversity conservation refers to all human activity aimed at the preservation of both the variety and variability of living organisms in a particular area of concern, or on earth in general. People value different aspects of biodiversity in different ways, and can have different priorities in biodiversity conservation e.g. to protect an endemic species or a species that supports an ecological process important to human wellbeing such as pollination.

Carbon dioxide equivalent
Carbon dioxide equivalent (CO2.eq) is a measure used to compare and combine the warming effect of emissions from different greenhouse gases, using single measure of impact. This is done on the basis of a conversion factor known as the Global Warming Potential (GWP), which is the ratio of the total energy trapped by a unit of greenhouse gas (e.g. a tonne of methane) over a specific period of time (normally 100 years), to that trapped by carbon dioxide over the same time period.

Carbon sequestration
Carbon sequestration is any process by which carbon dioxide is removed from the atmosphere and stored elsewhere, whether by biological or technological means. There are two main types of carbon sequestration, terrestrial (carbon plants and soils), and geologic (carbon stored in rock formations) . One classic example of carbon sequestration is reforestation.

Deforestation
Deforestation is the clearance of forest or standing trees from land as it is converted to non-forest use. Deforestation can include the conversion of forest land to ranches or other agricultural activities. Important drivers of deforestation are the use of land for agriculture, ranching, infrastructure, urban expansion, and mining. Deforestation is often defined in relation to a cut-off date – e.g. all forest land cleared after June 2008 could be considered to be deforestation. Deforestation is a particular form of land use change. The concept is not commonly used to refer to types of land use change where other areas that may contain native vegetation (e.g. hay, marshes, savannas) are converted.

Enteric fermentation
Enteric fermentation is a natural part of the digestive process of ruminant animals (e.g. cattle and sheep) where microbes decompose and ferment the food present in large rumen portion of the stomach. As a byproduct of this fermentation process, some bacteria species in the stomach produce methane.

GHGs
GHGs is an abbreviation for greenhouse gases. These include gases such as carbon dioxide, methane, and nitrous oxide, which affect outgoing radiation, leading to global warming.

Global warming potential
A commonly used means of quantifying the strengths of different greenhouse gas emissions relative to carbon dioxide (CO2). Derived from estimating the total change in atmospheric energy balance resulting from a pulse emission of the gas, relative to CO2, over a specified time-frame (typically 100 years).

GWP*
An alternative application of Global Warming Potentials to derive carbon dioxide equivalents (referred to as CO2e* if using GWP*) that primarily relates the change in the rate of short-lived greenhouse gases (such as methane) to a fixed quantity of CO2, rather than a direct equivalence between emissions of both short- and long-lived greenhouse gases, as is the case for conventional use of the 100-year Global Warming Potential.

Intensification
Intensification refers to a process by which farming systems (for crops or livestock) are reorganised – often through the application of new technologies, economies of scale, and the use of additional inputs, such as nutrients, chemicals, energy and water – in order to produce more of a desired output (e.g. meat) while using less land, human labour, or capital. The result is that the costs of production for a given amount of food are reduced, thereby increasing profits through larger profits per unit of food, or by expanding total consumption through lower prices, enabling more people to buy more. Often, environmental impacts per unit of product are also reduced, but may be counterbalanced by increases in total production. The impacts of intensification processes on animal welfare, biodiversity, and other issues is also a widely held concern.

IPCC
The Intergovernmental Panel on Climate Change (IPCC) is the international body for assessing the science related to climate change. It is administered by the United Nations with participation and decision making from 195 member states. The assessments that it produces provide the basis for government at all levels to create climate related policies.

Life cycle
In life-cycle assessment and carbon footprint analysis, the concept of life cycle refers to the entirety of phases a product or system passes through from its development, through to its use and, eventually, how it is managed as waste. A life cycle is generally understood to start at the growing and harvesting or mining of raw materials and to end when a product is disposed of as waste. While waste management is thought to be a part of a product's life cycle, potential recycling is generally considered to be part of the life cycles of other, new products. For example, the life cycle of a loaf of bread may be thought to consist of the following phases: the growing and harvesting of corn and other ingredients (including pre-production of inputs such as fertilisers), their transport to a bakery, bread production, transport and retail, consumption and waste.

Livelihood
A livelihood is a person's, household's, or group of people's means of making a living. It encompasses people's capabilities, assets, income, and activities that are required for securing the necessities of life, such as food, water, medicine, shelter and clothing.

Micronutrients
Micronutrients are minerals (e.g. iron) and organic compounds (e.g. vitamin A) found in food, which the body requires in very small amounts to produce substances such as enzymes and hormones. They are essential for proper growth, development and bodily functioning. Essential micronutrients are those that cannot be synthesised by the body and so must be obtained through diet.

Monogastric
A monogastric is a mammal with a single-compartmented stomach. Examples of monogastrics include humans, poultry, pigs, horses, rabbits, dogs and cats. Most monogastrics are generally unable

to digest much cellulose food materials such as grasses. Herbivores with a monogastric digestion system (e.g. horses and rabbits) are able to digest cellulose in their diets through microbes in their gut, but they extract less energy from these foods than do ruminants. A major proportion of the feed given to monogastrics reared in intensive systems comprises human edible grains and soybeans.

Organic farming
Organic farming is an approach to farming in which synthetic chemical insecticides and herbicides and inorganic fertilisers are entirely or largely avoided. Underpinning organic farming is the idea that farming should rely on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects (e.g. agrochemicals such as pesticides and synthetic fertilisers). Certification bodies (e.g. the Soil Association in the United Kingdom) specify the practices, methods of pest control, soil amendments and so forth that are permissible if products are to achieve organic certification.

Radiative forcing
The measure of how different factors (including greenhouse gases) change the balance between incoming and outgoing energy in the atmosphere. Expressed as the change in energy balance per unit area (in Watts per metre square; W m-2) over a given timeframe – typically contemporary compared to preindustrial conditions.

Ruminant
A ruminant is a mammal with a four-compartmented stomach which enables it to acquire nutrients from plant-based food such as grasses, husks and stalks. Examples of ruminants include cattle, sheep, goats, deer, giraffes and camels. After swallowing, microbes in the ruminant's rumen (its first stomach compartment) begin fermenting the food. This process generates fatty acids (nutrients which the ruminant absorbs through its rumen walls) and methane, which the ruminant eructs or burps. Through this process, ruminants are able to digest coarse cellulosic material which monogastrics and people cannot. Methane emissions from ruminants are a significant source of greenhouse gasses from ruminant-based livestock systems.

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