UK Net zero, Methane and Ruminants Fact File

Last updated – March 2025

About the Veterinary Policy Research Foundation (VPRF)

The VPRF is a not-for-profit organisation set up by Lord Trees with the purpose of employing a veterinary surgeon as an intern/researcher to facilitate Lord Trees' activities in the House of Lords.

Declarations by the authors

Professor the Lord Trees is a veterinary surgeon and a crossbench peer. Fiona Shuttleworth is a veterinary surgeon, who currently holds the position of Parliamentary Veterinary Intern. The Parliamentary Veterinary Internship is funded by The Veterinary Policy Research Foundation that receives sponsorship from several veterinary organisations, professional bodies and universities. Further information on the VPRF can be found on our website: www.vprf.co.uk

Authorship

Fiona Shuttleworth and Lord Trees

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AIMS AND OBJECTIVES

The purpose of this document is to provide an unbiased and factual summary of information relating to the UK's net zero targets, methane as a greenhouse gas, sources of methane emissions, and the livestock industry in the UK. The report primarily focuses on net-zero, the differences between short-lived climatic pollutants (SLCPs) and long-lived climatic pollutants (LLCPs), and how this affects metrics used in net-zero targets, how different sources contribute to methane emissions, and the methods of mitigating emissions within the ruminant agricultural sector. The report also brings together information on current activities being undertaken by the UK Government, human and veterinary healthcare professions, and the agricultural industry to combat the negative impacts of methane emissions on climate change and air pollution. It is important to note that release of methane into the atmosphere is not the only negative impact the agriculture industry can have on the environment. Globally, agriculture is a major driver of land-use change (draining wetlands, removing forests), monoculture formation, biodiversity loss, and water and soil pollution to name a few. This Fact File will focus on enteric fermentation in ruminants and manure management which produces methane and the possible impacts and solutions for climate change.

The report does not consider the role of carbon dioxide in climate change but stresses that ultimately carbon dioxide mitigation and adaptation strategies will be key in solving the climate crisis.

This report provides a summary of the data and information relating to methane emissions and current technologies and metrics known to the authors at the time of publication. The authors aim to update this report as new relevant information becomes available. The date of the latest update is displayed on the cover page. The authors welcome any constructive feedback on additional data to include or ways to further improve this document. These will be considered in future updates.

IMPORTANT NOTE FROM THE AUTHORS ON GLOBAL CONTEXT

Whilst this document largely focuses on the UK for practical reasons, it is important to recognise that fundamentally we all share the same atmosphere, and therefore methane emissions and its role in climate change is very much a global problem. Currently, there are over 150 countries signed up to the Global Methane Pledge, which aims to reduce methane emissions by 30% by 2030, however implementation of the pledge is proving slow. As of April 2024, the UK government, which signed the pledge at COP26, has no roadmap outlining how it will reduce methane emissions to reach this ambitious target, and the Climate Change Committee warn that the UK is 'falling behind' in reducing methane emissions. That being said, the UK has significantly reduced its methane emissions by over 62% from 1990 to 2020, primarily through making improvements in landfill management.

1.0 NET ZERO

- The UK is required to report estimated greenhouse gas (GHG) emissions to comply with international agreements and fulfil domestic policy goals. Under the Climate Change Act 2008, the UK government committed to reducing its GHG emissions by 80% by 2050, compared to 1990 levels. In 2019, the UK further advanced this commitment by proposing a 'net-zero' target, committing to bring all net GHG emissions to zero by 2050, as initially proposed in the 2019 Climate Change Committee (CCC) report[1].
    - The CCC, an independent advisory group to the government on climate change, recommends a 64% reduction in GHG emissions from 2017 levels in the agriculture and land-use sector to meet the UK's 2050 net-zero target[2]. This reduction is set at 64%, rather than 100%, to account for the essential functions of land, the inherent biological processes involved in food production and the critical importance of maintaining food production and security in the UK.
- The Department of Energy Security and Net Zero, is responsible for publishing estimates of the UK's GHG emissions related to the net-zero target. These estimates are used as the baseline for monitoring the Climate Change Act net zero target.
- Net zero estimates, also known as territorial estimates, are production-based assessments of emissions that take place within the UK's geographical borders. Box 1 highlights which emissions are included in net zero estimates, and those which are not included. These territorial emissions are used to track and inform progress on UK-wide emissions targets, including the net-zero goal.
    - In 2023, the UK territorial emissions were estimated to be 384 million tons of CO_2 equivalent (Mt CO_2e), which is a 52% reduction since 1990 levels[3].

BOX 1 – WHAT DOES NET ZERO INCLUDE AND NOT INCLUDE?

Net zero estimates **include** GHG emissions or removals from:

- Businesses based in the UK, regardless of where in the world they are registered.
- The activities of people that live in the UK, as well as non-UK visitors.
- Exported goods and services.
- Land i.e., forest, crop, or grazing land (anthropogenic release)

Net zero estimates **exclude** GHG emissions or removals from:

- International air travel
- International shipping
- UK business and residents which occur abroad.
- Emissions from biogenic origin i.e., burning of biomass, such as wood, straw, biogas, and poultry litter for energy production.
- Production of goods and services that the UK imports from other countries

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[1] Net Zero Government Initiative; UK Roadmap to Net Zero Government Emissions, December 2023; https://assets.publishing.service.gov.uk/media/6569cb331104cf000dfa7352/net-zero-government-emissions-roadmap.pdf

[2] Committee for Climate Change Report; Land-use Policies for a Net-Zero UK, January 2020 https://www.theccc.org.uk/wp-content/uploads/2020/01/Land-use-Policies-for-a-Net-Zero-UK.pdf

[3] https://www.ons.gov.uk/economy/environmentalaccounts/methodologies/measuringukgreenhousegasemissions

- Carbon footprint, also known as consumption-based emissions, is another measure of GHG emissions. It differs from net zero estimates as it includes emissions from the UK's consumption of goods and services anywhere they arise along the supply chain – crucially including UK imports. See Box 2 for details of what is included and not included in carbon footprint estimates.

    - In 2021, the most recent for which carbon footprint emissions have been estimated, they accounted for 705 $MtCO_2e$, which is a 36% reduction from 1990 levels[3].
    - Critically, carbon footprint measures will not be affected by 'carbon leakage', where the emissions associated with the importation of overseas goods for UK consumption **are not** captured in UK territorial emission estimates.

Box 2 – What does Carbon footprint include and not include?

Carbon footprint estimates **include** GHG emissions from:
- Goods and services produced in the UK.
- Goods and services consumed in the UK, including **all imports.**
- UK households.

Carbon footprint estimates **exclude** GHG emissions from:
- UK-produced exports.

- Residency-based emissions, or production emissions, cover emissions from UK residents and UK-registered businesses, whether they occur in the UK or overseas, and are published by the Office for National Statistics. In 2022, the UK residency-based emissions were estimated to be 512 $MtCO_2e$, which is a 39% reduction compared to 1990 levels[3].

    - They **include** emissions from aviation and shipping from British operators and UK tourists abroad.
    - They **exclude** emissions from foreign tourists in the UK and freight from foreign operators.

- Figure 1[4] highlights that substituting UK-produced goods for an imported equivalent (effectively exporting GHG emissions) aids progress towards UK net-zero targets, whilst having a less significant impact on UK's carbon footprint.

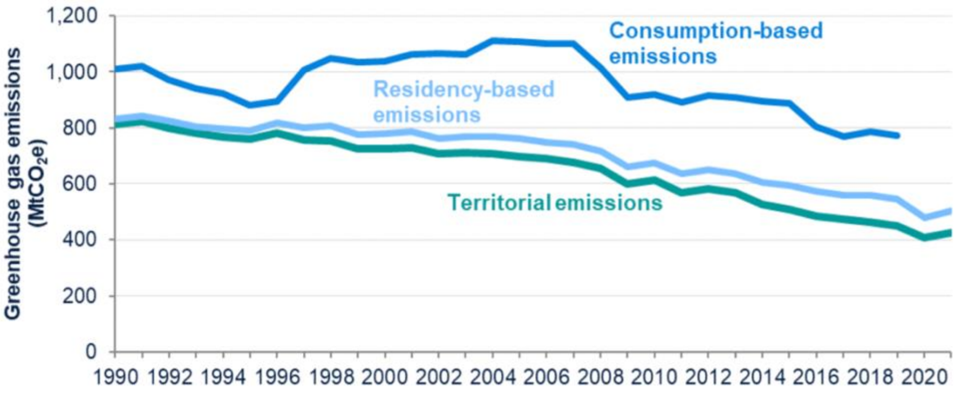

FIGURE 1: UK TERRITORIAL (NET-ZERO) VS CONSUMPTION (CARBON FOOTPRINT) GREENHOUSE GAS EMISSIONS FROM 1990 - 2020

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[4] 2022 UK Greenhouse Gas Emissions, Final Figures, National Statistics, Department of Energy and Net Zero, February 2024, https://assets.publishing.service.gov.uk/media/65c0d15863a23d0013c821e9/2022-final-greenhouse-gas-emissions-statistical-release.pdf

- Consumption-based emissions, i.e., carbon footprint emissions, have been falling at a slower rate compared to residency and territorial emissions[4].
    - Increasing imports effectively exports our GHG emissions and emits the same, if not more, GHGs into the atmosphere as goods and services may be produced less efficiently than they would be in the UK.
    - Put simply, the quickest and easiest way for the UK to reach net-zero would be to import all goods and services which exports the associated GHG emissions.

2.0 GREENHOUSE GASES

2.1 THE GREENHOUSE EFFECT

- The Greenhouse effect is the natural warming process that maintains the Earth's surface temperature. Without this effect, it is predicted the average global surface temperature would be -18°C[5].

- The sun emits shortwave radiation which enters the Earth's atmosphere and is absorbed by the surface of the Earth. GHGs naturally present within the atmosphere trap infra-red radiation radiated back from the planet's surface, causing an increase in surface temperature (Figure 2).

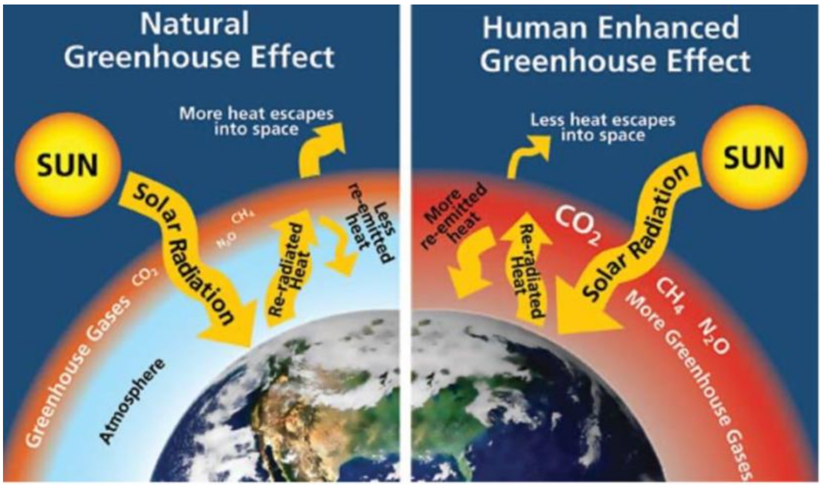

FIGURE 2: COMPARISON OF CLIMATIC WARMING FROM THE NATURAL GREENHOUSE EFFECT AND THE ENHANCED GREENHOUSE EFFECT

REFERENCE - HTTPS://MRGEOGWAGG.WORDPRESS.COM/2015/06/24/GREENHOUSE-EFFECT-AND-ANTHROPOGENIC-WARMING/

- This process is being exacerbated by excessive anthropogenic GHG emissions which are released from long-term carbon stores. Increased atmospheric GHGs enahnce the absorption and emission of infrared radiation, reducing the rate which the atmosphere emits longwave radiation back into space, which further increases the earth's surface temperature beyond the natural greenhouse gas effect.

- Radiative forcing is the change in incoming and outgoing energy (flux) in the atmosphere caused by both natural and anthropogenic factors influencing climate changes, measured in watts per square metre.
  - Radiative forcing varies due to factors like atmospheric concentrations of GHGs and aerosols. Different GHGs exhibit different radiative forcing, depending on the configuration of atoms and their ability to trap heat. For example, methane a high radiative forcing, often referenced colloquially as potency, as its one carbon atom is bonded to four separate hydrogen atoms which can configure in numerous different ways to trap infrared radiation. Some molecules, like carbon dioxide, where one carbon is bound to two oxygen molecules by a double covalent bond, have a limited number of arrangements of their atoms and therefore are not as prolific at trapping infrared radiation.
  - Methane exhibits both direct and indirect radiative forcing. It directly increases radiative forcing within the atmosphere and indirectly by interactions with oxygen compounds stimulated by sunlight increasing the atmospheric presence of other GHGs i.e. water vapour, to increase their effect time in the atmosphere. These interactions, and others, are responsible for the perturbation effect of methane in the atmosphere, where one methane molecule, and its warming impacts, last longer than the molecules atmosphere lifetime alone (approx. 8 years), resulting in 12 years of warming (see 2.4.2).

2.2 TYPES OF GREENHOUSE GAS

- Greenhouse gases can be grouped into two broad categories depending on their longevity within the atmosphere.

- Long-lived climate pollutants (LLCPs), such as CO_2, accumulate within the atmosphere and can persist for hundreds and even thousands of years[178].

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[5] https://web.archive.org/web/20041104033042/http://eesc.columbia.edu/courses/ees/climate/lectures/radiation/

  - The lifetime effect of CO_2 in the atmosphere is difficult to determine because several processes remove carbon dioxide from the atmosphere. Between 65-85% of atmospheric CO_2 dissolves into the ocean over a period of 20-200 years[6], while the remainder is removed much more slowly by a process that takes several hundred or even thousands of years[17]. Consequently, CO_2 can demonstrate warming effects after 10,000 years in the atmosphere through cycles of absorption and re-emission (naturally or from anthropogenic sources) in the carbon cycle[8].
  - The increase in anthropogenic CO_2 emissions since the industrial revolution has caused a 'backlog' of atmospheric CO_2, enhancing global warming as CO_2 accumulates in the atmosphere.

- Short-lived climate pollutants (SLCPs), including methane, nitrous oxide (N_2O), black carbons, and hydrofluorocarbons, have a shorter atmospheric lifetime and do not accumulate within the atmosphere. For example, the atmospheric lifetime of methane is approximately 9-12[7,9] years.

  - SLCPs are responsible for 33-50% of current radiative forcing[8]. Unlike LLCPs, where the warming effect is primarily determined by their cumulative historic atmospheric emissions, SLCPs have a relatively short atmospheric lifetime, and therefore their warming effects are not cumulative and less influenced by historical emissions and are instead more dependent on their current emission rates[9].
  - Current metrics used to quantify the impacts of these molecules on climatic warming indicate that SCLPs exhibit a higher warming potential compared to LLCPs[10].

- GHG data typically refers to the GHG emissions into the atmosphere rather than their total atmospheric concentration. This is an important distinction, as different GHGs remain in the atmosphere for different periods of time depending on whether they are a LLCP or a SLCP, and therefore contribute to climatic warming in different ways

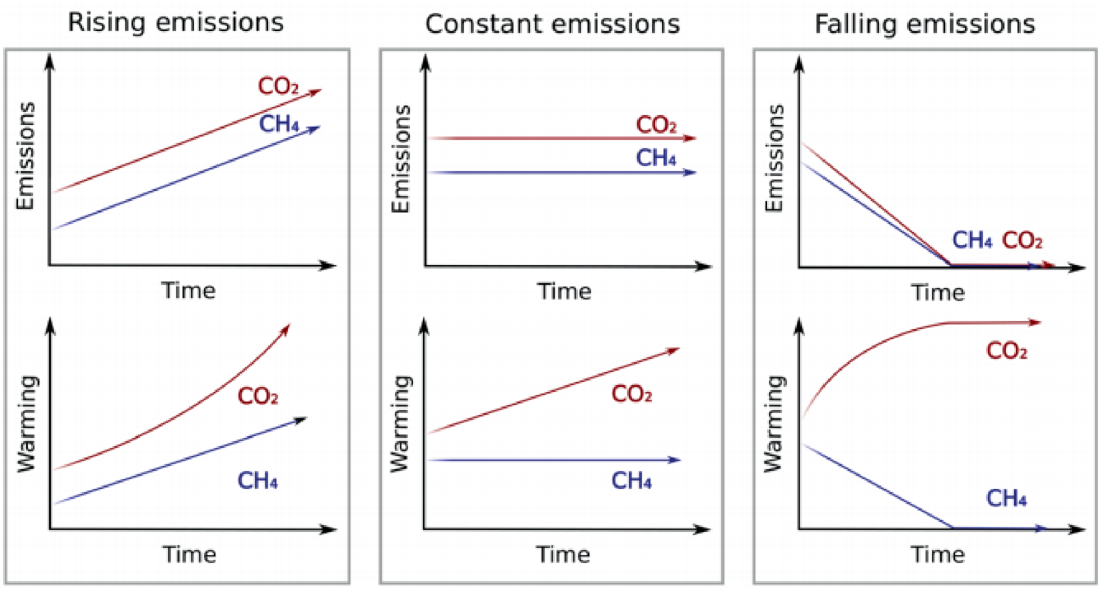

FIGURE 3: EMISSIONS SCENARIOS COMPARING LLCPS AND SLCPS AND THEIR EFFECTS ON CLIMATIC WARMING

REFERENCE - HTTPS://WWW.OXFORDMARTIN.OX.AC.UK/DOWNLOADS/ACADEMIC/CLIMATE_METRICS_%20UNDER_%20AMBITIOUS%20_MITIGATION.PDF

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[6] https://www.theguardian.com/environment/2012/jan/16/greenhouse-gases-remain-air

[7] Arora, V. K., Melton, J. R., and Plummer, D.: An assessment of natural methane fluxes simulated by the CLASS-CTEM model, Biogeosciences, 15, 4683–4709, https://doi.org/10.5194/bg-15-4683-2018, 2018.

[8] Costa Jr. C, Wironen M, Racette K, Wollenberg, E. 2021. Global Warming Potential* (GWP*): Understanding the implications for mitigation methane emissions in agriculture. CCAFS Info Note. Wageningen, The Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

[9] https://oms-www.files.svdcdn.com/production/downloads/reports/ClimateMetricsforRuminentLivestock_Brief_July2022_FINAL.pdf

[10] Liu, S., Proudman, J. & Mitloehner, F.M. Rethinking methane from animal agriculture. *CABI Agric Biosci* **2**, 22 (2021). https://doi.org/10.1186/s43170-021-00041-y

- Since methane's atmospheric lifespan is short, the warming impacts of different emissions scenarios (rising, constant or declining emissions) differs compared to CO_2 which has a long lifespan in the atmosphere. In Figure 3[11], CO_2 represents LLCPs (red) and methane represents SLCPs (blue).
  - Under rising emission scenarios, both CO_2 and methane contribute to climatic warming. As CO_2 accumulates any increase in emissions will cause concentrations in the atmosphere to increase and summate, trap more heat, and cause an exponential increase in climatic warming.
  - Constant methane emissions lead to stable methane concentrations in the atmosphere and atmospheric warming reaches a near stable level as methane is removed from the atmosphere at essentially the same rate it is being added. Thus, constant methane emissions cause little additional climatic warming. In fact, the warming experienced under these conditions rises extremally slowly due to the slow adjustment of the atmospheric balance of molecules over centuries in response to past increases in methane emissions[9]. Whereas, due to the accumulative nature of $CO_{2,}$ constant CO_2 emissions are associated with climatic warming.
  - A reduction in methane emissions will result in climatic cooling **before** emissions are reduced to zero due to its short lifetime within the atmosphere, if emissions reductions occur at a fast enough rate. However, a reduction in CO_2 emissions will still result in warming as long as emissions remain above zero. When emissions reach zero, the temperature response to CO_2 remains constant for many hundreds of years due to its longevity in the atmosphere until CO_2 is eventually removed from the atmosphere by a sink.

2.3 METRICS MEASURING GREENHOUSE GAS EMISSIONS

- Metrics are essential for quantifying how GHG emissions contribute to climatic warming. They enable the comparison of the effects of different GHGs to support and enable policy interventions and to prioritise mitigation strategies.

- Global warming potential (GWP) is the heat absorbed by any GHG in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of CO_2. GWP is 1 for CO_2. A pollutant's GWP depends on the number of years (denoted by the subscript) over which the warming potential is calculated.

- GWP_{100} is the most commonly used metric to quantify GHG emissions. It is calculated by measuring the GWP of a particular GHG over 100 years compared to 1 tonne of $CO_{2,}$ thereby creating a CO_2 equivalent for each GHG. This enables characterisation and comparison between the warming effects of different GHGs within the atmosphere.
  - Methane's GWP_{100} value of approximately 28 means that for every 1 tonne of CH_4 in the atmosphere it causes a warming equivalent to 28 tonnes of CO_2 in the atmosphere over 100 years[164].

- The use of traditional CO_2 equivalent targets (including GWP_{100}) across all GHGs (LLCPs and SLCPs) are ambiguous and do not consider the unique behaviours of different pollutants within the atmosphere[12]. GWP_{100} oversimplifies the effects of different GHGs and their attributed warming in the atmosphere and possibly misguides opportunities for climate mitigation and policy interventions.

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[11] https://www.oxfordmartin.ox.ac.uk/downloads/academic/Climate_Metrics_%20Under_%20Ambitious%20_Mitigation.pdf

[12] Allen, M., Fuglestvedt, J., Shine, K. *et al.* New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Clim Change* **6**, 773–776 (2016). https://doi.org/10.1038/nclimate2998

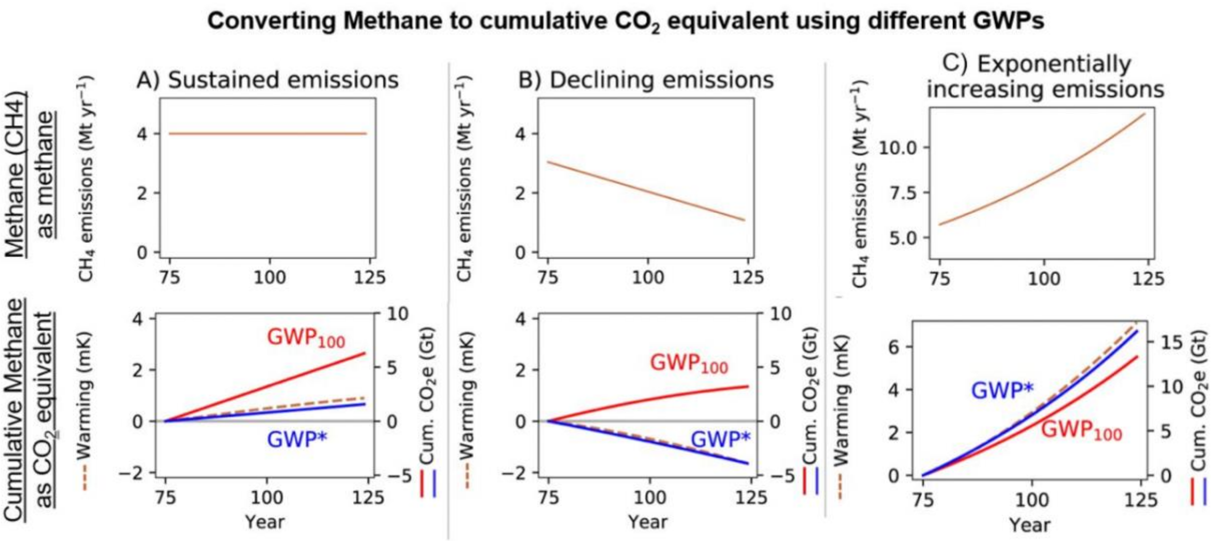
  - A gas which is rapidly removed from the atmosphere i.e., methane, may initially have a large effect on climatic warming, but over longer time periods, as it has been removed, it's warming effect becomes less important. Thus, methane has a GWP$_{20}$ of 84[13] but a GWP$_{100}$ of 28[164].
  - It has been estimated that GWP$_{100}$ exaggerates the warming effect to a constant methane source by a factor of 3-4 and underestimates the warming effects of newly emitted methane by a factor of 4-5[8,14]. Furthermore, GWP$_{100}$ can only be a positive value i.e., signifying global warming, and does not reflect the cooling effect experienced when methane emissions are reduced[15].

- An alternative model, GWP*, first proposed by Myles Allen *et al*, at the University of Oxford in 2018, better accounts for the short-lived nature of methane and thus more accurately reflects its true warming impact in the atmosphere. GWP* is intended to complement the traditional GWP$_{100}$ metric, to better link emissions of methane and their lifetime in the atmosphere with the actual warming effect it produces in the atmosphere given its transient nature. It equates an increase in rate of SLCP emissions with a one-off pulse emission of CO_2 (LLCP) therefore capturing the different behaviours of SCLPs and LLCPs and their impacts on global warming[8].

- When using GWP*, a 1.5% increase in methane emissions would lead to climate impacts 40% greater than indicated by GWP$_{100}$[8]. Furthermore, for methane emissions to have a neutral or net zero impact, emissions must still fall by 2050, but only by 0.35% each year to make no contribution to global warming[8].

  - To put these figures into context, a rapid reduction in methane emissions would lead to a cooling effect, whereas any increases in methane emissions causes substantially more warming than predicted using traditional metrics.

- Lynch *et al* 2020[16] (Figure 4) demonstrate that GWP$_{100}$ overestimates the warming effects of methane, when emissions are constant, and when emissions are reduced, but underestimates the effects of warming from rising methane emissions.



Source: John Lynch *et al* 2020 Environ. Res. Lett. 15 044023, Figs 5 & 6

FIGURE 4: COMPARISON OF GWP* AND GWP100 WARMING METRICS ON DIFFERENT EMISSIONS SCENARIOS OF METHANE (SLCP)

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[13] https://www.bcg.com/publications/2023/methane-global-warming-potential

[14] *Costa Jr. C, Wironen M, Racette K, Wollenberg, E. 2021. Global Warming Potential* (GWP*): Understanding the implications for mitigating methane emissions in agriculture. CCAFS Info Note. Wageningen, The Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)*

[15] Liu, S., Proudman, J. & Mitloehner, F.M. Rethinking methane from animal agriculture. *CABI Agric Biosci* **2**, 22 (2021). https://doi.org/10.1186/s43170-021-00041-y

[16] Lynch J, Cain M, Pierrehumbert R, Allen M. Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and longlived climate pollutants. Environ Res Lett. 2020 Apr 2;15(4):044023. doi: 10.1088/1748-9326/ab6d7e. Epub 2020 Jan 20. PMID: 32395177; PMCID: PMC7212016.

- Expressing methane emissions using GWP_{100} underestimates the positive impact of methane reductions on global warming. As a result, relying on a single CO_2-equivalent emission metric fails to capture the short-term benefits of reducing methane emissions and the corresponding decrease in global temperatures.
    - When using the GWP* model, it has been estimated that reducing livestock methane emissions by 1% per annum by 2100 would reduce their climatic warming levels similar to the early 1990s. Contrasting this, a global annual reduction of 1% CO_2 emissions would still result in 116% increase in warming experienced in 2100 compared to 2019[165].
    - Lynch *et al* highlight that the stable or declining temperatures referenced are relative to current temperatures, not to temperatures before the emissions were produced. Consequently, long-term sources of methane emissions contribute a significant warming legacy with their continued emissions sustaining elevated atmospheric temperatures[16]. Despite minor methane mitigation measures achieving no additional or even reductions in global temperature, they argue that sustained methane emitters have a significant responsibility to reduce their emissions to the greatest extent possible using GWP* as a metric for the assessment of national contributions to observed global warning[16].

- Using the GWP* metric illustrates that reducing methane emissions offers a short-term solution to the climate crisis. Targeting methane emission mitigation has a rapid and measurable cooling effect making it an appealing focus for immediate climate change mitigation. This approach presents an opportunity for high methane-emitting sectors, such as agriculture, to offset the delays in reducing LLCP emissions while new technologies and infrastructure are developed at scale[16].

- However, due to their short atmospheric lifetime, reducing SLCP emissions alone will not significantly impact long-term global temperature stabilisation. Achieving long-term climate goals is still determined by the reduction of CO_2 emissions, which must remain a priority for climate change mitigation[17]. It is essential that methane reduction efforts are employed alongside immediate and aggressive decarbonisation and mitigation strategies involving other GHGs across all sectors within the UK and global economies.

2.4 GREENHOUSE GAS CONCENTRATIONS IN THE ATMOSPHERE

2.4.1 CARBON DIOXIDE

- CO_2 concentrations naturally fluctuate within the Earth's atmosphere due to seasonal changes in photosynthesis (Figure 5).

- Photosynthesis is the process by which plants absorb CO_2 from the atmosphere and through multiple and complex reactions with water, requiring energy from sunlight, produce oxygen and glucose. The annual cyclic nature of CO_2 absorption and emissions from plants (explained in more detail below) is responsible for the saw-tooth pattern seen in Figure 5, which shows atmosphere CO_2 concentration data from Mauna Loa Observatory in Hawaii - the longest running direct measurement of CO_2 in the atmosphere.
    - During springtime in the northern hemisphere, plants absorb CO_2 as part of photosynthesis to produce sugars required for growth, reducing the amount of CO_2 within the atmosphere. In the autumn, plant growth stops, or is significantly reduced, reducing CO_2 is absorption by plants for photosynthesis. In addition to less absorption, there is an increased release of CO_2 into the atmosphere as plant matter decomposes within the soil.

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[17] Inman, M. Carbon is forever. *Nature Clim Change* **1**, 156–158 (2008). https://doi.org/10.1038/climate.2008.122

  - A similar, but less intense pattern occurs within the southern hemisphere in opposite months due to less land area and vegetation compared to the northern hemisphere. Therefore, the global seasonal cycle of CO_2 closely aligns with the patterns of photosynthesis from flora in the northern hemisphere.

Data source: NOAA, measured at the Mauna Loa Observatory

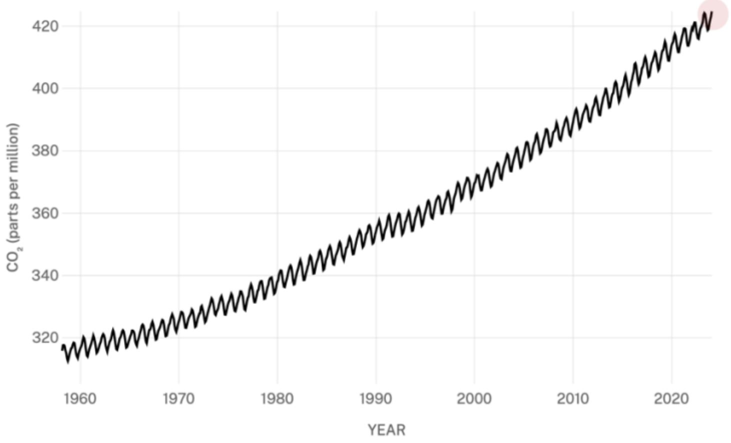

FIGURE 5: CO2 CONCENTRATIONS IN THE ATMOSPHERE FROM 1960 TO PRESENT.

Data source: Reconstruction from ice cores.
Credit: NOAA

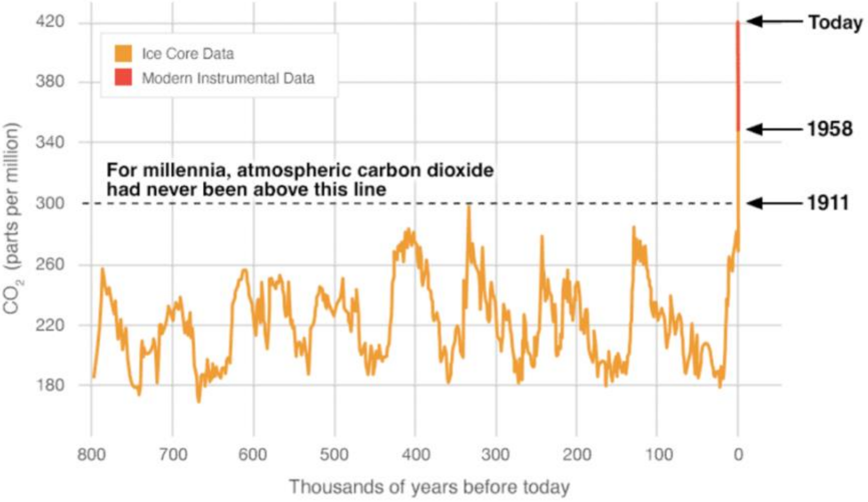

FIGURE 6: ICE CORE RECONSTRUCTION DATA OF CO2 CONCENTRATION IN THE EARTHS ATMOSPHERE FROM 800,000 YEARS AGO TO PRESENT[20]

- Figure 6 shows atmospheric CO_2 concentration, captured by air bubbles trapped within the ice sheets of glaciers during the Earths last three glacial cycles. Anthropogenic increase in CO_2 is more than the natural increase in CO_2 concentration observed after the last ice age approximately 20,000 years ago[18].

- In October 2023, the average atmospheric CO_2 concentration, adjusted for seasonal variation, was 422.17 ppm. This is an increase of around 50% from 280ppm during the 10,000 years prior to the beginning of the Industrial Revolution in 1760[19], and corresponds to an increase of global mean surface temperature by 1.1°C over the same period[20].

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[20] https://climate.nasa.gov/vital-signs/carbon-dioxide/?intent=121#:~:text=Since%20the%20onset%20of%20industrial,ice%20age%2020%2C000%20years%20ago.

[19] https://www.noaa.gov/news-release/carbon-dioxide-now-more-than-50-higher-than-pre-industrial-levels

[20] The Cenozoic CO2 Proxy Integration Project (CenCO2PIP) Consortium*†,Toward a Cenozoic history of atmospheric CO_2.*Science* **382**,eadi5177(2023).DOI:10.1126/science.adi5177

- Recent estimates predict that the present CO_2 concentration in the atmosphere is the highest in approximately 16 million years, since the middle Miocene[166].

- CO_2 is emitted into the atmosphere through anthropogenic activities, including the extraction and burning of fossil fuels, as well as from natural sources which include wildfires and volcanic eruptions.

2.4.2 METHANE

- Methane (CH_4) is the second most abundant GHG in the Earth's atmosphere and remains in the lower troposphere. Methane is often described as a potent GHG, if not the most potent, due to its initial large effect on climate warming.

- The mean atmospheric lifetime of methane in the atmosphere is approximately 9.6 years[167] where the vast majority of methane is removed in the troposphere by reactions with OH radicals. This degradation rate is influenced by the ratio of isotopes and various chemical reactions within the atmosphere[177].

    - Chemical feedback reactions in the atmosphere alter the duration of effect of some GHGs beyond their atmospheric lifetime – this is known as the perturbation time. For methane, the ratio between the perturbation time and lifetime in the atmosphere is 1.4[177]. This means that despite a single methane molecule having an average global lifetime of 9.6 years its perturbation time (length of time it causes warming effects in the atmosphere) is approximately 13.4 years[177].

- Despite methane's short atmospheric lifetime, methane emissions have contributed to approximately 30% of anthropogenic climate change[21], and its atmospheric concentration, currently 1,850 ppb, is approximately 2.6x more than the estimated pre-industrial level in 1750, which was believed to be in the range of 680-715 ppb.[22] This potency, is due to its greater warming potential compared to CO_2 as one molecule of methane traps more heat compared to one molecule of CO_2. The Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report found that methane from anthropogenic activities was responsible for 0.5°C of the present observed climatic warming.[179]

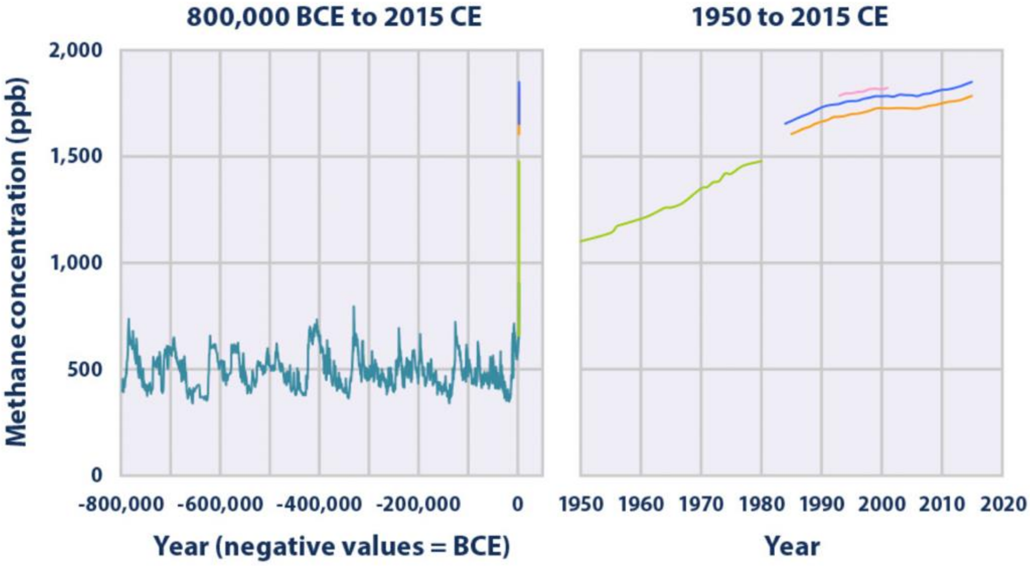

FIGURE 7: GLOBAL CONCENTRATION OF METHANE OVER TIME. THE DATA IS COMPLIED FROM 5 ICE CORE HISTORICAL DATA SETS TAKEN AROUND THE WORLD WITH EACH COLOURED LINE REPRESENTING A DIFFERENT DATA SOURCE[168].

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[21] IEA (2022), Global Methane Tracker 2022, IEA, Paris https://www.iea.org/reports/global-methane-tracker-2022, Licence: CC BY 4.0

[22] Saunois, M. et al, The Global Methane Budget 2000–2017, Earth Syst. Sci. Data, 12, 1561–1623, https://doi.org/10.5194/essd-12-1561-2020, 2020.

- The concentrations of methane in the atmosphere have been fluctuating for approximately one million years, in response to many factors (Figure 7). These fluctuations are not always directly comparable to changes in global temperature. As there are many different isotopes and ways of measuring atmospheric methane concentration, the dynamics of methane are hard to model. However, there has been a recorded consistent upward trend since the mid-1700s (Figure 7).

- Similar to CO_2, the atmospheric concentration of methane fluctuates as part of the natural methane cycle.
    - Methane emissions are directly related to temperature and moisture, and therefore emissions follow seasonal variation when released from natural sources (Figure 8)[23]. Methane concentrations peak in November and reach a minimum in April – May[24] due to this seasonal variation.
    - This fluctuation of methane emission can be attributed to several factors. Most methane sources are concentrated in the northern hemisphere due to its larger landmass and thus greater human and natural sources of methane[25], and contributes approximately 5% more than the southern hemisphere to global methane levels[177]. Furthermore, higher surface temperatures are associated with increased methane emissions and increasing vegetation cover and moisture levels are generally associated with lower methane emissions[25].

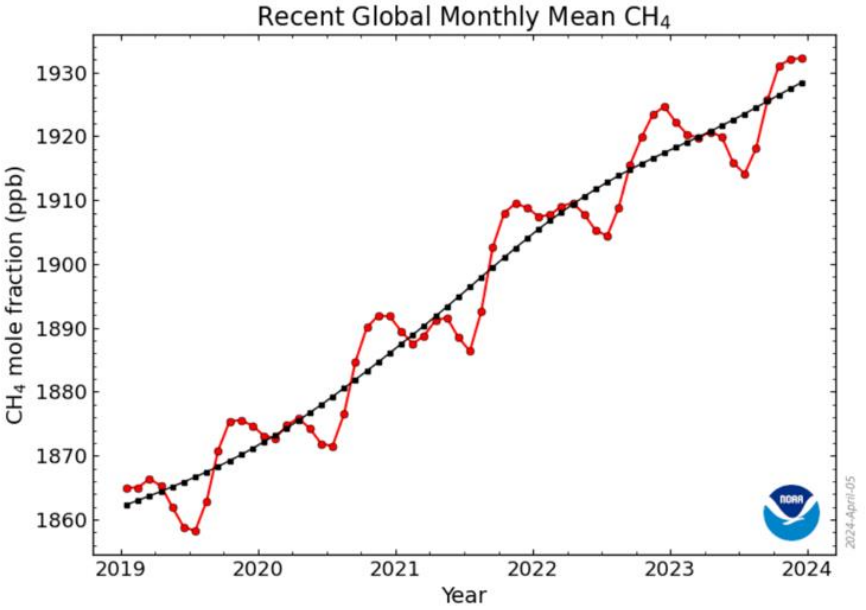

FIGURE 8: GLOBAL MONTHLY VARIATION IN METHANE ATMOSPHERIC CONCENTRATION (RED) AND YEARLY AVERAGE (BLACK) FROM 2019-2024.

- Global methane emissions are rapidly offset by atmospheric and soil sinks, making methane a SLCP. The different methane sources and sinks will be discussed in more detail in Section 3.4.

- Besides its warming effects within the atmosphere, methane also impacts air quality. Methane leads to the formation of tropospheric ozone, a harmful air pollutant which has been estimated to be responsible for over one million premature respiratory deaths worldwide[26]

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[23] Lan, X., K.W. Thoning, and E.J. Dlugokencky: Trends in globally-averaged CH4, N2O, and SF6 determined from NOAA Global Monitoring Laboratory measurements. Version 2024-04, https://doi.org/10.15138/P8XG-AA10

[24] C. Crevoisier, D. Nobileau, Raymond Armante, L. Crépeau, T. Machida, et al.. The 2007-2011 evolu- tion of tropical methane in the mid-troposphere as seen from space by MetOp-A/IASI. Atmospheric Chemistry and Physics, 2013, 13 (8), pp.4279-4289. 10.5194/acp-13-4279-2013 . hal-01103543

[25] Javadinejad, S., Eslamian, S. & Ostad-Ali-Askari, K. Investigation of monthly and seasonal changes of methane gas with respect to climate change using satellite data. *Appl Water Sci* **9**, 180 (2019). https://doi.org/10.1007/s13201-019-1067-9

[26] https://www.ccacoalition.org/news/one-million-premature-deaths-linked-ozone-air-pollution

2.4.3 INTERACTIONS BETWEEN GREENHOUSE GASES IN THE ATMOSPHERE

- Within the atmosphere, it is important to consider the interactions between different GHGs and how this impacts climatic warming.

- Since pre-industrial times, overall methane emissions have been increasing - driven by an increase in anthropogenic methane emissions. While seasonal variation affects the trends in the short-term, emissions from wetlands (a natural methane source) are highly variable and often significant enough to modify or shift the long-term trends of methane emissions. Similarly, the atmospheric methane concentration plateau seen between 2000-2007 (Figure 7) was most likely caused by the influence of increased concentrations of hydroxyl radicals in the atmosphere, produced from increased levels of CO_2 and nitrous dioxide (N_2O) in the atmosphere. This resulted in methane being removed from the atmosphere at a higher rate, despite increased methane emissions from anthropogenic sources in the same period[27].

- Furthermore, it is believed that the global methane concentration surge in 2020 was partly due to increased emissions from wetlands, which were associated with the 0.5°C higher global temperatures and 2-11% increase in precipitation in this year, but also due to a reduction in CO_2 and N_2O emissions during the pandemic[28]. The reduction in other GHGs reduced the concentration of hydroxyl particles in the atmosphere by 1.6% compared to 2019, which reduced the removal of methane from the atmosphere by hydroxyl oxidation[28].

- Additionally, the photoionisation of methane within the atmosphere increases the presence of ozone and water vapour. Water vapour, another GHG, and is thought to be responsible for up to 20% of methane's radiative forcing effect[29].

    - In addition, warmer air holds more water vapour compared to colder air. Therefore, the amount of water vapour in the atmosphere increases as the atmosphere is warmed through the enhanced greenhouse effect, creating a positive feedback cycle for the amount of water vapour present within the atmosphere.

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[27] Skeie, R.B., Hodnebrog, Ø. & Myhre, G. Trends in atmospheric methane concentrations since 1990 were driven and modified by anthropogenic emissions. *Commun Earth Environ* 4, 317 (2023). https://doi.org/10.1038/s43247-023-00969-1

[28] Peng, S., Lin, X., Thompson, R.L. *et al.* Wetland emission and atmospheric sink changes explain methane growth in 2020. *Nature* 612, 477–482 (2022). https://doi.org/10.1038/s41586-022-05447-w

[29] Myhre, G., J. S. Nilsen, L. Gulstad, K. P. Shine, B. Rognerud, and I. S. A. Isaksen (2007), Radiative forcing due to stratospheric water vapour from CH_4 oxidation, *Geophys. Res. Lett.*, 34, L01807, doi:10.1029/2006GL027472.

2.5 THE BIOGENIC CARBON CYCLE AND SOIL SEQUESTRATION

- Methane circulates naturally between the atmosphere and biosphere in the biogenic carbon cycle, simplified by Figure 9.

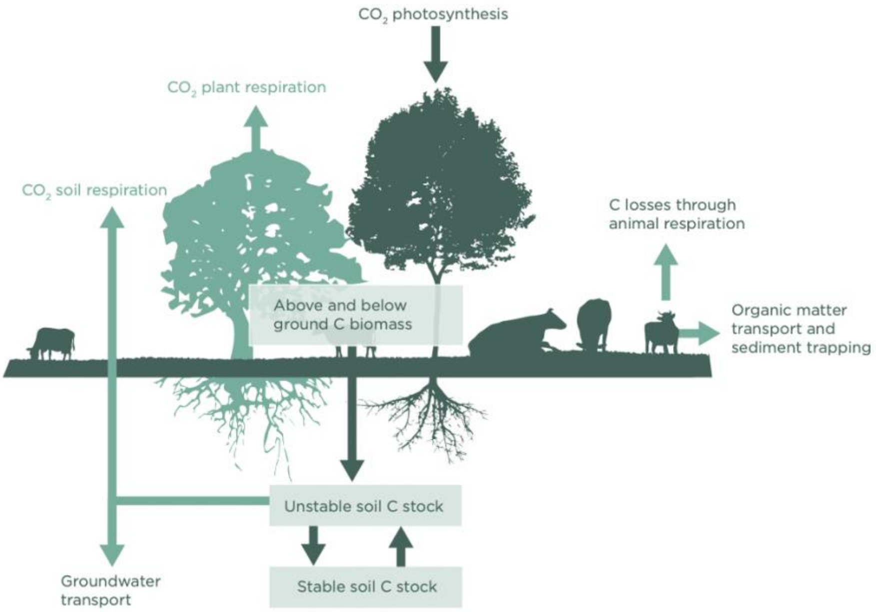

FIGURE 9: KEY DYNAMICS INVOVLED IN THE TERRESTRIAL CARBON CYCLE, A SIMPLIFIED SCHEMATIC. NOTE, THERE IS NO DIRECT MENTION OF METHANE CYCLING, BUT THE PROCESS IS EXPLAINED BELOW. REFERENCE – GRAZED AND CONFUSED? REPORT 2017[95].

  - Within the carbon cycle, plants absorb CO_2 for photosynthesis which is used to make numerous essential carbon-containing compounds in the plant. These include cellulose and other carbohydrates, which form part of the plant biomass, including the leaves, roots, and stem, with some carbon becoming sequestered within the soil.
  - Some of these plants are consumed by animals, and while most animals cannot breakdown cellulose, ruminants can, releasing methane as a by-product in a process called enteric fermentation.
  - A significant portion of the carbon ingested by ruminants from vegetation is lost from grassland systems as CO_2, via respiration, and methane through enteric fermentation. Some of this carbon becomes embedded in the animal carcass or milk, while another portion is returned to the soil through faeces[95].

    - When faeces becomes incorporated into the soil and the carbon within it is converted into more stable forms, it can enhance soil carbon storage, enabling soils to function as a carbon sink. However, soil carbon sequestration depends on various favourable conditions, including soil type and quality, climatic and seasonal factors, precipitation, nitrogen availability, the composition of soil flora and microbiome, and vegetation type. Despite this potential for sequestration, some carbon in faeces is inevitably released back into the atmosphere as CO_2, methane, or other gases[95].

  - Similarly, a portion of the above-ground plant biomass that remains uneaten eventually dies and decomposes. This decomposition can result in the release of CO_2 or, under certain conditions, methane. However, if the plant material is integrated into the soil and made into stable forms it can contribute to a net removal of carbon from the atmosphere - reinforcing the role of soil as a carbon sink.
  - These processes highlight the dynamic nature of the carbon cycle in grassland ecosystems and the fine balance between soil carbon release and sequestration.

        - Terrestrial ecosystems can become a net source of carbon when the rate of carbon release from animal respiration and organic matter decomposition (including decaying animals, plants and faeces) surpasses the rate of CO_2 fixation through photosynthesis. This shift often occurs in situations such as overgrazing, deforestation, biomass burning or the draining of carbon-rich peatlands. Conversely, if conditions are favourable for plant growth, these ecosystems can function as a carbon sink, facilitating a net transfer of carbon from the atmosphere into the soil and/or into the growing biomass[95].

    - After approximately 12 years in the atmosphere, the methane is oxidised to form CO_2 which can be reabsorbed by plants for photosynthesis to complete the carbon cycle. However, CO_2 remains in the atmosphere for a much longer time than methane, potentially hundreds of years depending on conditions[8], which therefore reduces the recycling potential of carbon.

- The source of methane emissions determines if the resulting CO_2 produced from the hydroxyl oxidation of methane in the atmosphere contributes to the enhanced greenhouse effect, outside of the natural carbon cycle.

    - Emissions from biogenic sources described in the carbon cycle **do not** contribute to increased CO_2 concentrations within the atmosphere, as there is no addition of carbon into the atmosphere due to the recycling of carbon in the carbon cycle. If herd sizes are kept constant, then the amount of carbon released in the form of methane will be the same as the amount of CO_2 that is absorbed in plants for photosynthesis and subsequently eaten and expelled from ruminants.

        - However, despite this carbon equivalence, the warming potential between one molecule of CO_2 and one molecule of methane is not equivalent as discussed in Section 2.3. For example, each molecule of methane in the atmosphere exhibits a stronger global warming potential compared to CO_2, illustrated by the GWP_{20} for methane of 84 i.e., 1 tonne of methane produces a warming equivalent to 84 tonnes of CO_2 in the atmosphere over 20 years[13].
        - Therefore, there is an additive effect on climatic warming when comparing the absorption of one molecule of CO_2 in photosynthesis and the release of one molecule of methane from enteric fermentation from the carbon cycle over a short period.

    - Conversely, emissions from fossil fuels will contribute to an overall increased CO_2 concentration in the atmosphere as there is release of carbon from long term stores and sinks into the atmosphere.

- It is important to distinguish between soil sequestration potential, which refers to the transfer of carbon from the atmosphere to soil or biomass, and carbon storage, which refers to the amount of carbon retained as a long-term stock in soil or woody biomass. Mature forests serve as important carbon stores, particularly in their woody biomass, but typically exhibit very low rates of carbon sequestration within the soil[30]. However, a recent 2024 study challenges the assumption that mature forests have limited capacity to respond to increases in atmospheric CO_2 concentrations, compared to younger trees[31]. In this study, a 180-year-old woodland in central England was exposed to free-air CO_2 enrichment for seven years. The findings revealed that in response to elevated CO_2 levels the forest enhances its carbon sequestration potential by increasing growth and the trees long-lived woody biomass - a crucial long-term carbon store[31]. These results highlight the potential role of mature temperate forests in climate change mitigation and emphasise the remarkable adaptability of ecosystems in response to rapidly changing environmental conditions.

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[30] Smith, P. (2004). How long before a change in soil organic carbon can be detected? Global Change Biology 10, pp. 1878-1883, acc. 19.2.20

[31] Norby, R.J., Loader, N.J., Mayoral, C. *et al.* Enhanced woody biomass production in a mature temperate forest under elevated CO_2. *Nat. Clim. Chang.* (2024). https://doi.org/10.1038/s41558-024-02090-3

- Soils are significant carbon stores, with global totals to a depth of 1m in the range of 1,500-2,400 Gt carbon or 5,500-8800 Gt CO_2[32].

    - Carbon and CO_2 have different molecular weights - 1 tonne of carbon is equal to 3.667 tonnes of CO_2 - and therefore are not directly comparable as stores. Technically CO_2 cannot be stored in the soil, but CO_2 equivalent metrics are commonly used for sequestration values to allow for easy comparison with GWP metrics[95].

- Soils acting as long-term carbon stores, store approximately three times the total amount of CO_2 found in vegetation and twice the amount of carbon found in the atmosphere[33].

    - In the UK, over 94% of UK carbon stocks are in soils, equating to 4,019MtC[34]. The majority of soil carbon stocks are stored in open wetlands, such as peat soils, followed by improved grassland habitats. Importantly, the volume of carbon stored in these grasslands is attributed to the predominance of this habitat class in the UK, rather than its ability to store carbon[34].
    - It has been estimated that up to 60% of the UK's soil carbon could be lost when converting forested land to agricultural land to be used for crops or grazing livestock[35]. Furthermore, the historical effects of land-use change and current soil management practices on agricultural land have direct long-term effects on soil health and the associated microbial community[33].

- Under favourable conditions, soils will sequester carbon until an equilibrium is reached, at which point no further sequestration occurs even if the carbon 'stock' in soil is not fully saturated. Soils can shift from being a net carbon source or carbon sink, and further increases in sequestration may be possible if there is a change in how the land is used or managed[36].

- Methanotrophic bacteria within the soil are a major sink of methane, accounting for 4-10% of the total methane sink[22]. Two different types of bacteria are mainly responsible for this sink – high-capacity, low affinity (HCLA) and low-capacity, high affinity (LCHA) bacteria. HCLA bacteria grow in areas of high methane concentration i.e., wetlands, and use methane as a predominant energy source. Whereas LCHA bacteria grow in areas of low methane concentration i.e., they utilise the methane within the atmosphere to grow[37].

- Forest soils are good sinks for atmospheric methane as they are optimally moist for methanotrophic bacterial activity and the diffusion of methane between the soil and the atmosphere is high[38]. If the water table is low, methane has to pass through methanotrophic bacteria within the soil before it can reach the Earth's atmosphere. However, in wetlands, where the water table is often significantly higher, methane is able to diffuse into the air via plant-mediated transport or ebullition (through small air pockets within the soil), avoiding being utilised by the soil methanotrophic bacteria on its way to the surface[39].

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[32] Smith P, Soussana JF, Angers D, Schipper L, Chenu C, Rasse DP, Batjes NH, van Egmond F, McNeill S, Kuhnert M, Arias-Navarro C, Olesen JE, Chirinda N, Fornara D, Wollenberg E, Álvaro-Fuentes J, Sanz-Cobena A, Klumpp K. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. Glob Chang Biol. 2020 Jan;26(1):219-241. doi: 10.1111/gcb.14815. Epub 2019 Oct 6. PMID: 31469216; PMCID: PMC6973036.

[33] Post Note, Research briefing 601, Sustaining the Soil Microbiome, May 2019; https://researchbriefings.files.parliament.uk/documents/POST-PN-0601/POST-PN-0601.pdf

[34] https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/uknaturalcapital/experimentalcarbonstockaccountspreliminaryestimates#:~:text=The%20carbon%20stored%20in%20UK,or%2094.2%25%20of%20the%20total.

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[36] Smith, P. (2014). Do grasslands act as a perpetual sink for carbon? Global Change Biology, 20(9), pp. 2708-2711.

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[38] http://www.ghgonline.org/methanesinksoil.htm#:~:text=Woodland%20soils%20can%20act%20as,30%20million%20tonnes%20per%20year.

[39] Cui, S., Liu, P., Guo, H. *et al.* Wetland hydrological dynamics and methane emissions.*Commun Earth Environ* **5**, 470 (2024). https://doi.org/10.1038/s43247-024-01635-w

- Soils are under enormous pressure from multiple factors, including agricultural intensification, urbanisation, and climate change. Conventional agricultural practices – such as intensive tillage, monocultures, and the extensive use of fertilisers and other chemicals - have resulted in the depletion soil organic matter, the primary food source for soil microbes, which is crucial for maintaining a healthy, functional soil microbiome[40]. As a result, soils are becoming less productive, creating a vicious cycle where increasing inputs, such as fertilisers, are required to artificially replace essential soil nutrients, further exacerbating soil degradation. It has been estimated that any disturbance to the soil microbiome, by agricultural practices such as intensive tilling or overgrazing, can stimulate microbial decomposition, increasing emissions from the soil, at a cost of £3.21 billion to the UK[40].

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[40] The Hidden Cost of UK Food – Sustainable Food Trusts 2019 Report

3.0 METHANE

3.1 INTERNATIONAL COMMITMENTS TO REDUCING METHANE

- THE KYOTO PROTOCOL 1997
    - The Kyoto Protocol extended the 1992 United Nations Framework Convention on Climate Change (UNFCCC) which commits members to reduce GHG emissions based on the scientific consensus that anthropogenic factors are driving global warming[41]. The protocol came into force in February 2005, and as of 2020, there are 192 member parties[41]. The GHGs included in this protocol are CO_2, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride.
    - The protocol aims to reduce GHG concentrations in the atmosphere to '*a level that would prevent dangerous anthropogenic interference with the climate system*.' It acknowledges that individual countries have different capabilities in combating climate change and emphasised the historic role played by developed countries and placed the obligation on them to reduce current emissions[41]. To provide specific targets for GHG emissions reductions of the protocol, the GWP_{100} metric was created to avoid the need for the creation of separate targets for each GHG, and instead implements a multi-gas approach under one figure[42]. Ever since its inception, it has caused turbulence within the scientific community, particularly for its oversimplification of GHG behaviours in the atmosphere, see Section 2.3.

- THE PARIS AGREEMENT 2015
    - The Paris Agreement is a legally binding international treaty on climate change that was adopted in 2015. As of 2023, 195 states have joined the agreement[43]. Of the three UNFCCC member states which have not joined the agreement, only Iran is the major emitter.
    - The agreement sets long term goals for all participating nations to mitigate and adapt to climate change. This includes the pledge to limit global temperature rise to 1.5°C above pre-industrial levels and to keep warming well below 2°C above pre-industrial levels[43]. Every 5 years, each country is expected to submit a national climate action plan to provide necessary actions to reach the goals of the agreement. It includes assessments of the collective progress towards achieving the long-term goals and provide finance for developing countries in mitigating climate change[43].
    - The current UK national targets to reduce GHG emissions are insufficient to meet the requirements as stipulated in the agreement. The CCC's report on the UK's third national action plan, published in May 2024, says that the UK has '*lost its place as a leader of climate adaptation*', and that the report *'fails to set out a compelling vision for what the government's 'well adapted UK' entails, and only around 40% of the short-term actions to address urgent risks identified in the last Climate Change Risk Assessment are progressed'*[44].

- THE GLOBAL METHANE PLEDGE
    - An alliance of over 150 countries, representing more than 50% of global anthropogenic methane emissions[45], established the Global Methane Pledge[46] at the COP26 conference in Glasgow in 2021.

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[41] https://unfccc.int/kyoto_protocol

[42] https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review/methods-for-climate-change-transparency/common-metrics#:~:text=The%20GWP%20for%20a%20time,operational%20in%20the%20Kyoto%20Protocol.&text=The%20COP%20in%20its%20decision,in%20CO2%20eq%20terms.

[43] https://www.un.org/en/climatechange/paris-agreement

[44] https://www.theccc.org.uk/publication/independent-assessment-of-the-third-national-adaptation-programme/?chapter=executive-summary#executive-summary

[45] https://www.globalmethanepledge.org

[46] https://www.iea.org/policies/14257-global-methane-pledge#

- This pledge commits participating nations to reducing methane emissions by 30% from 2020 levels by 2030, with the aim to help achieve the UNFCCC's global warming reduction target of 1.5°C[45].
- According to scenarios analysed by the Intergovernmental Panel on Climate Change (IPCC), global methane emissions must be reduced by 40-45% by 2030 to achieve the least-cost pathways which limit global warming of 1.5°C this century. This reduction must be accompanied by substantial simultaneous reductions of all climate pollutants, including CO_2 and other SLCPs[47].

    - Achieving these reductions would avoid between 0.1-0.3°C of global warming by the mid-century and would be consistent with keeping the Paris Climate Agreement's goal of limiting global temperature rise by 1.5°C[45]. Beyond the environmental benefits, meeting the pledge would also prevent 26 million crop losses, 255,000 premature deaths, 775,000 asthma-related hospitalisations each year[45].

- However, a joint assessment by UNEP and the World Meteorological Organisation indicated that, in the absence of additional mitigation measures, anthropogenic methane emissions are projected to increase by 25% by 2030 compared to 2005 levels. This rise is driven by increased emissions from the fossil fuel industry (including coal mining, oil, and gas production), as well as growing emissions from agriculture and municipal waste sectors[48].
- Figure 10[49] shows that, as of 2024, out of the top four methane emitting nations, China, India and Russia, are yet to sign up for the pledge.

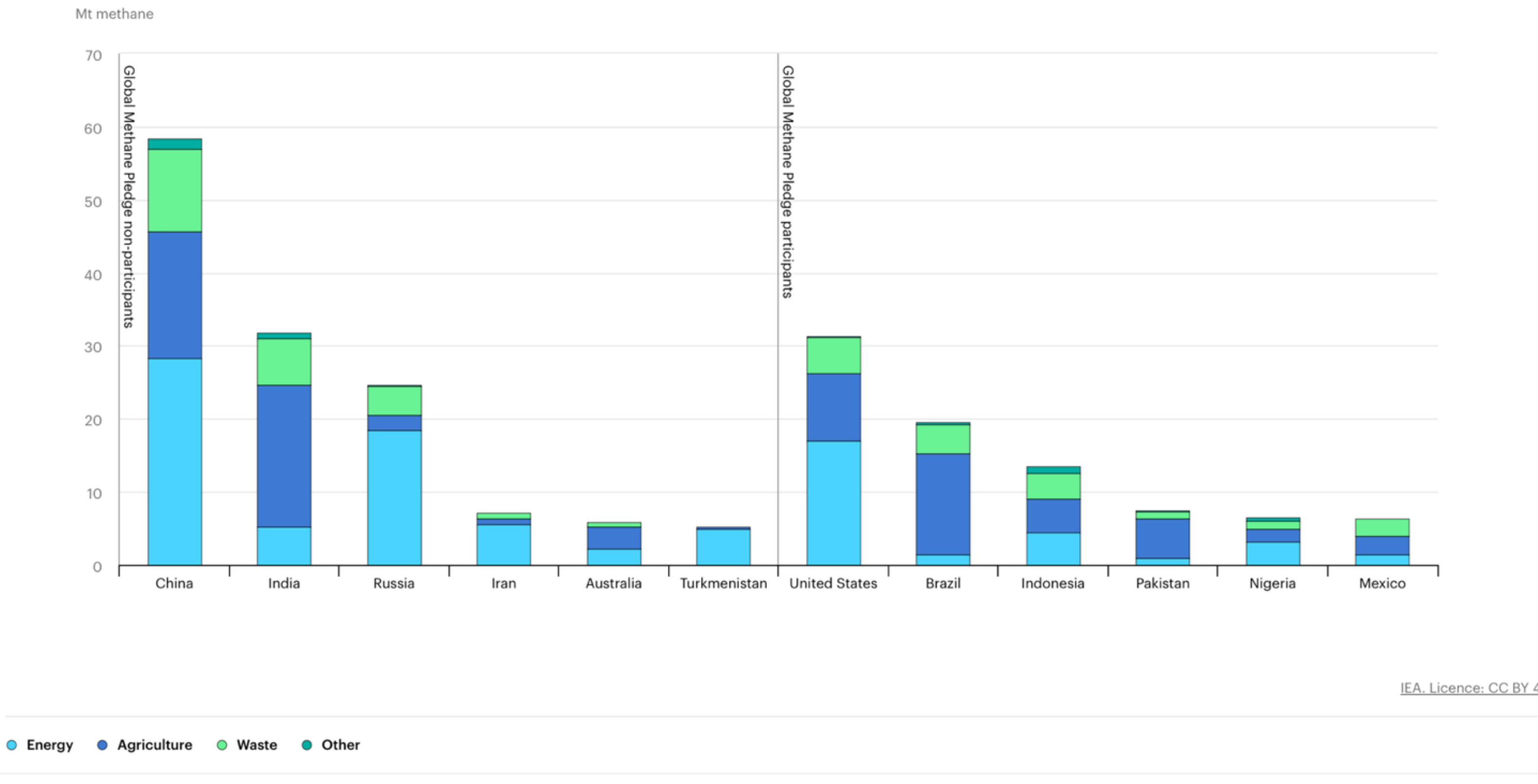

FIGURE 10: TOP 12 METHANE EMITTERS WITH SECTOR BREAKDOWN, 2021 DATA.

REFERENCE - IEA (2022), *TOP TWELVE EMITTERS OF METHANE WITH BREAKDOWN BY SECTOR, 2021*, IEA, PARIS HTTPS://WWW.IEA.ORG/DATA-AND-STATISTICS/CHARTS/TOP-TWELVE-EMITTERS-OF-METHANE-WITH-BREAKDOWN-BY-SECTOR-2021, LICENCE: CC BY 4.0

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[47] United Nations Environment Programme and Climate and Clean Air Coalition (2021). Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. Nairobi: United Nations Environment Programme.

[48] https://csl.noaa.gov/assessments/ozone/2022/executivesummary/

[49] IEA (2022), *Top twelve emitters of methane with breakdown by sector, 2021*, IEA, Paris https://www.iea.org/data-and-statistics/charts/top-twelve-emitters-of-methane-with-breakdown-by-sector-2021, Licence: CC BY 4.0

- To meet the targets set by the Global Methane Pledge, the UK would need to reduce its total methane emission by 72% from the 1990 baseline[50]. However, among the countries that have signed the pledge, fewer than 60 countries have developed or are in the process of developing a national methane action plan, which is essential for outlining the strategies ad measures they will implement to achieve a 30% reduction in methane emissions by 2030[51].

3.2 Global GHG and Methane Emissions

- A 2019 IPCC report estimated that 23% of all anthropogenic GHG emissions originated from the agriculture, forestry and other land use industries. In total, these industries accounted for 13% CO_2, 44% methane, and 81% N_2O of anthropogenic emissions during 2007-2016[52].
    - The Food and Agriculture Organisation (FAO) estimates that the livestock sector alone is responsible for 14.5% anthropogenic GHG emissions: of this, beef production contributes 41%, dairy 20%, pigs 9%, and poultry 8%[103]. However, this is likely an overestimate as data was collected in 2013 when unprecedented amounts of deforestation (predominantly for land-use change for the agricultural industry) occurred. More recent estimates suggest the sector contributes approximately 12% of all anthropogenic GHG emissions, with a similar proportion of within sector livestock species contributions[153].
    - Emissions from livestock arise through various pathways, including enteric fermentation in ruminants, manure management, feed production, processing and transport of animals and their by-products and energy consumption[153].

- Globally, approximately 40% of methane emissions are attributed to natural sources, predominantly wetland environments, while the remaining 60% are from anthropogenic sources, primarily the fossil fuel, agriculture, and waste sectors, as shown in Figure 11.

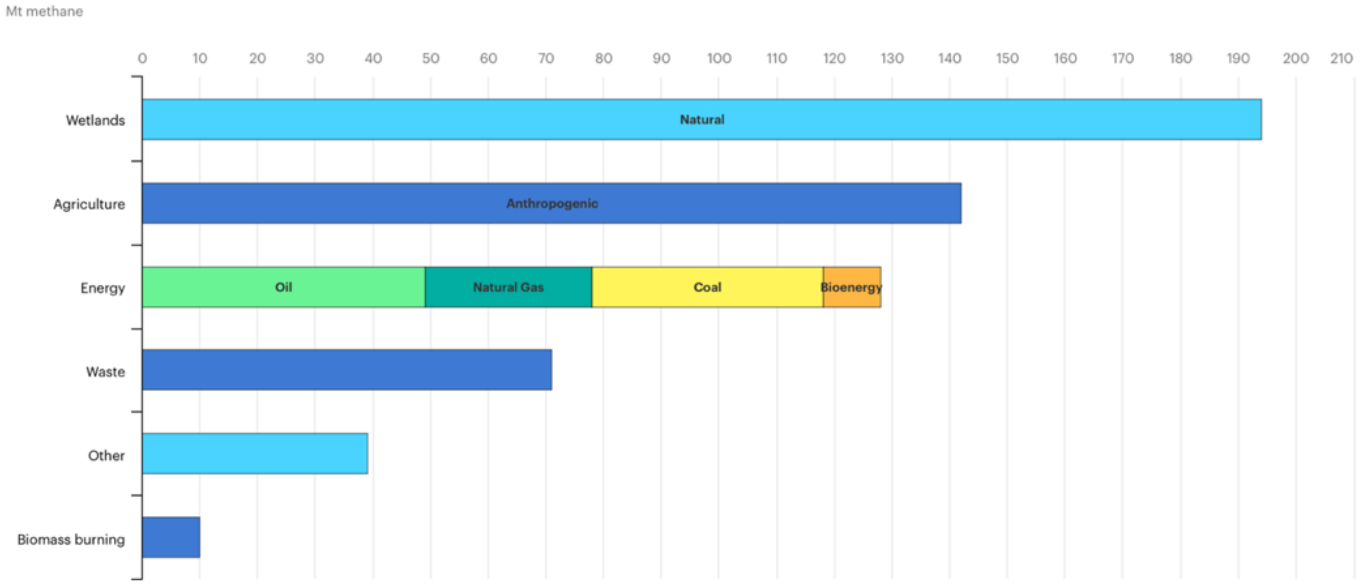

FIGURE 11: SOURCES OF METHANE EMISSIONS, 2023[21].

REFERENCE - HTTPS://WWW.IEA.ORG/REPORTS/GLOBAL-METHANE-TRACKER-2024/UNDERSTANDING-METHANE-EMISSIONS

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[50] https://green-alliance.org.uk/wp-content/uploads/2022/10/Global-methane-pledge.pdf

[51] https://www.ft.com/content/65a346e4-1ce8-4027-9427-a3347691e8bd

[52] IPCC, 2019: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management,foodsecurity,andgreenhousegasfluxesinterrestrialecosystems*

- Globally, methane emissions from the agriculture, forestry and land use sector contribute approximately 44% of all global methane emissions. Of this, 46% of methane emissions are produced from enteric fermentation by domesticated ruminants[53]. This accounts for 46% and 43% of total emissions in dairy and beef supply chains, respectively[54].

3.3 UK METHANE EMISSIONS

- Total methane emissions in the UK have decreased by 62.5% since 1990, a reduction significantly greater than the 46.3% decline in CO_2 emissions over the same period[55]. In comparison, methane emissions in the USA and EU have only decreased by 15% and 41%, respectively, since 1990[55].

- In 1990, UK methane emissions accounted for 17% of UK GHG emissions, equivalent to 135 $MtCO_2e$. By 2020, methane's contribution to total UK GHG emissions has decreased to approximately 13%, or 52 $MtCO_2e$[55] (Figure 12. Of this, the agricultural sector made up approximately 48% (25$MtCO_2e$) of total methane emissions[55]. Despite this trend of reducing methane emissions, in 2022 methane accounted for 14% of the UK's GHG emissions[56].

Source: BEIS, UK 1990-2020 Greenhouse Gas Inventory

FIGURE 12: UK NET GHG EMISSIONS FROM 1990-2020

- Methane emissions in the UK primarily originate from three sectors; agriculture, forestry and land-use, energy, and waste. The CCC reported that methane emissions in the UK reduced substantially between 2000-2015, predominately driven by decreases in emissions from landfill and a decline in UK coal production (see Figure 13). However, in recent years the progress has slowed.
    - Since 1990, methane emissions have reduced by 75% (47$MtCO_2e$) in the waste sector, 84% (32$MtCO_2e$) in the energy sector and by approximately 15% (4$MtCO_2e$) in the agriculture sector[55].

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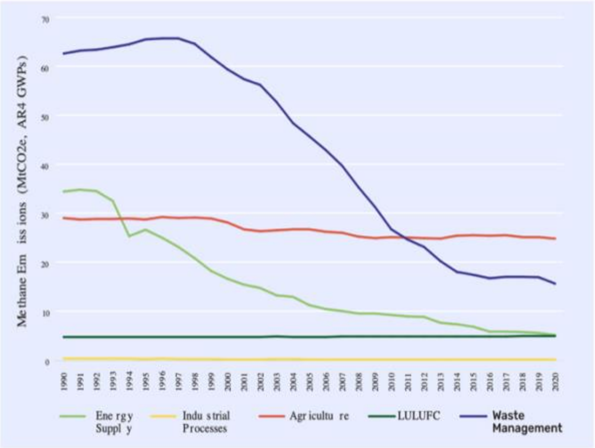
[53] L.R. Thompson, J.E. Rowntree, Invited Review: Methane sources, quantification, and mitigation in grazing beef systems, Applied Animal Science, Volume 36, Issue 4, 2020,

[54] https://www.fao.org/4/i3437e/i3437e04.pdf

[55] https://www.gov.uk/government/publications/united-kingdom-methane-memorandum/united-kingdom-methane-memorandum

[56] https://environmentagency.blog.gov.uk/2024/04/10/reducing-methane-emissions-to-help-combat-climate-change/

- In 2022, the UK government published the methane memorandum[55], which highlights the importance of reducing methane emissions, outlines the UK's progress to date, and details the future mitigation strategies under consideration to reduce methane emissions[55]. It states that methane is the last '*low hanging fruit*' in tackling climate change as mitigation methods are both currently available and cost effective. It goes on to say that 40% of current methane emissions could be avoided at no extra cost and available measures could reduce emissions by 45% by 2030 across agriculture, energy, and waste sectors[55].



Source: BEIS, UK 1990-2020 Greenhouse Gas Inventory.

FIGURE 13: UK METHANE EMISSIONS BY SECTOR FROM 1990 TO 2020

- Figures 14 and 15 illustrate the trends in the UK's total GHG and methane emissions within the agricultural sector from 1990 to 2021, respectively[57]. While there has been a modest reduction in all GHG emissions in the sector the decrease has been minimal and largely attributed to reductions in cattle and sheep populations over the same period[57].

- Since 2011, the agriculture sector has become the largest anthropogenic source of methane emissions in the UK[55]. Projections suggest that if current trends in emission reductions continue in other sectors, the agricultural industry could become the second-largest emitter of GHGs by 2050 in the UK[58].

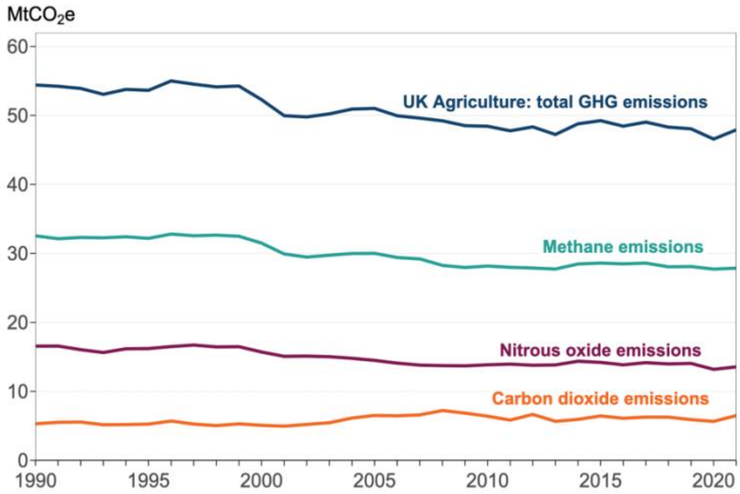


FIGURE 14: GHG EMISSIONS FROM UK AGRICULTRE SECTOR 1990-2021. SOURCE – DEPARTMENT FOR BUISNESS, ENERGY AND INDUSTRIAL STRATEGY

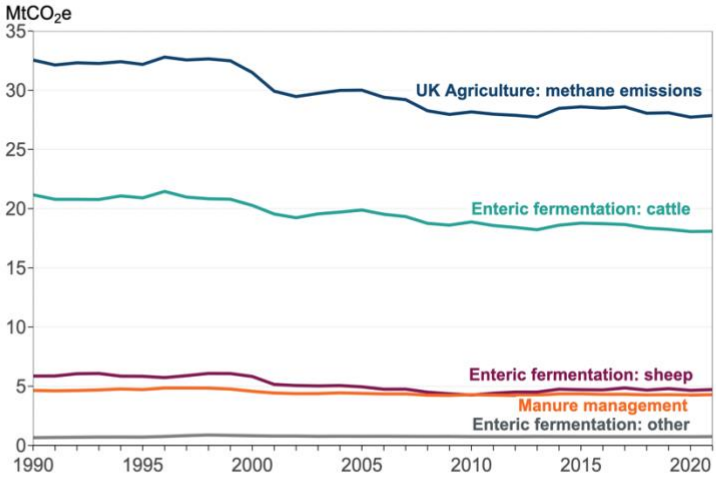


FIGURE 15: METHANE EMISSIONS FROM UK AGRICULTURE SECTOR BY SOURCE 1990-2021. SOURCE – DEPARTMENT FOR BUISNESS, ENERGY AND INDUSTRIAL STRATEGY

- Given what we know about SLCPs, it can be assumed that atmospheric methane emissions from UK ruminants are stable or potentially decreasing from the atmosphere, as the methane emissions are being removed at a rate equal or faster than it is being emitted. This trend can be attributed to the short-lived nature of methane in the atmosphere and the reduction in the UK ruminant population over the past 30 years. Consequently, it can be inferred that the UK ruminant sector has not contributed to active climatic warming from enterically

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[57] https://www.gov.uk/government/statistics/agri-climate-report-2023/agri-climate-report-2023
[58] Post Note, Number 600, Climate Change and Agriculture, May 2019, https://researchbriefings.files.parliament.uk/documents/POST-PN-0600/POST-PN-0600.pdf

produced methane, given the declining herd sizes (See 4.1.1). However, despite this reduction, ruminants were still estimated to be responsible approximately 45% of UK's methane emissions in 2017[59], a trend which is stable.

- When applying the GWP* metric to calculate GHG emissions from the UK's agricultural sector in 2016, the warming potential reduces significantly from 45.6 $MtCO_2e$ to 9.5$MtCO_2e$*. The warming potential of CO_2 and N_2O – both LLCPs – remains consistent with traditional GWP metrics, totalling 19.9$MtCO_2e$. However, the warming potential of methane emissions were recalculated as -10.6$MtCO_2e$*, reflecting a reduction in methane levels since the 1996 base year in the sector[60].

3.4 METHANE SINKS AND SOURCES

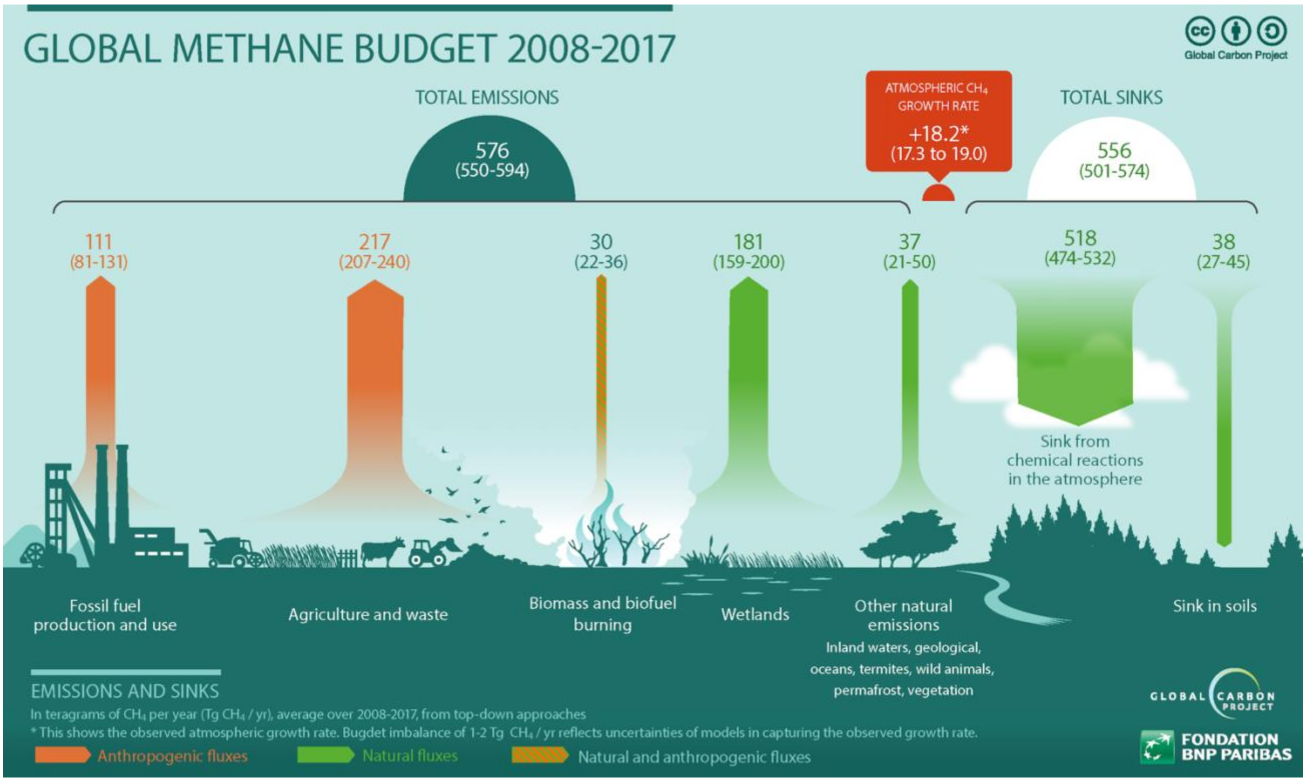

FIGURE 16: GLOBAL METHANE EMISSION SOURCES AND SINKS.
REFERENCE - BY THE GLOBAL CARBON PROJECT - HTTP://WWW.GLOBALCARBONATLAS.ORG/EN/CH4-EMISSIONS / HTTPS://ESSD.COPERNICUS.ORG/ARTICLES/12/1561/2020/, CC BY-SA 4.0, HTTPS://COMMONS.WIKIMEDIA.ORG/W/INDEX.PHP?CURID

- The amount of methane present within the Earth's atmosphere is determined between the production of methane from the Earth (source) and the destruction and removal of methane, predominately within the atmosphere (sinks).

- Measuring methane emissions is inherently variable. For instance, livestock emissions are often extrapolated based on feed intake, which can differ significantly between individual animals and production systems due to variations in feed type, quantity, and quality, as well as factors such as the health status of animals. Additionally, there is often considerable variation between top-down and bottom-up estimates of methane emissions, even when measuring the same emission source. These variations in estimation methods will not be explored in this

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[59] Agricultural Emissions and Climate Change, DEFRA, September 2019, 9th Edition https://assets.publishing.service.gov.uk/media/5d93884ced915d5569b5dbe8/agriclimate-9edition-02oct19.pdf

[60] Costain, f. (2019), 'Livestock are not the global warming enemy'. Veterinary Record, 185: 449-449. https://doi.org/10.1136/vr.l5963

FactFile but their uncertainties are acknowledged here and should be noted with any methane emission estimation.

3.4.1 SINKS

- In the atmosphere, methane is degraded by hydroxyl radicals within the troposphere and stratosphere in a process called hydroxyl oxidation, which produces CO_2 and water vapour (both of which are GHGs). Other radicals in the atmosphere, including chlorine, also interact with methane and cause further degeneration in the atmosphere. It is believed that these processes are responsible for 90-96% of the global methane sink[61].

- Soil sinks account for approximately 4-10% of methane degradation from soil methanotrophic bacteria, and the ocean accounts for a very small amount of atmospheric methane sinks[61].

3.4.2 SOURCES

- Anthropogenic methane accounts for 20% of global GHG emissions annually, using the GWP_{100} metric[21].

- During 2019, approximately 60% of total global methane emissions were from anthropogenic sources, while natural sources contributed around 40%[62].

    - Of this, agriculture is the largest source of anthropogenic methane emissions (40%). Within agriculture, livestock are the largest contributor to emissions (32%), with enteric fermentation from ruminants (85%) and manure management (15%) within this sector[158] (Table 1).
    - Other anthropogenic sources of methane include fossil fuel extraction, transportation and use, wetlands (rice paddies and peat degradation) and waste management. See Table 1 for a complete breakdown.

- It is an oversimplification to assume that natural and anthropogenic methane sources operate independently or that their interactions are unaffected by climate change. In reality, natural sources of methane are highly sensitive to climatic changes, which can significantly influence their emission patterns.

    - For instance, anthropogenic increases in GHG emissions have accelerated the melting of Arctic permafrost, resulting in permafrost lakes becoming increasingly significant natural methane sources. Similarly, over the past 20 years, wetland methane emissions are estimated to have increased by 1.2-1.4 million tonnes annually[63]. Wetlands are particularly sensitive to warmer and wetter conditions, which may amplify methane emissions in response to climate change, potentially creating a positive feedback loop[63].
    - Moreover, land-use changes, such as converting forests or other natural ecosystems into agricultural land, increases the amount of nitrogen trapped within the soil. This nitrogen inhibits the methane oxidation capacity of methanotrophic (methane absorbing) bacteria within the soil, and therefore reduces the ability of the soil to act as a methane sink. Additionally, increased soil nitrogen also stimulates methanogenic (methane producing) bacteria and therefore it increases the methane emissions produced from microbes in the soil while simultaneously decreasing methane removal[64].

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[61] FAO. 2023. *Methane emissions in livestock and rice systems – Sources, quantification, mitigation and metrics*. Rome. https://doi.org/10.4060/cc7607en

[62] https://www.iea.org/reports/methane-tracker-2021/methane-and-climate-change

[63] Zhang et al. (2023) Recent intensification of wetland methane feedback, Nature climate change, doi:10.1038/s41558-023-01629-0

[64] Nazaries, L., Murrell, J.C., Millard, P., Baggs, L. and Singh, B.K. (2013), Methane, microbes and models. Environ Microbiol, 15: 2395-2417. https://doi.org/10.1111/1462-2920.12149

3.4.2.1 Natural Methane Sources

- Natural sources of methane have always, and will always be, part of the biogenic carbon cycle. Their emissions fluctuate depending on a variety of parameters including, but not limited to, the atmospheric conditions, soil conditions and water levels. By far the largest natural methane source is from wetlands, which are volatile environments that can act as carbon sinks or methane emitters depending on a range of conditions. Other natural sources include methane emissions from permafrost lakes, termite mounds, geological sources, and those from wild ruminants, but contribute to natural methane emissions a significantly smaller extent compared to wetland emissions as shown in Figure 16.

- Wetlands
  - Wetlands are distinct ecosystems, predominantly found in the northern hemisphere, characterised by water-logged soils and host a unique variety of flora and fauna which have adapted to this constant presence of water. They include marshes, swamps, peatlands, and bogs to name a few, and cover approximately 1.6 billion hectares across the globe or 6% of the globes surface[65]. The high levels of water saturation, and therefore low levels of oxygen concentration, creates environments where methanogenic bacteria and anaerobic bacteria survive and flourish.
  - The levels of methanogenesis which occur in wetlands predominantly depends on soil temperature, oxygen concentration and soil composition. For example, a warm anaerobic environment with high soil organic matter content would create the most favourable conditions for methanogenesis in wetland environments[66]. However, the amount of methane emitted from wetlands also depends on the abundance of methanogenic vs methanotrophic bacteria, the water table, transport mechanisms of the methane from the soil, and the type of plants present in the ecosystem. Due to the complex interplay of these factors, a single wetland environment has the capacity to be a net source, as well as a net store of carbon, depending on the conditions present[66].
  - The 2021 Global Wetland Outlook Report finds that 35% of the world's wetlands have been lost since 1970[65]. Currently, human activities are reducing global wetland habitats by 1% each year[65].

    - In 2023, it was estimated that methane emissions from wetlands contributed to over 83% of the natural global methane emissions, which was approximately 194 Mt of methane released into the atmosphere that year[67].
    - Bio-geomorphic wetland environments, which include peatlands, mangroves, salt marshes, and seagrass meadows store as much as 20% of the global organic carbon, despite only covering approximately 1% of the Earth's surface[68].

3.4.2.2 Anthropogenic Methane Sources

- The increase in anthropogenic methane emissions have been the leading cause of increased methane concentration within the atmosphere since pre-industrial times[22] and research estimates that 25% of current warming, or 0.5°C[178], is driven by this anthropogenic methane[55].

- Anthropogenic emissions include those from the waste sector, including wastewater and landfill, the fossil fuel industry, including oil and natural gas extraction, distribution, and usage, and those from agriculture, primarily consisting of livestock sources (enteric fermentation and manure management) and from rice paddies[22].

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[65] Convention on Wetlands. (2021). *Global Wetland Outlook: Special Edition 2021*. Gland, Switzerland: Secretariat of the Convention on Wetlands.

[66] Christensen, Torben Røjle & Ekberg, Anna & Strom, L. & Mastepanov, Mikhail & Oquist, M. & Svensson, Bo & Nykänen, Hannu & Martikainen, Pertti & Óskarsson, Hlynur. (2003). Factors controlling large scale variations in methane emissions from wetlands. Geophysical Research Letters. 30. 1414-1419. 10.1029/2002GL016848.

[67] IEA (2024), *Sources of methane emissions, 2023*, IEA, Paris https://www.iea.org/data-and-statistics/charts/sources-of-methane-emissions-2023-2, Licence: CC BY 4.0

[68] Ralph J. M. Temmink ***et al.*** Recovering wetland biogeomorphic feedbacks to restore the world's biotic carbon hotspots.*Science***376**,eabn1479(2022).DOI:10.1126/science.abn1479

- Tables 1 and 2 show anthropogenic sources of methane by sector globally and in the UK, respectively.

TABLE 1: GLOBAL ANTHROPOGENIC SOURCES OF METHANE EMISSIONS AND ASSOCIATED METHANE EMISSIONS IN 2023[67].

Sector	Major Sources	IEA Annual Methane Emissions 2023 (million tons)[67]	UNEP % Global Anthropogenic Emissions 2021 (%)[69]
Fossil Fuel	Oil	49	23
	Natural Gas	29	
	Coal	40	12
	Biomass burning	10	-
Biofuels	Anaerobic Digestion	10	-
Agriculture	Enteric Fermentation	142	32
	Manure Management		
	Rice Paddies		8
Waste	Waste Water	71	20
	Landfill		
Other	Other	-	5
Total Anthropogenic Methane Emissions		351	100

Sector	Source	UK Methane Emissions ($MtCO_2eq$)	UK Methane Emissions 2022 (% of total)
Fossil Fuels/Energy	Oil, natural gas, biogas and coal	5.6	10
Land	Land use., land use change and forestry	5.7	10
Agriculture	Enteric Fermentation	23.5	41.7
	Manure	4.3	7.6
Waste	Waste water and landfill	16.9	30
Other	Other	0.4	0.7
Total Anthropogenic methane emissions		56.4	100

TABLE 2: UK TERRITORIAL METHANE EMISSIONS BY SECTOR AND SOURCE IN MTCO2E AND % OF TOTAL TERRESTRIAL EMISSIONS IN 2022[70]

- FOSSIL FUELS – OIL, GAS, AND COAL EXTRACTION AND BURNING
    - The main component of natural gas is methane, which is emitted into the atmosphere at every stage of production, including the processing, storage, transportation, and distribution of natural gas. Furthermore, the incomplete combustion of fossil fuels also releases methane into the atmosphere.
    - In addition, methane makes up a significant proportion of the GHGs which leak from coal mining facilities. In 2019, the International Energy Agency estimated that methane emissions leaking from these mines contributes to the same global warming rate as the shipping and aviation industries combined[70].
    - Accumulating research is showing that methane emissions from the fossil fuel sector, primarily concerning the use of flaring to dispose of natural gas, is significantly higher than previously believed.

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[70] https://www.theguardian.com/environment/2019/nov/15/methane-emissions-from-coal-mines-could-stoke-climate-crisis-study

Using air-borne sampling methods, Plant *et al* 2022, found that unlit flares and inefficient combustion of methane contributes to a 5-fold increase in methane missions above present assumptions[71].

- WASTE SECTOR
    - LANDFILL
        - The presence of large quantities of organic matter within landfill sites results in significant methane emissions from this sector, thus separating biodegradable food waste from other waste is an important mitigation strategy in this sector.
        - When waste is added to landfill, there is an initial abundance of oxygen which is used to aerobically digest organic waste. However, once oxygen levels are reduced, anaerobic microorganisms, which often produce methane as a by-product, dominate the decomposition process. These methanogens are able to emit methane into the atmosphere long after the landfill is closed due to the often-enormous mass of decaying matter[72].
        - In the UK, landfill is the largest contributor to methane emissions in the waste sector, accounting for 81% of all methane emissions from the sector[55]. Most of the improvement in the UK's methane emissions have been attested to changes in policy and improvements in landfill sites across the UK. This includes landfill tax, introduced in 1996, and operates under the '*polluter pays'* principle to reduce the amount of biodegradable waste going into landfill and by increasing the efficiency of methane collection from landfills already containing biowaste[55].
    - WASTEWATER
        - During the wastewater treatment process, essential to remove potential hazardous microbes, sediment, chemicals, and protozoa from human drinking water, methane can be produced as a by-product of the anaerobic treatments of organic compounds as well as through the anaerobic biodegradation of sludge[73].
- AGRICULTURE
    - RICE PADDIES
        - Rice paddies are waterlogged fields used to grow rice often in hot and humid climates. Paddies essentially act like a natural wetland and emit methane through the same processes but will only ever act as methane source due to the high water table associated with this agricultural practice.
    - LIVESTOCK
        - Globally, livestock contribute approximately 11.6% of the GHG emissions associated with anthropogenic sources. Of this 11.6%, cattle make up over 80% of anthropogenic ruminant GHG emissions[74]. Cattle are the main contributors of GHG emissions, producing 3.8GtCO_2e per year, approximately 61% of the sectors emissions[75].
        - Livestock contribute an estimated 32% of all anthropogenic global methane emissions[61], approximately 54% of which are attributed to methane[57]. Of the direct methane emissions

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[71] Genevieve Plant ***et al.*** Inefficient and unlit natural gas flares both emit large quantities of methane. *Science* **377**, 1566-1571 (2022). DOI: 10.1126/science.abq0385

[72] Themelis, Nickolas & Ulloa, Priscilla. (2007). Methane generation in landfills. Renewable Energy. 32. 1243-1257. 10.1016/j.renene.2006.04.020.

[73] Cyprowski M, Stobnicka-Kupiec A, Ławniczek-Wałczyk A, Bakal-Kijek A, Gołofit-Szymczak M, Górny RL. Anaerobic bacteria in wastewater treatment plant. Int Arch Occup Environ Health. 2018 Jul;91(5):571-579. doi: 10.1007/s00420-018-1307-6. Epub 2018 Mar 28. PMID: 29594341; PMCID: PMC6002452.

[74] IPCC, 2023: Sections In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team H.Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi:10.59327/IPCC/AR6-9789291691647

(3.7 $GtCO_2e$, or 60% of total[75]), enteric fermentation by ruminants is estimated to account for 85% of all livestock methane emissions and manure management is estimated to contribute the remaining 15% of the sector's direct emissions[70]. Indirect emissions account for the remaining 40% of the sectors total methane emissions and include manufacture and processing of fertilisers and pesticides, feed production, transportation of feed, food, and animals, and land-use change[76].

- As UK contributes 1% to all global methane emissions, then it follows that the UK livestock sector is responsible for 0.5% of all global methane emissions (extrapolating from Table 2).
- As this is the focus of the FactFile, both sources of methane will be considered individually below as well as their targeted methane mitigation strategies within the livestock agriculture sector.

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[75] https://openknowledge.fao.org/server/api/core/bitstreams/a06a30d3-6e9d-4e9c-b4b7-29a6cc307208/content

4.0 RUMINANTS

- Livestock can directly contribute to GHG emissions through multiple pathways, including enteric fermentation, manure management, and energy consumption[76]. Livestock can also indirectly increase GHG emissions from emissions associated with land use change, deforestation and resulting biodiversity loss, fossil fuels used to manufacture fertiliser and produce feed, the decomposition of manure on pasture, and the process of applying manure itself[77].

- The agricultural sector is extremely heterogeneous, with huge variety in livestock species and breeds, production systems, geographical climates and management regimes. Therefore, GHG emissions attributed to the agricultural industry vary widely depending on all these factors[77]. This complicates the ability to directly compare GHG emissions between different livestock systems, for example comparing emissions produced from pasture fed beef cattle compared to dairy cattle in an intensively managed system and beef in extensive systems compared to beef in feedlots, often results in inequivalent comparisons being made and incorrect conclusions drawn between them. Even a farm producing the same end-product can vary in their GHG emission intensity by as much as 12 fold[169].

    - Over the past decade, total livestock GHG emissions from high-income countries have remained stable, whereas there has been an increasing trend of emissions from low- and middle- income countries[170]. In 2019, livestock GHG emissions (methane and nitrous oxide) from low- and middle- income countries represented approximately 78% of total livestock GHG emissions[170].

        - This trend arises from population increases, urbanisation, increased income per capita, and greater demand for animal protein[170]. In developing countries, low feed digestibility results in higher enteric and manure emissions, poor animal husbandry slows the growth rates and results in lower slaughter weights, which increases emissions per kilogram of product produced. Similarly, and older age at slaughter contributes to greater lifetime emissions[77].
        - It is important to acknowledge that comparing the current emissions of low- and middle-income countries with those of high-income countries, such as the UK, overlooks the significant historical emissions produced during the development of high-income nations, which have significantly contributed to the global warming we experience today.

    - Cattle production for dairy and meat products generates approximately 4.6Gt of GHG emissions –72% of all global livestock emissions. Of this, 3.3 Gt is methane and N_2O emissions released from enteric fermentation and manure[107]. Of the 3.3Gt, methane from enteric fermentation is the largest source, accounting for approximately 71% of these emissions. N_2O from manure, particularly the deposition on pasture, accounts for 25% with the remaining 4% from methane from manure[107].
    - This huge contribution from cattle is reflective of their dominant share in global livestock biomass, their large size and their fermentative digestive systems[107].
    - Other livestock species emit GHG emissions but often at much lower value compared to cattle. For example, pigs and poultry are predicted to emit 0.7 $GtCO_2e$, buffalo $0.6GtCO_2e$ and other smaller ruminants (sheep and goats) $0.5GtCO_2e$[107].

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[76] Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G. 2013. *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities.* Food and Agriculture Organization of the United Nations (FAO), Rome.

4.1 ENTERIC FERMENTATION

- Ruminants, which include cattle, sheep, and goats, are herbivores which exhibit pre-gastric fermentation digestion. Similar to humans, ruminants do not possess the ability to digest plant structural carbohydrates. However, within their forestomach (rumen) they have a microbial community, including various bacteria, archaea, protozoa, and fungi, which are capable of breaking down this plant matter into volatile fatty acids (VFAs) required for metabolism and energy production in the ruminant (Figure 17)[78].
    - Firstly, organic matter, including plant structural carbohydrates, are broken down into their monomer components by primary anaerobic fermenters. These monomers are then converted into VFAs, CO_2 and dihydrogen (H_2) by both primary and secondary fermenters[77]. Methanogenic archaea, utilise these end-products of fermentation, notably CO_2, and H_2, as substrates for methane production[78] in order to reduce H_2 accumulation within the rumen, by the following reaction:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

- Of the three essential volatile fatty acids (VFA), acetate and butyrate have a role in the production of methane, whereas the formation of propionate acts as a competitive substrate to methanogens for H_2 and therefore reduces enteric methane production[78].
    - It is rumen archaea, single-celled organisms similar in structure but evolutionary distinct from bacteria, which represent 3% of the microorganisms within the rumen and which produce all the enteric methane. Other ruminal microbes indirectly contribute to this methane production by shifting the VFA balance in the rumen either towards acetate and therefore methane production, or towards propionate production and therefore methane reduction[79], as well as producing substrates used by methanogens or by the creation of environments optimal for methanogen functioning[78].

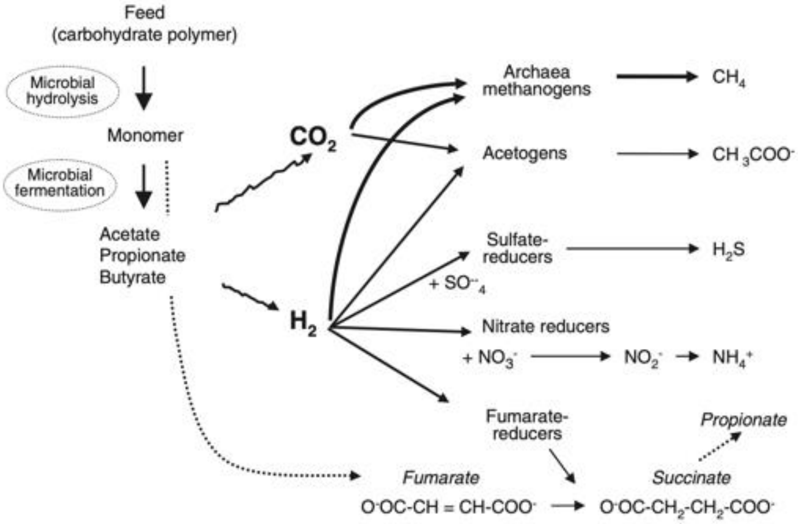

FIGURE 17: DIAGRAM OF MICROBIAL FERMENTATION OF FEED POLYSACCHARIDES AND DIHYDROGEN REDUCTION PATHWAYS WITHIN THE RUMEN.

DIAGRAM TAKEN FROM MORGAVI DP, FORANO E, MARTIN C, NEWBOLD CJ. MICROBIAL ECOSYSTEM AND METHANOGENESIS IN RUMINANTS. ANIMAL. 2010 JUL;4(7):1024-36. DOI: 10.1017/S1751731110000546. PMID: 22444607.

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[77] Morgavi DP, Forano E, Martin C, Newbold CJ. Microbial ecosystem and methanogenesis in ruminants. Animal. 2010 Jul;4(7):1024-36. doi: 10.1017/S1751731110000546. PMID: 22444607.

[78] Palangi V, Lackner M. Management of Enteric Methane Emissions in Ruminants Using Feed Additives: A Review. Animals (Basel). 2022 Dec 7;12(24):3452. doi: 10.3390/ani12243452. PMID: 36552373; PMCID: PMC9774182.

[79] Baca-González V, Asensio-Calavia P, González-Acosta S, Pérez de la Lastra JM, Morales de la Nuez A. Are Vaccines the Solution for Methane Emissions from Ruminants? A Systematic Review. Vaccines (Basel). 2020 Aug 20;8(3):460. doi: 10.3390/vaccines8030460. PMID: 32825375; PMCID: PMC7565300.

- Methane production and subsequent eructation is an evolutional adaptation which removes hydrogen from the rumen. This avoids increases in H_2 inhibiting the functioning of ruminal microbial enzymes, which may reduce rumen function and therefore energy production[61]. The archaeal pathway of H_2 reduction is the most common reduction pathway from a substrate availability and energy perspective point of view, although importantly other H_2 reduction pathways also exist but occur infrequently (Figure 17). Ruminants have therefore evolved to optimise the utilisation of fibrous feed found in grasslands all over the world.

- Of the methane produced by ruminants, the vast majority is produced in the reticulo-rumen and then belched where it then escapes into the environment, whilst a much smaller percentage is released back to the atmosphere via the rectum[107]. The amount of methane produced by enteric fermentation depends on several factors including animal species, age and bodyweight, feed quality, quantity, and composition, ambient temperature, grazing management and production system.

4.1.1 RUMINANT POPULATIONS – PAST, PRESENT, AND FUTURE

- Two studies which analysed and compared pre-European enteric methane emissions from bison herds and other wild ruminants to modern farmed ruminants, found that methane emissions for wild ruminants pre-European settlement were similar to modern emissions rates from domestic herds (Figure 18)[80,81].
  - One study which estimated methane emissions from wild herbivores at various periods in history and prehistory found that during the late Pleistocene (12–13,000 years ago) the estimated methane emissions from megafauna were virtually equivalent to those of farmed ruminants today[82].
    - Using global datasets to develop a series of allometric regressions relating mammal body mass to population density and methane production, they estimated that emissions of Late Pleistocene megafauna were 138.5 million tons methane per year and the emissions from modern day ruminant livestock and wildlife ruminants was estimated to be 160 million tons methane per year globally in 2006[83]. Megafauna numbers significantly reduced in the late Pleistocene, as part of the great megafaunal extinctions, with the most likely cause being hunting from humans and habitat alteration[83].

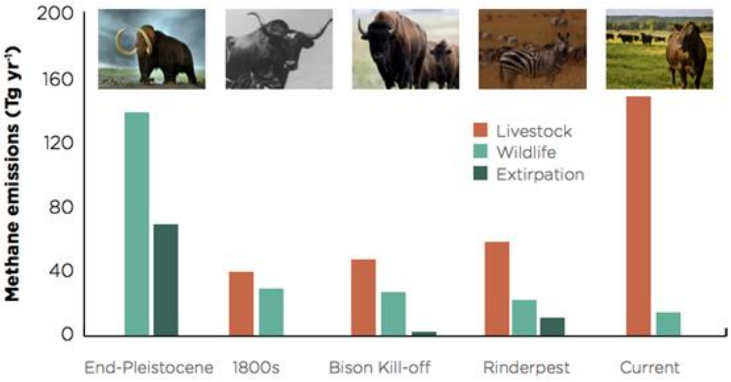

FIGURE18: ENTERIC METHANE PRODUCTION FROM WILD AND DOMESTIC RUMINANTS. THE PREDICTED REDUCTION IN METHANE EMISSIONS RESULTING FROM EXTIRPATION (INCLUDING EXTINCTIONS) IS ALSO SHOWN.

REFERENCE - SMITH *ET AL*, 2016. EXPLORING THE INFLUENCE OF ANCIENT AND HISTORIC MEGAHERBIVORE EXTIRPATIONS ON THE GLOBAL METHANE BUDGET. DOI: 10.1073/PNAS.1502547112, ACC. 14/2/20

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[80] A. N. Hristov, Historic, pre-European settlement, and present-day contribution of wild ruminants to enteric methane emissions in the United States, *Journal of Animal Science*, Volume 90, Issue 4, April 2012, Pages 1371–1375, https://doi.org/10.2527/jas.2011-4539

[81] Francis M. Kelliher, Harry Clark, Methane emissions from bison—An historic herd estimate for the North American Great Plains, Agricultural and Forest Meteorology, Volume 150, Issue 3, 2010, Pages 473-477, ISSN 0168-1923, https://doi.org/10.1016/j.agrformet.2009.11.019.

[82] Smith *et al*, 2016. Exploring the influence of ancient and historic megaherbivore extirpations on the global methane budget. doi: 10.1073/pnas.1502547112, acc. 14/2/20

  - Furthermore, the authors also suggest that prehistoric megafauna might have had other complex effects on the climate. For example, as the megafauna died out, the forests expanded, causing a carbon uptake which cooled the climate. On the other hand, in northern latitudes, the replacement of a pale reflective surface (grassland) by darker encroaching conifers caused the earth to absorb more of the sun's heat[83].
  - It is important to point out that the net impacts are unclear, and a full accounting would need '*to include enteric methane emissions, soil greenhouse gas emissions related to changes in hydrology and temperature, and changes in surface albedo and evapotranspiration related to vegetation structure*'[83].

- Similarly, it has been estimated that mid-century sheep populations are comparable to those of today[83].

- Although some estimates suggest that methane emissions from cattle during the late Pleistocene and sheep during the Industrial Revolution were similar to current levels, this notion is debated. Several studies challenge the idea that methane emissions from livestock, whether from domesticated or wild ruminant populations, have remained constant over time. A 2017 study analysing trends in global livestock methane emissions found that methane emissions from ruminant livestock increased by 332% between 1890 and 2014, representing an increase of 73.6Mt of methane[84].

- Modern domestic ruminant populations have been declining in the UK since 1984[85].

  - The UK cattle herd has reduced by 28.3% over the 39 years between 1984 and 2023[86] across both the beef and the dairy sectors in the UK from 13,331,269 to a population of 9,555,426[86]. Similarly, the UK sheep population has also reduced, though by a lesser extent, of 9.1% between the same time period[87], falling from 34,985,137 in 1984 to 31,802,536 in 2023. Much of the underlying decline over this period has been in the dairy herd due to the result of restrictions on milk production from milk quotas[87].
  - The UK total factor agriculture productivity, a measure of the ability of an agricultural system in generating outputs from its inputs, has increased by 59.6% from 1973 to 2022. This is due to a 31.8% increase in outputs and a 17.4% decrease in inputs[171].
  - Given the decline in the UK's domestic ruminant population over the last 39 years and considering the average atmospheric lifetime of methane is approximately 10 years, it can be assumed that total methane production by ruminant livestock has also been decreasing, and thus a cooling effect experienced.

    - In real time, this reduction in methane would be experienced as less of a gain in heat rather than cooling *per se*, given methane is still released from enteric fermentation of livestock and in significant quantities from other sources, as well as other GHGs.
    - Importantly, this does not rule out the potential increases in other GHG emissions attributed to increased livestock productivity. For example, herds are able to reduce in size as long as productivity is maintained or improved, but many factors that improve productivity i.e., improved food conversion efficiency (FCE) may be linked to higher upstream GHG emissions attributed to the production and distribution of concentrate feed, for example.
    - Improved productivity within herds results in more absolute methane emissions per animal, but a reduction in the methane emissions produced per unit of desired product i.e., the methane emission intensity.

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[83] Fussell, G. E., & Goodman, C. (1930). Eighteenth Century Estimates of British Sheep and Wool Production. *Agricultural History*, *4*(4), 131–151. http://www.jstor.org/stable/3739415

[84] https://onlinelibrary.wiley.com/doi/10.1111/gcb.13709

[85] UK Annual Timeseries on Agricultural Systems from 1984-2023

[86] https://www.gov.uk/government/statistics/livestock-populations-in-the-united-kingdom/livestock-populations-in-the-united-kingdom-at-1-june-2023

[87] Defra, Analysis of recent data for dairy cows in England and implications for the environment (2009), Section 3

- Through the development of the GWP* metric, it has been shown that long-term sustained methane emissions do not always necessary result in climatic warming. This may be taken as a 'get-out-of-jail-free' card from some within the agricultural sector, given that it is likely, especially in the UK where ruminant herd populations have declined, that the methane emissions from livestock are not contributing to active warming in the UK. However, the global atmosphere, is shared and it has been predicted that if methane emissions remain stable in the agricultural sector it is highly unlikely that we will be able to meet the requirements specified in the Paris Agreement[88]. Given that global ruminant populations are predicated to increase in the future (Figure 19[153,89]), which can directly correlate to a rise in GHG emissions, GHG mitigation within the sector is needed more than ever to reduce the impact of the livestock industry on climate change.

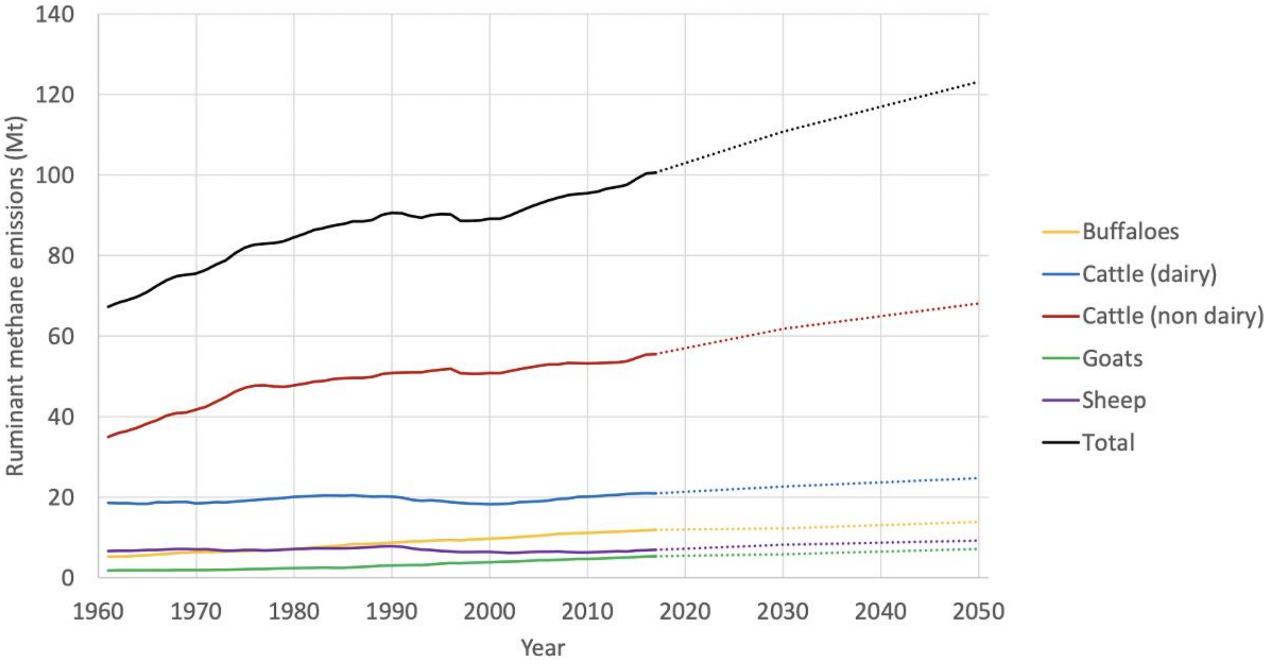

FIGURE 19: FIGURE 21: PAST AND FUTURE PROJECTION OF DIRECT METHANE EMISSIONS FROM RUMINANT LIVESTOCK 1960-2050. DATA FROM FAOSTAT

4.2 MANURE MANAGEMENT

- Livestock manure also contributes to global GHG emissions. Manure contains organic matter that can be digested to methane as well as containing nitrogen that can produce N_2O. Methane is produced via anaerobic digestion and occurs when manure is in liquid form i.e., slurry, lagoons, or tanks.

- Temperature, pH, and the moisture content of manure affect the formation of methane, with higher temperatures, moisture level, and neutral pH conditions more favourable for methane production. Furthermore, the composition of manure is related to animal species and their diets. Dairy cattle are associated with higher feed intakes and therefore higher manure excretion rates compared to non-dairy cattle[89]. However more manure produced doesn't necessarily result in more methane produced as other factors affect methane production from the manure itself.

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[88] https://tabledebates.org/sites/default/files/2021-09/FCRN%20Building%20Block%20-%20Methane%20and%20the%20sustainability%20of%20ruminant%20livestock.pdf

[89] Moeletsi ME, Tongwane MI. 2004 Methane and Nitrous Oxide Emissions from Manure Management in South Africa. Animals (Basel). 2015 Mar 31;5(2):193-205. doi: 10.3390/ani5020193. PMID: 26479229; PMCID: PMC4494408.

- Solid manure management i.e., stacks, dry lots, or deposition on pasture where there tends to be aerobic decomposition produces little methane, however, it does still produce N_2O[61].

4.3 LIVESTOCK GRAZING AND SOIL CARBON SEQUESTRATION POTENTIAL

- There is huge variation in GHG emissions associated with livestock depending on species and breed, production system, agroecological conditions, and supply chain management[90].
    - Land-use change associated with livestock grazing or the cultivation of arable crops for livestock feed production contributes substantially to GHG emissions[61].
        - For instance, in Latin America and the Caribbean, one-third of livestock emissions, amounting to 24 kg CO_2 equivalent per kilogram of carcass weight, are attributed to the conversion of forests to pasture for livestock grazing. However, this estimate should be interpreted cautiously due to significant methodological and data uncertainties surrounding land-use change emission estimates[91].
    - Grazing systems generally exhibit higher GHG emission intensity compared to mixed or intensive systems due to differences in feed quality and herd management. They often have lower productivity relative to the land area used, resulting in longer times for animals to reach slaughter weight or age at first parturition, which in turn leads to higher methane emissions per unit of the desired product[92].
- In 2018, the CCC suggest that UK agricultural activities were responsible for 10% of total anthropogenic GHG emissions, equating to 45.4MtCO_2e of a 451 MtCO_2e total[94]. Forests and grasslands sequestered a total of 27 MtCO_2e, however other land use activities released 17 MtCO_2e[94]. For the UK to achieve the net-zero target, the agricultural industry will need to reduce emissions from production and increase the ability to sequester carbon in the soil, both directly from grazing cattle or indirectly by intensification (increasing productivity and reducing demand for land)[93].
- Grazing ruminants can enhance soil carbon sequestration by stimulating carbon uptake by plants. This can be achieved by altering grazing management practices, particularly optimising stocking densities of livestock for the resources of the land and adjusting grazing duration.
    - Plants respond to grazing by increasing root growth, which augments the carbon content in the soil, enhancing the potential of carbon to be retained in the soil in more stable forms as a long-term carbon sink[94]. However, the effectiveness of this process depends heavily on climatic and soil conditions, plant species diversity, and the availability of essential nutrients such as nitrogen and phosphorus. Different plant species also vary in how they allocate growth and root depth, which influences their carbon sequestration potential.
    - Conversely, continuous livestock grazing and overstocking – where livestock numbers exceed the land's carrying capacity – can lead to reduced plant biodiversity, ground cover and productivity, as well as increased soil compaction. These effects diminish soil microbial activity, exacerbate soil erosion, and reduce the carbon inputs into the soil from plant roots[95], ultimately turning soils in carbon sources

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[90] Smith, P *et al* (2008). Greenhouse gas mitigation in agriculture. Philos Trans R Soc, 363(1492), pp. 789–813

[91] https://www.thecattlesite.com/articles/3740/where-are-cattle-emissions-currently-at/

[92] Garnett T, Godde C, Muller A, Röös E, Smith P, de Boer IJM, Ermgassen E, Herrero M, van Middelaar C, Schader C and van Zanten H (2017). Grazed and confused? Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question. Food Climate Research Network, University of Oxford ***www.fcrn.org.uk***

[93] https://www.theccc.org.uk/wp-content/uploads/2020/12/Non-CO2-abatement-in-the-UK-agricultural-sector-by-2050-Scottish-Rural-College.pdf

[94] Grazed and Confused - https://tabledebates.org/sites/default/files/2022-04/fcrn_gnc_report.pdf

  which release CO_2 and methane into the atmosphere. It has been estimated that 20-35% of permanent pasture worldwide suffers from livestock-induced degradation[95].
  - A 2024 meta-analysis suggests that reducing the grazing intensity on 75% of global grasslands while increasing it on the remainder, can improve carbon uptake in vegetation and soil sequestration by 63PgC[96].
  - While trampling by livestock can aid in incorporating manure and the carbon it contains into the soils[97], excessive trampling, especially in wet conditions, can lead to adverse outcomes on soil carbon. These include, soil compaction, damage to forage plants, reduced grass growth, increased vulnerability to wind and water erosion, reduced water infiltration and increased run-off, accelerated release of soil carbon, and, for leguminous plants, a reduction in nitrogen fixing capacity[93].

- Managing the intensity of grazing, through livestock stocking density and grazing duration, can improve plants uptake of carbon from the atmosphere and its allocation to long-term carbon stores within the soil. Improved livestock grazing and biodiversity restoration can provide soil carbon sequestration at a low-cost climate solution for grassland systems. The predicted soil carbon sequestration potential in global grasslands is between 2.3-7.3 $BtCO_2e$ per year for biodiversity restoration, 148-699 $MtCO_2e$ for improving grazing management and 147 $MtCO_2e$ for increasing legume content in pasture[98]. However, soils need to be appropriately managed to ensure they remain a carbon sink and their capacity for carbon sequestration is maximised.

- Rotational grazing can be utilised to maximise the soil sequestration potential of grazing ruminants and protect pasture from overgrazing to maintain the soil composition and quality, and carbon sequestration potential. However, the mitigation impacts of rotational grazing is hotly contested. Soils are often continually grazed for a year which in temperate areas, like the UK, can still inflict significant soil erosion and damage. Furthermore, the conversion of land for grazing pasture contributes indirectly to land-use change GHG emissions[95].

- Grazing ruminants on grass and making changes to farming management practices could help mitigate overall GHG emissions leading to net-zero, especially in well-managed farming systems within the UK.

  - Recent research showed that when GHG emissions are decoupled from historic land-use changes such as deforestation, incentivising production practices that actively reduce emissions rather than penalising consumption of GHGs, can reduce GHG emissions and have a net positive effect in terms of climate[99].
  - The potential for soil carbon sequestration through the management of grazing ruminants is estimated to result in the net reduction in GHG emissions between 295-800$MtCO_2e$ per hectare per year globally. This reduction could offset 20-60% of the average annual emissions from the grazing ruminant sector[100, 101].
  - The effectiveness of grassland carbon sequestration as a mitigation strategy depends on the initial health of the soil and the implementation of effective land management practices, such as optimising stocking densities and livestock grazing durations. While this approach is promising, there is a need for

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[95] Conant, R.T. (2010). Challenges and opportunities for carbon sequestration in grassland systems. A technical report on grassland management and climate change mitigation, Integrated Crop Management. Food and Agriculture Organisation of the United Nations, Rome. doi:10.3329/jard.v7i1.4430.

[96] Ren, S., Terrer, C., Li, J. *et al.* Historical impacts of grazing on carbon stocks and climate mitigation opportunities. *Nat. Clim. Chang.* **14**, 380–386 (2024). https://doi.org/10.1038/s41558-024-01957-9

[97] Drewry, J.J. *et al* (2008). Pasture yield and soil physical property responses to soil compaction from treading and grazing—a review. Australian Journal of Soil Research, 46, pp. 237–256.

[98] Yongfei Bai, M. Francesca Cotrufo, Grassland soil carbon sequestration: Current understanding, challenges, and solutions.*Science***377**,603-608(2022).DOI:10.1126/science.abo2380

[99] Silva *et al* (2016). Increasing beef production could lower greenhouse gas emissions in Brazil if decoupled from deforestation. Nature Climate Change. 6. 10.1038/nclimate2916.

[100] Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. Global Change Biology, 22, pp. 1315-1324. doi: 10.1111/gcb.13178;

[101] Conant, R.T., and Paustian, K. (2002). Potential soil carbon sequestration in overgrazed grassland ecosystems. Global Biogeochemical Cycles, 16(4), pp. 1-9. Available at: https://doi. org/10.1029/2001GB001661

affordable and accurate methods to quantify soil carbon sequestration potential. Additionally, a deeper understanding of industry requirements, economic feasibility and the possible impact on livestock productivity is necessary before such strategies can be implemented on a large scale and integrated into evidence-based policy decisions.

- Maximising the soil carbon sequestration effects of grazing ruminants in an important consideration of GHG mitigation in grassland systems, but owing to the complex, reversible and highly variable effects, it should not be the focus of mitigation efforts[95]. This variability and reversibility is highlighted by a meta-analysis of the effects of grazing livestock on grassland soil carbon which found equally distributed gains or losses of approximately 5.5tCO_2 per hectare per year[102]. Additionally, there is a risk of increased GHG emissions if more land is converted to pasture for livestock to improve soil carbon sequestration at the detriment of the significant emissions associated with land-use change[95]. A balanced approach that considers the broader landscape and implications of grazing ruminants and soil carbon, and which is able to integrate multiple mitigation strategies is essential for effective GHG mitigation and adaptation in the livestock sector.

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[102] McSherry, M.E. and Ritchie, M.E. (2013). Effects of grazing on grassland soil carbon: a global review. *Global Change Biology,* 19, pp. 1347–1357, doi: 10.1111/gcb.12144

5.0 METHANE MITIGATION STRATEGIES IN THE LIVESTOCK SECTOR

- There is a very real requirement for the widespread implementation of methane mitigation strategies across the livestock sector in the UK and globally. The livestock industry is one of the fastest-growing sectors of the worldwide agricultural economy. By 2050, the demand for meat is expected to increase from 350 million tonnes in 2023, to between 460-570 million tonnes[103], and the demand for milk is expected to increase by 58% compared to 2010 levels[104]. This growth is primarily driven by the projected increase in global population to 9.8 billion by 2050[105] and, to a lesser extent, by improved education regarding healthy and balanced diets. As the demand for meat and dairy products rises in the coming decades, methane emissions associated with livestock production are also expected to increase. To meet this growing food demand while minimising environmental impact it is essential to produce more food using less land and with lower GHG emissions whilst simultaneously increasing the yield and productivity of food production. Adopting innovative and sustainable farming practices within the livestock sector to balance the increasing demand for animal products is necessary to with minimise the industry's contribution to climate change.

- Mitigation strategies include measures to reduce methane emissions associated with enteric fermentation by ruminants, mainly cattle, which is the single largest emission source from the global livestock sector, and reducing methane emissions from slurry and manure[61].

    - Enteric fermentation strategies include improving productivity and herd health through reducing livestock mortalities and morbidities, feed supplementation, and improvements to forage quality. Furthermore, selective and precision breeding is a novel mitigation strategy for the permanent, self-sustaining and cost-effective formation of naturally low-emitting methane herds and flocks[61]. Focusing on mitigation strategies to reduce enteric methane production will have the greatest impact in reducing methane production from the livestock industry as 85% of methane from cattle is produced from this process[70].
    - For manure, capturing and processing methane as a sustainable natural gas source and changing storage and pasture application techniques can all be used as GHG mitigation techniques.
    - Due to the huge variation across the livestock agricultural sector, the sustainability and efficacy of mitigation strategies varies across species, production system and management system. These factors need to be considered on a case-by-case basis when choosing appropriate methane mitigation strategies for each farm and region[77].
    - It is important that mitigation strategies are mindful of the potential for pollutant swapping, whereby the reduction in one GHG leads to unintended increases in another, as most mitigation strategies show strong interactions between sources of GHG emissions[61].

        - The benefits of methane reduction include, climate change mitigation, public and animal health benefits, and environmental benefits. Often, technologies which reduce methane also often reduce the production of other harmful volatile organic compounds and hazardous pollutants, like tropospheric ozone[48]. This is attributable to approximately half a million premature deaths globally each year and reduces growth and yield of ecosystems and crops[26].

    - There needs to be balance with other climate targets, for example those which reduce CO_2 emissions, capture excess carbon in soil or vegetation, and restore and protect biodiversity and habitats in order to fully maximise the benefit of these strategies and protect policy and subsidies already in place.

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[103] https://www.theworldcounts.com/challenges/foods-and-beverages/world-consumption-of-meat

[104] **FAO.** 2011. World Livestock 2011 – Livestock in food security. Rome, Fao.

[105] Giampiero Grossi, Pietro Goglio, Andrea Vitali, Adrian G Williams, Livestock and climate change: impact of livestock on climate and mitigation strategies, ***Animal Frontiers***, Volume 9, Issue 1, January 2019, Pages 69–76, https://doi.org/10.1093/af/vfy034

- The majority of mitigation methods and technologies are already widely available on a global scale.

    - For methane mitigation strategies to be effectively adopted across the UK agricultural sector, it is essential that technologies are practical, cost-effective and easy to implement, without adversely affecting productivity. Any reduction in productivity could undermine efforts to decrease methane emissions. Successful strategies should enable the simultaneous application of multiple mitigation approaches thereby maximising the methane reduction in UK livestock.

- Methane mitigation strategies can have an impact on absolute enteric methane emissions, absolute methane emissions, methane produced per unit of dry matter intake (DMI) and methane emission intensity. These indices need to be carefully considered when addressing the efficiency of a methane mitigation strategy[61].

    - **Absolute enteric methane emissions** represent the amount in grams of methane produced as part of enteric fermentation per animal per day.
    - **Absolute methane emissions** represent the total amount in grams of methane produced per animal per day. This includes emissions from eructation and from flatulence.
    - The **methane yield** represents the methane produced relative to the unit of dry or organic matter consumed by the animal.
    - **Methane emission intensity** represents the amount in grams of methane produced for a given unit of productivity i.e., kilograms of meat or litres of milk, produced by the animal.

        - Increasing the efficiency of production and animal productivity, can reduce the methane emission intensity, even if absolute methane emissions increase[106]. This is because there is a dilution effect of the energy used in animal maintenance and the energy used for productivity[108, 172].
        - The daily nutrient requirement of all animals is split between the energy needed to maintain the animal's vital functions (maintenance energy) and the energy required to support growth, reproduction, or lactation (productive energy).

            - The maintenance energy requirement does not change as a function of production. However, the daily energy requirement will increase as more yield is produced (milk or meat) and thus the proportion of total energy required for animal maintenance will decrease[107].

        - Methane emissions associated with animal maintenance energy are essentially wasted emissions, as this energy must be met before the animal becomes productive. If there is any increase in the energy required for maintenance, for example if the animal has an ongoing disease or illness, then emissions intensity will increase per unit product produced as the energy is shifted away from productivity and towards maintenance.
        - Whereas methane emissions associated with productive energy will dilute the GHG emissions associated with maintenance as the animal is producing more product which will reduce the overall emission intensity.

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[106] Gerber PJ, Hristov AN, Henderson B, Makkar H, Oh J, Lee C, Meinen R, Montes F, Ott T, Firkins J, Rotz A, Dell C, Adesogan AT, Yang WZ, Tricarico JM, Kebreab E, Waghorn G, Dijkstra J, Oosting S. Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. Animal. 2013 Jun;7 Suppl 2:220-34. doi: 10.1017/S1751731113000876. PMID: 23739465.

[107] Capper, J.L. and Williams, P. (2023) 'Investing in health to improve the sustainability of cattle production in the United Kingdom: a narrative review', *The Veterinary Journal*, 296-297, article number 105988.

    - Therefore, mitigation strategies that shift the balance of livestock methane emissions towards productive energy, compared to simply maintenance energy requirements, reduce the emission intensity of methane, thus produce fewer GHG emissions per unit of desired product.
    - To put this into context, a high-yielding dairy cow will require more energy in the form of feed per day compared to a low-yielding dairy cow, but all the extra energy consumed is used for milk production and therefore the methane produced per litre of milk is reduced compared to the low-yielding dairy cow[108].

5.1 IMPROVING PRODUCTIVITY

- Improving productivity, either by increasing yield from the same quantity of input resources or by maintaining yield while reducing input resources, can significantly decrease the demand for non-renewable energy inputs. This, in turn, reduces the GHG emissions associated with land-use change, fertiliser production, distribution and application, and fossil fuel consumption. Ultimately, this approach reduces the GHG emissions per unit of desired end-product i.e., the methane emission intensity[61].

  - Improving productivity is fundamentally linked to the efficiency of energy utilisation within the animal. Higher productivity reduces the proportion of feed required for maintenance energy, thereby lowering methane emission intensity. Consequently, the animal will reach slaughter weight faster[108], or will be able to undergo parturition sooner.
  - However, increasing productivity may have unintended consequences on other GHG emissions. For instance, if higher productivity is associated with an increased feed intake this could lead to greater N_2O emissions from manure due to increased excretion[61]. Additionally, upstream GHG emissions associated with feed production, distribution, and storage, may also increase[61].

- Productivity can be increased through improvements in farm management, nutrition, disease control and prevention, reproductive performance, and reducing environmental stress on animals[61].

  - It has been shown that modest improvements in dairy cow fertility can reduce methane emissions by 10%, with potential mitigation of methane emissions as high as 24% if optimal fertility levels are achieved[108]. Improved fertility reduces GHG emissions by reducing the number of replacement animals required in the herd[61].
  - Improving the daily liveweight gain by optimising health and nutrition reduces the days to slaughter (beef and sheep) or to first parturition (dairy and replacement ewes) improves productivity.
  - Improved FCE reduces the levels of inputs (feed additives, supplementation etc.) required and thus their associated GHG emissions, as well as directly improving growth rates and reproductive performance.
  - Reducing mortalities associated with disease, involuntary culling or abortion in breeding stock will decrease the number of replacements required to be kept in a herd. This improvement enhances reproductive performance, safeguards the genetics of animals that naturally emit lower levels of methane and minimises the need for increased resources and medicines for sick animals, which are often associated with substantial upstream GHG emissions[109].

5.1.1 REDUCING MORBIDITY AND MORTALITY IN LIVESTOCK

- There is a long rearing period prior to animals becoming productive i.e., producing milk, or reaching appropriate slaughter weight. The methane emissions produced in the rearing period, prior to productivity, will be wasted if the animal never becomes productive, for example, through premature death. Any morbidity in the rearing

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[108] P.C Garnsworthy, The environmental impact of fertility in dairy cows: a modelling approach to predict methane and ammonia emissions, Animal Feed Science and Technology, Volume 112, Issues 1–4, 2004, Pages 211-223, ISSN 0377-8401, https://doi.org/10.1016/j.anifeedsci.2003.10.011.

[109] https://theconversation.com/vaccinating-livestock-against-common-diseases-is-a-form-of-direct-climate-action-214514

period will likely elongate the time it takes for the animal to reach productivity and thus increases the GHG emissions associated with that animal.

  - Reducing the mortality in young stock will reduce GHG emissions as fewer non-productive animals will need to be maintained in the herd. Similarly, improving health in adult animals will reduce culling rates as well as the need for growing replacements, keeping the herd size small whilst maximising productivity[110].

- Suboptimal animal health is a major constraint on the efficiency of livestock production and is therefore a source of excess methane emissions. Diseases that negatively impact yields, growth rates, or reproductive performance result in inefficient production, requiring increased inputs to achieve the same level of output, thereby leading to a corresponding increase in GHG emissions[108]. On a metabolic level, improving animal health decreases the energy from feed used by the immune system in response for disease and the energy required for animal maintenance[49], and thus increases the energy that can be used for productivity. Numerous studies indicate that improving the health status of herds and flocks alone could reduce GHG emissions by approximately 10% with further emissions reductions achievable through enhancements in fertility and nutrition[111].

  - Enhancing livestock health status not only improves animal welfare and profitability, but also maximises the methane mitigation potential of other strategies which can be employed in the herd, such as the use feed-additives and the optimisation of genetic potential through selective breeding[61]. Moreover, improvements in herd health can be implemented immediately with existing knowledge, diagnostic technologies and available treatments.

- In 2011, Defra, ADAS, and others, identified 10 endemic cattle diseases believed to have the largest impact on cattle productivity in the UK[112]. They sought out to investigate the possible GHG emission reductions associated with improved disease control as a cost-effective mitigation strategy to reduce GHG emissions on farms.

  - They estimated the GHG emissions associated with the full impacts of each disease (red bars), the GHG emissions associated with treatment and/or recovery from disease (green bars) and the GHG emissions associated with disease intervention and control strategies (yellow bars) compared to the GHG emissions produced when a healthy animal produced 1,000L of milk, estimated to be 0.89tCO_2e, presented in Figure 20, or 1,000kg beef estimated to be 17.1tCO_2e, presented in Figure 21.
  - They showed that endemic disease interventions provide major GHG emission mitigation strategies, shown by the difference between the red and the green bars in Figures 20 and 21.
  - Johne’s disease, a chronic disease, estimated to affect between 20-50% of UK cattle herds[113], has a huge impact on animal health and welfare, with associated costs and productivity losses. This study estimated that Johne’s disease will increase GHG emissions (half of which are methane) by 25% per litre of milk, and by 40% per kg of beef, likely due to reduced yields and increased culling rates associated with its control[113].
  - They suggest that implementing endemic disease control measures, including improving nutrition, biosecurity, vaccination, and colostrum management, to move 50% of cattle from baseline to *‘good health’* could reduce GHG emissions from the cattle sector by 6% i.e., 1,436 ktCO_2e. Furthermore, the

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[110] Hristov, A. N., et al. "FAO animal production and health paper No. 177." *Mitigation of Greenhouse Gas Emissions in Livestock Production: A Review of Technical Options for Non-CO2 Emissions* (2013).

[111] Moredun Research Institute, Acting on Methane – opportunities for the UK cattle and sheep sectors, April 2022, https://ruminanthw.org.uk/wp-content/uploads/2022/04/SO-634-Ruminant-Report-Methane-April-2022-web.pdf

[112] ADAS (2015) Study to Model the Impact of Controlling Endemic Cattle Diseases and Conditions on National Cattle Productivity, Agricultural Performance and Greenhouse Gas Emissions. ADAS UK Ltd, Helsby, UK.

[113] https://www.nadis.org.uk/disease-a-z/cattle/johnes-paratuberculosis/

authors speculate that given many of these diseases interact and co-exist, the potential GHG mitigation effects may be even greater.

- However, due to multiple assumptions made on the impacts of mitigation strategies and those of disease and its treatment, and the consideration of diseases individually, the authors recommend that the analysis is an important first estimate on GHG mitigation potential for endemic disease in the UK and should not be taken as robust data.

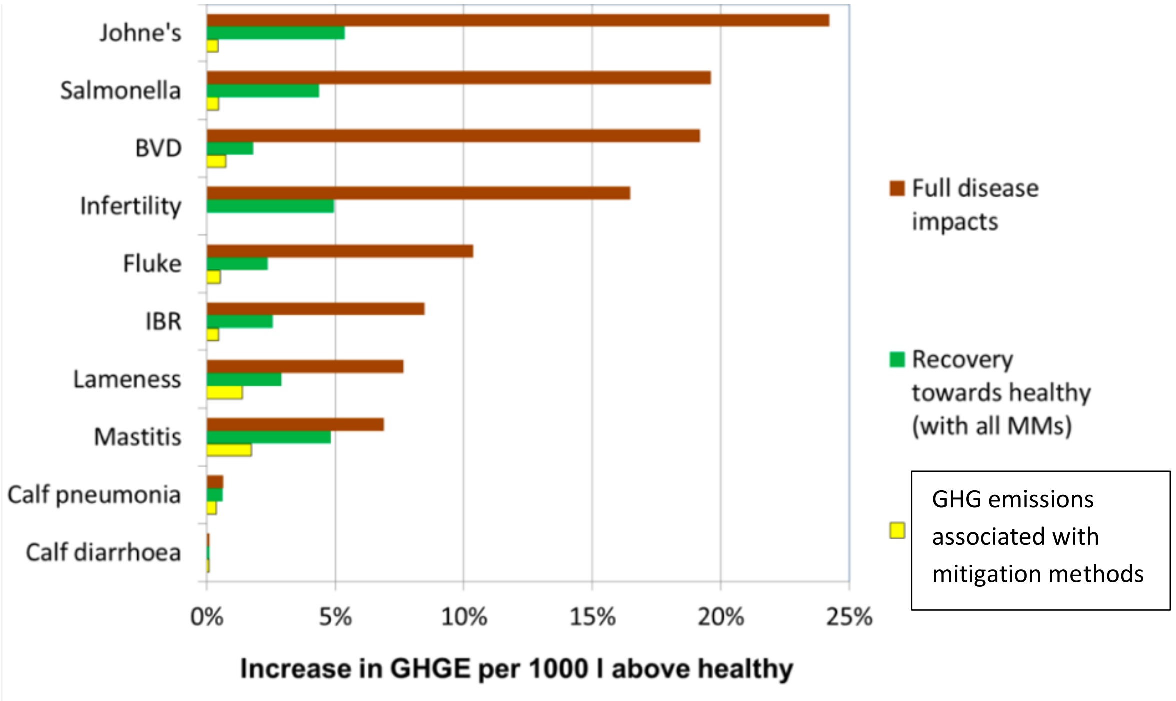

FIGURE 20: GHG EQUIVALENTS OF 10 ENDEMIC CATTLE DISEASES IN THE UK, THEIR FULL IMPACT, AND EMISSIONS ASSOCIATED WITH THEIR RECOVERY AND THE MITIGATION METHODS EMPLOYED AGAINST GHG EMISSIONS FROM AN AVERAGE HEALTHY DAIRY COW PRODUCING 1,000L MILK

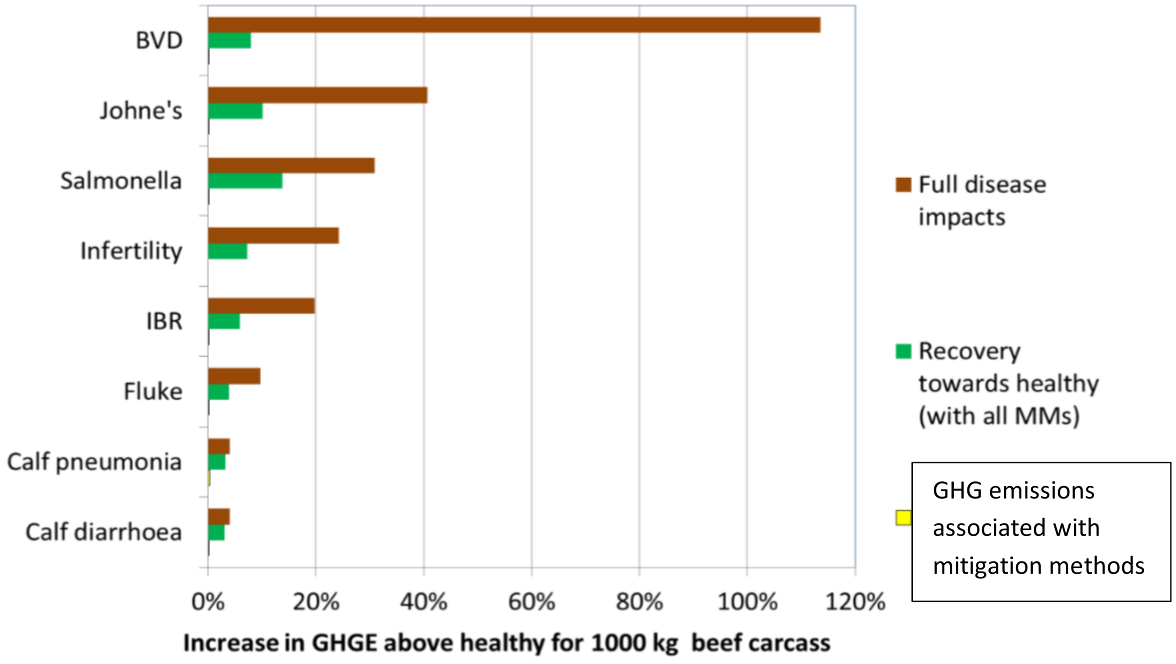

FIGURE 21: FIGURE 15: GHG EQUIVALENTS OF 10 ENDEMIC CATTLE DISEASES IN THE UK, THEIR FULL IMPACT, AND EMISSIONS ASSOCIATED WITH THEIR RECOVERY AND THE MITIGATION METHODS EMPLOYED AGAINST GHG EMISSIONS FROM AN AVERAGE HEALTHY BEEF SUCKLERCOW PRODUCING 1,000KG BEEF

- Similarly, a 2020 study reported that mitigating bovine viral diarrhoea (BVD) would reduce GHG emissions per kg of milk by 4% in the average UK dairy herd, and by 11% in the worst 10% of dairy herds. Furthermore, improvements in fertility and mastitis control will reduce GHG emissions per kg of milk by 7% and 6% in average herds, and by 16% and 12% in the worst 10% of herds in the UK, respectively[114], as shown in Table 3.

- A more recent study in 2022, which aimed to assess the impact of cattle liver fluke infections on GHG emission intensity, found that fluke infection adds, on average, an extra 11 days until slaughter weight is reached, reduces the growth rate by 4% and increases overall GHG emissions produced by 1.5%[116]. The authors suggest that appropriate and sustainable liver fluke control has additional production benefits which are not included in their estimations meaning that there is a likely a greater impact on GHG emission intensity[115].

5.1.2 VACCINATION AS A DISEASE CONTROL MEASURE

- Improving vaccination in both intensive and extensive livestock can have considerable methane mitigation impacts. These can have direct effects by reducing the morbidity and mortality within a herd, or indirectly by reducing GHG emissions from upstream inputs, for example, feed production and transport, and the production of veterinary medicines.

- Despite the recognised benefits of vaccination, the implementation and uptake of routine vaccination protocols on UK livestock farms is limited and adoption rates are low. Several barriers contribute to this issue, including improper vaccine storage, inadequate administration techniques and resistance from farmers to changing established farming practices.

    - A 2022 study by the Royal Veterinary College found that only 26.1% of its 370 participants correctly identified the proper location for a subcutaneous injection in a sheep, while 45.5% stored vaccines for 48 hours or more after their initial use and 11.1% retained vaccines until their next planned vaccination[116]. Although the study surveyed approximately 1.1% of the UK's sheep farmers, the findings raise significant concerns about the effectiveness and cost-efficiency of the few vaccination protocols that are being implemented on UK sheep farms.
    - As of 2022, vaccine adoption rates were reported at 43% for calf pneumonia, 40% for BVD, 29% for infectious bovine rhinotracheitis (IBR) and 30% for leptospirosis[117], based on annual sales data. However, sales data may not accurately reflect the actual number of vaccinations administered which is likely to be lower. This low vaccine uptake suggests there is significant potential for improving vaccination uptake in the cattle livestock sector to prevent early-life mortality, improve productivity and ultimately reduce GHG emissions.
    - To improve the efficiency of vaccination adoption on farms, vaccination protocols should be implemented alongside other disease prevention measures such as improvements to husbandry practices, and comprehensive farmer training and education of available vaccines and their cost-effectiveness. This integrated approach will help prevent the misuse of vaccines as a substitute for proper husbandry[117], ensure vaccines are stored and administered correctly, and raise awareness of the cost-benefits of endemic disease vaccination.

- The 2011 Defra/ADAS study[113], found that the greatest, and most cost-effective, GHG mitigation reductions in the dairy cattle sector came from preventing infectious disease by vaccination. The top three diseases with the

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[114] Statham J., Scott H., Statham S. et al. (2020) Dairy cattle health and greenhouse gas emissions pilot study: Chile, Kenya and the UK. https://globalresearchalliance.org/wp-content/uploads/2020/10/Dairy- Cattle-Health-and-GHG-Emissions-Pilot-Study-Report.pdf

[115] Jonsson NN, MacLeod M, Hayward A, McNeilly T, Ferguson KD, Skuce PJ. Liver fluke in beef cattle - Impact on production efficiency and associated greenhouse gas emissions estimated using causal inference methods. Prev Vet Med. 2022 Mar;200:105579. doi: 10.1016/j.prevetmed.2022.105579. Epub 2022 Jan 7. PMID: 35066320.

[116] Hall LE, Reilly B, Blackie N. Surveying UK sheep farmers' vaccination techniques and the impact of vaccination training. Vet Rec. 2022;e1798.https://doi.org/10.1002/vetr.1798

[117] AHDB(2022) Vaccine uptake report for cattle and sheep. https://ahdb.org.uk/knowledge-library/use-of-vaccines-in-cattle

greatest impact on GHG mitigation through vaccination included IBR, Johne's disease and Salmonella, with a reduction of GHG emissions of 227.1ktCO_2e, 167.8 ktCO_2e and 83.5 ktCO_2e, respectively[84]. Similarly, vaccinating beef cattle against IBR, Johne's and Salmonella also reduced GHG emissions, but to a lesser extent of 101.6ktCO_2e, 26.3ktCO_2e and 4.6ktCO_2e, respectively[113].

5.1.3 MITIGATION POTENTIAL

- The methane mitigation potential of this strategy is thought to be higher in low-productivity systems, especially in low-income countries[77] where there is greater potential to increase productivity through disease prevention measures, compared to more developed countries with more intensively managed livestock systems and resource availability[61].

    - A study which used IPCC Tier II data to quantify the longer-term changes in methane emissions from ruminant livestock populations globally found that the global livestock methane contribution of developing regions, for example Africa, Asia and Latin America increased from 51.7% in the 1890s to 72.5% in the 2010s[118]. The authors believe the changes are due to increases in livestock numbers in developing countries. Whereas, over the same period, in developed countries their results showed reductions in emissions intensity (emissions/km^2) of 32%[119]. Similarly, Asia, sub-Saharan Africa, Latin America and the Caribbean have the highest emissions intensities for beef production. This is caused by lower feed digestibility increasing enteric and manure methane emissions, poorer animal husbandry, lower slaughter weights and increased aged at slaughter[77].
    - Conversely, a 2020 pilot study aimed to establish the magnitude of GHG emission reductions achievable with animal health improvement measures in the dairy sectors of Chile, Kenya, and the UK found that significant improvements are possible across all regions. Table 3 illustrates the potential reductions in GHG emissions intensity for three conditions - BVD, mastitis, and infertility – across averages herds and the worst 10% of herds within each country. Although Kenya showed the highest potential for reducing GHG emissions for certain conditions, the UK also demonstrated considerable scope for long-term, cost-effective improvements in animal health that would contribute to a reduced GHG emission intensity[115].

TABLE 3: POTENTIAL FOR GHG EMISSION INTESNSITY REDUCTION BY IMPROVEMENTS IN DAIRY CATTLE HEALTH IN CHILE, KENYA, AND THE UK[115]

Condition	Potential Reductions in GHG Emission Intensity (%)		
	Chile	Kenya	UK
BVD (average)	5	4	4
BVD (worst 10%)	9	8	11
Mastitis (average)	6	6	6
Mastitis (worst 10%)	10	11	12
Infertility (average)	7	24	7
Infertility (worst 10%)	10	44	16

- Maintaining animal health and welfare not only directly reduces GHG emission intensity by ensuring that feed energy is efficiently converted to productive energy but also indirectly enhances the outcomes when other methane mitigation strategies are applied. For example, the successful application of novel genetic technologies, such as precision breeding as a methane mitigation strategy depends on maintaining optimal animal health to fully optimise gene expression and maximise the methane mitigation potential of this emerging technology.

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[118] Dangal, S.R., Tian, H., Zhang, B., Pan, S., Lu, C. and Yang, J., 2017. Methane emission from global livestock sector during 1890–2014: Magnitude, trends and spatiotemporal patterns. *Global Change Biology*, *23*(10), pp.4147-4161.

- Numerous disease control and mitigation strategies are readily available and easy to implement. These strategies include routine vaccination, maintaining good animal husbandry practices, ensuring adequate colostrum intake by neonates, and, in extreme instances, applying prophylactic treatments during a disease outbreak or when outbreaks are anticipated[113]. Furthermore, the Agriculture Act 2020 financially incentivises for '*action by farmers, vets, and other organisations to improve animal health and welfare, reduce endemic disease and keep livestock well maintained and healthy*'[119]. These measures could include incentives to participate in national disease control schemes and diagnostic testing for the control and management of endemic diseases.

- To accurately assess the effectiveness of improving morbidity and mortality in herds and flocks as a methane mitigation strategy, it is crucial to first understand the overall disease prevalence within livestock populations. This understanding allows for accurate predictions of the GHG mitigation potential of various disease control strategies[120]. Additionally, since livestock are often simultaneously affected by multiple pathogens, the interaction between these pathogens and their implication for disease control must be evaluated to avoid double counting of GHG emission reductions[113].

- For the continual optimisation of animal health in the future, improved disease surveillance - both active and passive - and improved access to novel diagnostic tests, treatments, vaccines, and disease control strategies are essential. More research is needed to better understand how disease epidemiology may change as a response to climate change, including improved surveillance for the detection of exotic and emerging disease outbreaks. Integrating this data into GHG emissions assessment tools will be crucial in establishing reliable benchmarks to track health improvements and GHG emission reductions, thereby informing evidence-based policy decisions.

- Overall, improving morbidity and mortality in livestock presents a win-win situation, offering economic benefits through improvements in farm productivity and therefore profitability, social benefits through enhanced animal welfare and environmental benefits through a reduction in methane and other GHG emissions[173].

5.2 SELECTIVE AND PRECISION BREEDING

- Like many traits, there is natural variation within species regarding the amount of methane emissions each animal produces. Selecting for low methane producing animals is inexpensive, permanent, and a cumulative mitigation strategy, exploiting this natural variation[61]. Numerous studies have assessed the heritability of methane production and estimate it to be between 0.12-0.45, presenting a very real opportunity to reduce methane emission through appropriate genetic selection[121].

- Methane mitigation technologies could involve directly selecting for low methane production via genetic technology, or indirectly through the selection for other factors which increase productivity and therefore reduce methane emission intensity, for example, the selection of animals with a high FCE.

    - Selecting for reduced methane emission intensity – fewer, more productive cows which produce more absolute methane emissions, but have a lower methane emission intensity – may be more environmentally advantageous than selecting for cows with lower absolute methane emissions, which is often a result of lower productivity and therefore a higher methane emission intesntiy[108].
    - Further research is needed to assess the potential co-option of other genetic traits which may be maladaptive, either physiologically or economically, when selecting for direct methane reduction.

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[119] https://researchbriefings.files.parliament.uk/documents/CBP-8702/CBP-8702.pdf

[120] https://www.researchgate.net/publication/309542180_Endemic_sheep_and_cattle_diseases_and_greenhouse_gas_emissions

[121] I.S. Breider, E. Wall, P.C. Garnsworthy, Short communication: Heritability of methane production and genetic correlations with milk yield and body weight in Holstein-Friesian dairy cows, Journal of Dairy Science, Volume 102, Issue 8, 2019, Pages 7277-7281, ISSN 0022-0302, https://doi.org/10.3168/jds.2018-15909.

- Currently, there is a large-scale commercial trial with sheep farmers in New Zealand, as well as a programme in Netherlands which integrates methane emissions into breeding dairy values[61].
    - When methane production was incorporated into the Dutch national dairy breeding index - which currently includes 15 traits related to yield, health and conformation, longevity, and FCE - it was estimated that a 24% reduction in methane intensity in the dairy industry is achievable by 2050[122]. However, the study highlighted a significant gap in genotypic and phenotypic data, which is crucial to achieve the desired reliability of genomic predictability for methane reducing traits[124]. To gather the necessary data, the authors suggest that a study involving 100 farms, each with an average of 150 cows, over 2 years period would be required. This duration is necessary to account for variables such as time of day, season, lactation stage, and feed composition which all affect absolute methane emissions[123].
    - In New-Zealand, there have been successful long-term outcomes associated with the selection of low-methane emitting traits in over 1,300 sheep[124]. In 2019, breeding values for low-methane emissions were made available to selective ram breeders in New Zealand. They found numerous physiological traits that were associated with low methane producing animals. These include animals with smaller rumens, selection for those which eat little and often, and an increase in lean tissue muscle[125]. Furthermore, they found no evidence of a reduced yield or productivity in naturally low methane emitting sheep[125]. Following this success, the New Zealand Agricultural GHG Research Centre are funding similar work in dairy cattle with the further assessment of potential markers of low methane producing cattle from plasma, milk and gut microbes[125].
    - A recent study conducted in Ireland investigated the potential use of residual methane emissions (RME) as a selection index for breeding programmes to mitigate enteric methane production in grazing dairy cows. They found that RME can be used to select for naturally low enteric methane emitting cows, which had both lower methane yield and lower emission intensity, with no significant phenotypic correlations with animal production traits, for example liveweight and milk production[126]. However, this study only assessed the phenotypic correlations to productivity and did not explore possible genetic associations which may influence these traits.
        - RME is the difference between measured methane yield and the New Zealand inventory emission factor (21.6gCH_4/kg DMI) which was established by the IPCC. Numerous studies have reported that the emission factor is likely an overestimation of enteric methane production[127] - possibly overestimating the methane mitigation potential of this strategy.
    - Current methods for measuring methane production in individual cattle is expensive and difficult to implement. Scientists have developed mid-infrared (MIR) milk sensors which can detect low methane producing cows from their milk. As half of all milk fatty acids are produced in the rumen their proportions correlate to rumen fermentation and thus methane production. MIR measures these milk fats and uses models to genetically evaluate methane emissions produced from large populations of dairy cattle A study which compared MIR and direct methane measurement methods found that MIR is a rapid and accurate alternative. Following this, MIR has been officially implemented for use in

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[122] Y. de Haas, R.F. Veerkamp, G. de Jong, M.N. Aldridge,Selective breeding as a mitigation tool for methane emissions from dairy cattle, Animal, Volume 15, Supplement 1, 2021, 100294, ISSN 1751-7311, https://doi.org/10.1016/j.animal.2021.100294.

[123] Jan Lassen, Peter Løvendahl, Heritability estimates for enteric methane emissions from Holstein cattle measured using noninvasive methods, Journal of Dairy Science, Volume 99, Issue 3, 2016, Pages 1959-1967, ISSN 0022-0302, https://doi.org/10.3168/jds.2015-10012.

[124] https://www.nzagrc.org.nz/domestic/methane-research-programme/breeding-low-emitting-sheep/

[125] https://www.nzagrc.org.nz/domestic/methane-research-programme/breeding-low-emitting-dairy-cattle/

[126] Starsmore, K., Lahart, B., Villalobos-Lopez, N., Egan, M., Herron, J., Burke, J., & Shalloo, L. (2023). Residual methane emissions in grazing lactating dairy cows. *New Zealand Journal of Agricultural Research*, *67*(3), 285–295. https://doi.org/10.1080/00288233.2023.2277239

Holstein dairy cows in Canada as of April 2023 to select for cattle with reduced methane emissions without affecting milk fat, milk yield, and milk protein levels[127].

- Selection for reduced methane production may alter the organic matter digestibility of the cow[61]. Some studies suggest that solely selecting for a reduction in enteric methane production will simply select for lower DMI. This could result in lower productivity, a longer life to reach optimal productivity and therefore an increased emissions intensity[108]. Therefore, the relationship between methane production, productivity, heritability of feed intake, diet type, and economic viability of this approach requires more research to assess the viability of this mitigation strategy[61].

- The use of precision breeding technology could play a vital role in producing cows which produce significantly less enteric methane. Genome editing is the modern technology which can be used to alter an organism's DNA. Recent advances in the technology include the CRISPR-Cas9 tool, made up to two parts. CRISPR is a short section of single stranded RNA which is homologous to a target DNA sequence. Cas9 is an enzyme which cuts double-stranded DNA at these target sequences[128]. This gene editing tool can produce numerous effects at the target site, which include gene knockout, transcriptional regulation, epigenetic regulation, and others, which all ultimately affect the expression of target genes. For reducing livestock enteric methane production this could including reducing the expression of methane-producing genes in ruminal archaea or upregulating the expression of immune-related genes to target, and therefore remove, ruminal archaea in the cow. However, there is limited research into the relationship between cattle genomics and the composition of the ruminal microbiome, and if this is altered if there will be any longer-term effects for the cow given the role of methanogens for pH regulation within the rumen.

5.3 VACCINATION AGAINST METHANOGENS

- The aims of vaccination would involve the stimulation of the ruminant's immune system to produce antibodies within the saliva that suppress methanogen activity in the rumen[61].

- Studies into this mitigation strategy produce mixed results in rumen culture experiments[61]. However, an *in vivo* study in 30 sheep showed that an anti-methanogenic vaccination increased the concentration of IgA and IgG antibodies present in the saliva which aided their delivery to the rumen[129]. They found that immunoglobulin levels and longevity within the rumen varied depending on the vaccine adjuvants and the presence of protease inhibators[130]. Additionally, another study showed that vaccination against the five most commonly found methanogens in sheep rumens (>50% of the methanogenic ruminal flora), did not affect the abundance of methanogens in the rumen after vaccination, but rather increased their diversity[130]. They suggest the diversity of the methanogen population increased due to the reduction in the dominant strains which were targeted with the vaccine, resulting in the proliferation of non-target methanogens. This explains the increase in methane emissions by nearly 18% in vaccinated sheep when compared to controls and suggests the lack of methane mitigation effects may be due to the lack of broad-spectrum vaccines used against the entire rumen methanogenic community[131].

- There needs to be evaluation of the effects of methanogen vaccination on productivity and product quality to assess its commercial viability[61]. More research is required for the selection of appropriate antigens present

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[127] https://www.jdscommun.org/article/S2666-9102(24)00011-5/pdf

[128] Dr Harriet Davenport, Genomic Editing Fact File, VPRF, November 2023

[129] Subharat S, Shu D, Zheng T, Buddle BM, Kaneko K, et al. (2016) Vaccination of Sheep with a Methanogen Protein Provides Insight into Levels of Antibody in Saliva Needed to Target Ruminal Methanogens. PLOS ONE 11(7): e0159861. https://doi.org/10.1371/journal.pone.0159861

[130] Williams YJ, Popovski S, Rea SM, Skillman LC, Toovey AF, Northwood KS, Wright AD. A vaccine against rumen methanogens can alter the composition of archaeal populations. Appl Environ Microbiol. 2009 Apr;75(7):1860-6. doi: 10.1128/AEM.02453-08. Epub 2009 Feb 6. PMID: 19201957; PMCID: PMC2663202.

across the diversity of rumen methanogens, to determine vaccine efficacy in culture and *in vivo* studies, and assess the persistence of the immune response across ruminant populations[61].

- In August 2024, the Royal Veterinary College was awarded £1.2 million in funding from the Bezos Earth Fund to explore, in a first of its kind study, how methane-producing microorganisms colonise the rumen of neonatal cattle and how this impacts the developing immune system. Similarly, the Bezos Earth Fund is funding a separate project at the Pirbright Institute to improve the understanding of the antibodies involved in an immunological response to a methanogen vaccine to see if vaccination is a feasible methane mitigation opportunity.

- This is an attractive strategy for extensive grazing systems with limited potential for intensification, where supplements are used infrequently, and it is difficult to achieve the optimal concentration of feed-additives[61]. However, there could be a financial impediment to uptake in farms, which would benefit from government or industry led-vaccination programmes once, or if, methanogenic vaccination becomes a viable methane mitigation strategy in ruminants.

5.4 DIETARY MANAGEMENT INCLUDING FEED ADDITIVES

- The majority of dietary methane mitigation methods shift rumen fermentation towards propionate production, which acts as an alternative hydrogen sink, reducing methane production, through a variety of mechanisms, which will be discussed individually below.

- With these mitigation strategies, it is important to consider there may be significant upstream GHG emissions associated with the processing, manufacture and transportation of additives. In the case of some feed additives, for example lipid supplementation, these upstream emission may be particularly substantial if they have been associated with significant land-use change, for example in the production of soya bean or palm oil[61].

- FEED ADDITIVES
    - 3-NITROOXYPROPANOL
        - In December 2023, the feed additive 3-Nitrooxypropanol (3-NOP), sold under the brand name '*Bovaer*', was the first methane-reducing feed additive to be approved in the UK.
        - 3-NOP works by inhibiting the enzyme methyl-coenzyme M reductase which reduces the conversion of hydrogen to methane within the rumen in the final step of methanogenesis[131]. As a result, methane production is inhibited and rumen fermentation shifts from acetate and methane production towards propionate, butyrate, and valerate production[61].
        - It has been shown to reduce methane emissions from dairy cows by 30-40% when fed regularly, with no discernible effect on feed intake and productivity[132]. Furthermore, it has been predicted that a 30% uptake in dairy cow populations would reduce agricultural methane emissions by 5% by 2030, and only cost the average consumer an extra 33p per year[133].
        - When used in combination with other feed additives, for example, unsaturated lipids, and monensin and other ionophores, there is an additive effect for the reduction of enteric methane emissions[61].
        - However, there are concerns about the uptake of this approach by farmers in the UK. Since the majority of UK cattle are grazed, it is challenged to ensure consistent and adequate

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[131] Yu G, Beauchemin KA, Dong R. A Review of 3-Nitrooxypropanol for Enteric Methane Mitigation from Ruminant Livestock. Animals (Basel). 2021 Dec 13;11(12):3540. doi: 10.3390/ani11123540. PMID: 34944313; PMCID: PMC8697901.

[132] Pitta, D.W., Indugu, N., Melgar, A. *et al.* The effect of 3-nitrooxypropanol, a potent methane inhibitor, on ruminal microbial gene expression profiles in dairy cows.*Microbiome* **10**, 146 (2022). https://doi.org/10.1186/s40168-022-01341-9

[133] https://green-alliance.org.uk/wp-content/uploads/2022/10/Global-methane-pledge.pdf

consumption of the additive in grass-fed systems. The development of bolus forms of 3-NOP could facilitate administration in these more extensively managed systems and could reduce a potential barrier for its uptake.

- In December 2024, Arla announced a trial of the additive on 30 farms in the UK, sparking controversy and the spreading of misinformation online regarding its safety for human consumers despite passing a full risk assessment by the Food Standards Agency and an independent advisory committee. In a statement on their website, Arla maintain their commitment to use the additive to reduce methane emissions in their herds in the UK.

- IONOPHORES
  - Dietary supplementation with ionophores helps to improve FCE, reduce the acetate:propionate ratio in the rumen, therefore reducing enteric methane production[61].
  - Ionophores are lipid-soluble molecules that work by modifying the transport of ions, including protons (H^+), calcium, potassium, and sodium, across the cell membranes of certain bacteria and protozoa[134]. The microorganisms use excess energy to remove the accumulation of H^+ and other ions within their cytoplasm, resulting in reduced growth and cell death[135]. This alters the bacterial population within the rumen, shifting VFA production in favour of propionate, and away from acetate, resulting in reduced methanogenesis[61].
  - Methane emissions can reduce by 18% with the short-term use of ionophores, but there is evidence to suggest that bacteria within the rumen can adapt to their presence[136], limiting their long-term efficacy as a methane mitigation strategy. Consequently, it has been suggested that using different combinations of ionophores, or rotational feeding of ionophores, may help avoid this adaptation[137].
  - Monensin is an ionophore used extensively in the beef and dairy industry as an in-feed anticoccidial and helps to improve FCE[173].

    - The use of monensin, the first ionophore approved for use as an anticoccidial in the USA in 1971, was banned for use in cattle in the EU in January 2006 as part of the Feed Additive Regulation[137]. This regulation bans the use of antibiotics for growth promotion, therefore monensin can only be used if there is a veterinary requirement i.e., in the instance of coccidiosis in the herd. However due to ionophores not being used in human medicines, in some regions, like Canada, ionophores are still permitted as in-feed growth promoters in livestock.

  - Despite the use of ionophores being solely for animals, there is debate surrounding the widespread use of ionophores which may contribute to the selection for vancomycin-resistance bacteria, with possible repercussions for human health[138].
  - Furthermore, ionophores are toxic compounds. Toxicity can occur with the accidental overdose, misuse in non-target species, feed-mill mixing errors and accidental ingestion by wildlife and other non-target domestic species[135]. Horses are particularly sensitive, but at a high enough doses ionophores can induce respiratory distress in dogs. There are no specific treatments of antidotes of ionophore toxicosis[135].

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[134] https://www.msdvetmanual.com/pharmacology/antibacterial-agents/ionophores-use-in-animals

[135] Duffield TF, Bagg RN. Use of ionophores in lactating dairy cattle: a review. Can Vet J. 2000 May;41(5):388-94. PMID: 10816832; PMCID: PMC1476247.

[136] G. W. Mathison, E. K. Okine, T. A. McAllister, Y. Dong, J. Galbraith & O. I.N. Dmytruk (1998) Reducing Methane Emissions from Ruminant Animals, Journal of Applied Animal Research, 14:1, 1-28, DOI: 10.1080/09712119.1998.9706212

[137] https://ec.europa.eu/commission/presscorner/detail/en/IP_05_1687

[138] Wong A. Unknown Risk on the Farm: Does Agricultural Use of Ionophores Contribute to the Burden of Antimicrobial Resistance? mSphere. 2019 Sep 25;4(5):e00433-19. doi: 10.1128/mSphere.00433-19. PMID: 31554722; PMCID: PMC6763768.

  - LIPIDS
    - Lipid supplementation reduces enteric methane production through a variety of pathways. They can be directly toxic to methanogenic bacteria and protozoa in the rumen, act as a H^+ sink which shifts the ruminal fermentation process towards propionate production[139], and encapsulate feed to reduce its fermentability within the rumen[61].

      - The anti-methanogenic activity of this strategy varies depending on the form of lipid, amount of lipid administered, number of carbons of the fatty acid chain, and the nutrient and fatty acid composition of the basal diet[61]. This variability has resulted in highly variable results in the reduction of enteric methane production from lipid supplementation[107].

    - The practicable application of lipid supplementation is potentially limited by their associated reduction in productivity and quality of end-product. Multiple studies have shown that with increasing medium-chain lipid and polyunsaturated fat content, there is often a reduction in methane emissions, but these emissions reductions are frequently associated with a compromise in milk components, milk yield and a reduced DMI[111]. Despite this, it has been shown that when 3-NOP feed additive is combined with lipid supplementation, their effects on reducing methane emissions is additive[140].

  - BROMOFORM SEAWEEDS
    - Red macroalgae of the *Asparagopsis* genus, containing bromoform, can reduce enteric methane emissions by 98% in cattle and sheep when included at low levels in their diet[181]. Bromoform is believed to competitively inhibit key enzymes (coenzyme M methyltransferase and methyl coenzyme M reductase) involved in rumen methanogenesis[181] and has been associated with reductions in ruminal methanogen populations[182]. This redirects the energy otherwise lost through the formation of methane (estimated at 2-12%) towards metabolism, improving feed conversion efficiency[181]. However, large-scale implementation faces significant challenges; the effects of bromoform are short-lived as ruminal microbes may develop resistance[182]; harvesting the seaweed at the levels required is highly resource intensive; and the aquaculture is not yet developed for this[181].

- FEEDING STRATEGIES

  - INCREASING FEED INTAKE
    - Increasing the feed intake decreases retention time of food in the rumen due to an increased transit time. This limits rumen microbial access to organic matter from feed, reducing the extent of ruminal fermentation and therefore methane emission intensity per unit DMI[61].
    - Similarly, increasing feed intake shifts the nutrients and energy absorbed away from maintenance and towards production. Total methane production increases as there is more feed consumed and therefore more fermentable material, but the methane produced as a proportion of DMI or per unit of animal product reduces and therefore there is a reduction in methane emissions intensity[141].

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[139] Honan M., Feng X., Tricarico J.M., Kebreab E. (2022) Feed additives as a strategic approach to reduce enteric methane production in cattle: modes of action, effectiveness and safety. *Animal Production Science* **62**, 1303-1317.

[140] Zhang XM, Smith ML, Gruninger RJ, Kung L, Vyas D, McGinn SM, Kindermann M, Wang M, Tan ZL, Beauchemin KA. Combined effects of 3-nitrooxypropanol and canola oil supplementation on methane emissions, rumen fermentation and biohydrogenation, and total tract digestibility in beef cattle. J Anim Sci. 2021 Apr 1;99(4):skab081. doi: 10.1093/jas/skab081. PMID: 33755112; PMCID: PMC8051842

[141] Capper, Jude & Cady, Roger & Bauman, D.. (2009). Increased production reduces the dairy Industry's environmental impact. Proceedings of the 18th Annual Tri-state Dairy Nutrition Conference.

- REDUCING THE FORAGE TO CONCENTRATION RATIO
  - Concentrates which are high in sugars, starch, and highly fermentable fibre, shift the VFA production in the rumen towards propionate, which reduces enteric methane production and increases the rumen outflow rate[61]. Whereas forages, which are mainly composed of structural carbohydrates, like cellulose, favour the production of acetate in the rumen, causing higher methane production per unit of feed[142]. Therefore, reducing forage, whilst maintaining or increased the concentrate portion of livestock diets will reduce enteric methane emissions.
  - This method of methane emission mitigation does not account for the beneficial impacts of carbon sequestration in soils resulting from grazing cattle. Additionally, it overlooks the accompanied upstream GHG emissions associated with land-use changes from pasture to cropland for animal feed, including the associated loss of soil carbon, as well as emissions related to the production, distribution, and storage of concentrate feed[61].

- INCREASING THE LEGUME CONTENT OF FEED.
  - The addition of legumes to a forage mix can reduce methane emissions on farm directly and indirectly.

    - Legumes directly increase the digestibility of fibre within the feed, shifting ruminal fermentation to increased propionate production and reduce methanogenesis[61]. Furthermore, legumes often contain secondary compounds, including tannins and saponins, which also reduce methane production, although the concentration of these compounds within legumes is highly variable and therefore so are their effects on methane mitigation[61].
    - Feeding legumes, such as alfalfa, indirectly reduce methane emissions by reducing methane produced from slurry when fed to dairy cows, compared to dairy cows fed corn silage[143]. Furthermore, legumes have a high crude protein content and overall nutritional value, which reduces the requirement for feed supplementation and therefore indirectly reduces upstream GHG emissions associated with the manufacturing and distribution of supplements[144].

  - Despite these theoretical benefits, the effect of legumes has been shown to produce inconsistent results when implemented in grazing systems. This is due to significant variation in the proportion of legumes present in pasture, concentration of tannins, DMI, organic matter digestibility, and feed transit time through the rumen[145].
  - Legumes also have extra effects on reducing other GHG emissions. They have a symbiotic relationship with *Rhizobium* bacteria[174] in the soil which can fix atmospheric nitrogen in the form of ammonia for use by the plant. This reduces the amount of nitrogen required in fertiliser and therefore the upstream GHG emissions associated from the manufacture and transport of fertiliser[61]. In addition to their role in nitrogen fixation, legumes also contribute to increasing soil carbon by providing organic matter that supports soil microbes[145]. This, in turn, improves soil structure and enhances its capacity for carbon storage[145]. However, it has been suggested that in poorly draining wet soils, particularly under warm conditions, legume-enriched soils emit a significant quantity of N_2O. In one particular study, only in 10% of the

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[142] Peter H. Janssen, Influence of hydrogen on rumen methane formation and fermentation balances through microbial growth kinetics and fermentation thermodynamics, Animal Feed Science and Technology, Volume 160, Issues 1–2, 2010, Pages 1-22, ISSN 0377-8401, https://doi.org/10.1016/j.anifeedsci.2010.07.002.

[143] Massé, Daniel & Jarret, Guillaume & Benchaar, Chaouki & Hassanat, Fadi & Saady, Noori. (2016). Effect of increasing levels of corn silage in an alfalfa-based dairy cow diet and of manure management practices on manure fugitive methane emissions. Agriculture Ecosystems & Environment. Accepted. 10.1016/j.agee.2016.01.018.

[144] Schultze-Kraft, Rainer & Rao, Idupulapati & Peters, Michael & Clements, Robert & Bai, Changjun & Liu, Guodao. (2018). Tropical forage legumes for environmental benefits: An overview. Tropical Grasslands-Forrajes Tropicales. 6. 1. 10.17138/TGFT(6)1-14.

[145] Vargas J, Ungerfeld E, Muñoz C, DiLorenzo N. Feeding Strategies to Mitigate Enteric Methane Emission from Ruminants in Grassland Systems. Animals (Basel). 2022 Apr 28;12(9):1132. doi: 10.3390/ani12091132. PMID: 35565559; PMCID: PMC9099456.

grazing land examined did the carbon-sequestration benefits of legumes outweigh the associated N_2O release[146].

5.5 MANURE MANAGEMENT

- An important aspect of manure methane mitigation measures is that they can be extended to all livestock species to help reduce methane emissions across all agricultural livestock sectors. This is especially important as pig manure is the largest source of manure derived methane emissions globally[163], but makes up a substantially lower proportion of manure emissions in the UK.

- The majority of methane is produced from the storage of manure and therefore mitigation practices which reduce manure storage time, store manure at low temperatures and capture methane for combustion are all effective methane mitigation strategies[147].

- ANAEROBIC DIGESTORS
    - Manure can be collected and used to produce methane by microbes under anaerobic conditions. This process forms biogas, a mix of approximately 60% methane and 40% CO_2[148], which can be used as an alternative sustainable energy source[61] and reduce the need for fossil fuels. Biogas can be purified to make biomethane which can be used as a natural gas source[149]. Biogas collection from manure storage can either be through a traditional manure store or from purpose-built anaerobic digestors[61].
        - In 2020, approximately 6.7% of the UK's total energy contribution came from heat produced by anaerobic digestors[149].
    - Purpose-built anaerobic digestors can be expected to produce twice as much methane compared to more conventional storage systems[150]. If manure is stored in a gas-tight structure, preventing fugitive emissions, the methane produced can be collected and used for electricity generation[151].
    - This methane mitigation approach leads to an increase in the production and release of CO_2 into the atmosphere, both directly and indirectly. When biomethane is used as natural gas in electricity generation it undergoes combustion resulting in the release of CO_2 into the atmosphere instead of methane. Although this process obviously increases CO_2 emissions, some may consider it a methane mitigation strategy as by capturing and converting methane into CO_2 through combustion the higher global warming potency of methane in the atmosphere is avoided. Additionally, CO_2 production is directly elevated during anaerobic digestion; however, this CO_2 can be collected and utilised as a component of biogas[61].
    - Anaerobic digesters offer further GHG mitigation benefits. The digestate, the residual material following anaerobic digestion, can serve as a substitute for conventional fertilisers for use on pastures. This substitution provides further mitigation against the upstream GHG emissions associated with fertiliser production, transport, and application[61]. In addition, the process of anaerobic digestion reduces the carbon content of the manure and therefore provides less energy required by denitrifying bacteria to produce nitrous oxide when manure is applied to the soil[61]. However, this relationship is not

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    simple as in certain circumstances application of reduced soil organic matter manure has led to increased emissions of nitrous oxide once applied to pasture[111].
  - Anaerobic digesters are readily available, well-developed and applicable across various livestock types and farming systems[61]. The primary challenge for the adoption of anaerobic digestion for manure management is the relatively high cost associated with the infrastructure and biogas production compared to other available energy sources[61]. While centralised anaerobic digester plants have been proposed for smaller farms, the energy and time required for manure transport remains a significant limitation[151]. Additionally, anaerobic digestion systems are generally not recommended for geographical areas where the average temperature falls below 15°C, unless supplementary heat and temperature control are provided[111].

- MANURE STORAGE TEMPERATURE
  - Storing slurry at low ambient temperatures significantly reduces methanogen activity, thereby decreasing methane emissions. In cold or temperate climates, particularly during winter months when temperatures frequently drop below 10°C, storing manure outdoors can lead to reduced methane emissions. However, microbial activity is influenced by several factors, including moisture content of the slurry, oxygen levels and the availability of organic matter. As a result, the effectiveness of this as a mitigation strategy can vary widely[61].
  - Multiple studies have demonstrated that cooling pig slurry storage units to temperatures below 10°C can reduced GHG emissions 30%-46%[152]. In experiments on cattle slurry, a temperature reduction of just 1-2°C has been shown to reduce methane emissions by 5-10%[61].
  - The active cooling of manure is likely to be expensive to implement and have associated GHG emissions. It may be a cost-effective and attractive option if the exchanged heat can be harnessed for electricity or heat production, or if groundwater can be used to cool the slurry in indoor units, as it is in the Netherlands[151]. On the other hand, passive cooling, achieved by storing manure in cold or temperate climates, such as during the UK winter when temperatures after often below 10°C, offers a less expensive approach to reducing methane emissions from manure storage[61].
  - Furthermore, the complete emptying of slurry storage tanks, or increasing emptying rates up to four times can reduce fugitive methane emissions by up to 97% and 80%, respectively[180].

- MANURE ACIDIFICATION
  - Manure acidification can be achieved indirectly through the acidification of livestock diets to produce more acidic manure, or directly through the addition of acids to manure post-excretion. The low pH of an acidic environment inhibits methane-forming microorganisms within the manure and therefore reduces methane emissions.

    - Indirectly, incorporating organic acids into animal diets can lower urinary pH which subsequently reduces the pH of slurry. This method has shown promise as a GHG mitigation strategy and may also enhance growth performance, reduce gastrointestinal substrates for microbial fermentation and decrease emissions of ammonia and hydrogen sulphide[153]. For example, the inclusion of benzoic acid in pig diets has been shown to reduce manure pH, thereby mitigating nitrogen and methane emissions[155]. Benzoic acid is metabolised in the liver and converted into hippuric acid, which is excreted via the urine[154]. Hippuric acid lowers

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        urinary pH and acidifies slurry when mixed together. However, some studies suggest that acidifying pig diets could potentially increase methane production due to extended methanogen potential[155]. There is limited available research of this mitigation strategy in cattle, necessitating further investigation to determine its viability and if there are any consequences for productivity, DMI, FCE and economic feasibility.
        - The direct addition of acids to slurry, reduces the pH which inhibits the growth of methanogenic bacteria present in the slurry. This approach has shown significant reductions in methane emissions, with a 2020 study reporting a 77% reduction in methane emissions from recently acidified dairy cattle manure, and even a 38% reduction in slurry that had been acidified a year prior[156]. A 2013 study similarly reported methane reductions of 67-87% in cattle manure slurries[157].

    - While manure acidification can lower soil pH to around 5.5, which generally does not pose a risk to crop production and can improve nitrogen fixation by reducing nitrogen loss via ammonia, it may have unintended consequences for soil and crop quality when applied to arable land[61]. A study examining soil acidification over a two-month period found that reduced soil pH led to reductions in CO_2 and methane emissions from the soil, as well as a reduction in soil phosphorus levels[158]. However, long-term studies are needed to quantify any potential negative effects of acidification on soil health and the overall viability of this as an effective methane mitigation strategy.
    - A recent DEFRA-funded study[159] which investigated the effects of slurry acidification on soil quality over a two-year period found no lasting impacts of acidification on soil or crop quality. Although an initial reduction in soil pH was observed, it was eventually buffered to control levels at the end of each growing period[160]. However, excessive acidification may overwhelm the soils natural buffer system and disrupt the soil microbiome, potentially affecting soil carbon sequestration, ammonia release and water drainage. Further research is necessary to fully understand the long-term implications of acidification on both methane emissions and soil health.

- MANURE APPLICATION TECHNIQUES

    - MANURE AERATION
        - Manure aeration is a technique which creates aerobic conditions within the manure, thereby inhibiting anaerobic methanogens responsible for methane production during the breakdown of organic matter within the manure. Realistically, it is difficult to achieve fully aerobic conditions and therefore frequently both aerobic and anaerobic conditions exist in the manure resulting in some level of methane production despite aeration efforts.
        - There are three different types of aeration: 1) passive, whereby manure is left undisturbed allowing for minimal natural aeration; 2) extensive composting, whereby manure is mechanically turned to enhance aeration; and 3) intensive, whereby manure is actively aerated using mechanical means[61].
        - The aeration of solid manure with biological (bacteria and enzyme) mixtures from pig slurry has been estimated to reduce methane emissions by up to 99% compared to untreated

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manure[175]. However, while methane emissions are reduced, some studies indicate a significant increase in N_2O emissions due to the frequency turning and mixing of manure during the composting process[61].

- INJECTION OF MANURE INTO SOIL
  - Manure injection involves introducing manure 15-20cm below the soil surface where methanotrophic bacteria within soil can oxidise the carbon-containing components of the manure. While this method can reduce methane emissions, it may also increase methane production if soil conditions favour the growth of methanogenic bacteria. Soil methane emissions typically spike immediately following manure application but quickly reduce to very low levels after incorporation or injection[61]. Additionally, ammonia emissions are reduced with this technique, although there may be an associated increase in nitrous oxide emissions.
  - Surface application of manure can result in a reduction in methane emissions, as the organic matter is more likely to decompose under aerobic conditions, thus minimising methane production.
  - The mitigation impacts of manure injection is improved when combined with anaerobic digestion and solid separation before spreading, which can further reduce methane emissions from injected manure compared to surface-applied manure[61].

6.0 LIVESTOCK MITIGATION OUTCOMES – CONCLUDING REMARKS

- Globally and in the UK, ruminants are a significant source of anthropogenic methane emissions which are predominantly produced through enteric fermentation. It has been estimated that the global livestock agricultural sector contributes between 9-18% of global anthropogenic GHG emissions[160], 56% of which is methane[176].

- In 2018, the UK agricultural industry accounted for 10% of anthropogenic UK greenhouse gas emissions. Since 1990, methane emissions in the UK have decreased significantly in several sectors: by 75% (47 $MtCO_2e$) in the waste sector and 84% (32 $MtCO_2e$) in the energy sector[55]. However, reductions in the agricultural sector have been more modest, with only a 15% reduction (4 $MtCO_2e$)[55]. Consequently, agriculture has become the largest anthropogenic source of methane emissions in the UK since 2011[55]. Projections indicate that if current trends in emission reductions continue, the agricultural sector could become the second-largest emitter of all GHGs in the UK by 2050[58].

- Given the global demand for meat and dairy products is predicted to increase along with global population by 2050 it is more important than ever for the agriculture sector to adapt to climatic uncertainties and mitigate against GHG emissions.

    - Ruminant farming is also associated with other substantial climatic and environmental issues. In addition to red meat and dairy industries contributing an estimated 55% to the total global agriculture GHG emissions, approximately 30% of global biodiversity has been affected by livestock-associated deforestation, including land used directly for livestock grazing or land destroyed for crops to generate livestock feed[161]. Furthermore, a significant amount of N_2O is produced from animal manure, the production and usage of artificial fertilisers, and during feed production. Similarly, CO_2 is released from fossil fuels for the transport, processing, and production of feed and in land-use change where deforestation releases long-term carbon stores[61]. Some livestock agricultural systems, particularly intensive feed-lot systems, are responsible for significant soil erosion and degradation, and water contamination. These impacts vary depending on the livestock, production system, management system and scale of production[161].
    - There is potential for production systems in the livestock sector to generate positive environmental and sustainable outcomes. More diverse and extensive systems can improve sustainable farming practices by employing grazing strategies to improve soil health, increase soil carbon sequestration, restore degraded areas, improve biodiversity and animal health and welfare. This can be achieved through rotational grazing, mixing herbivores on pasture (equids and bovids), agroforestry, improving feed quality and livestock management in general.

- Given the longevity and thus accumulation of CO_2 in the atmosphere a globally coordinated effort focused initially on reducing CO_2 emissions to as low as possible followed by CO_2 removal from the atmosphere to counteract inevitable residual emissions are critical to achieving a lasting climate solution. Methane mitigation strategies provide a short-term solution for the climate crisis by creating time for necessary advancements in CO_2 emission reduction technologies and the development and implementation of CO_2 removal technologies at scale.

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[161] https://iris.who.int/bitstream/handle/10665/370775/9789240074828-eng.pdf?sequence=1

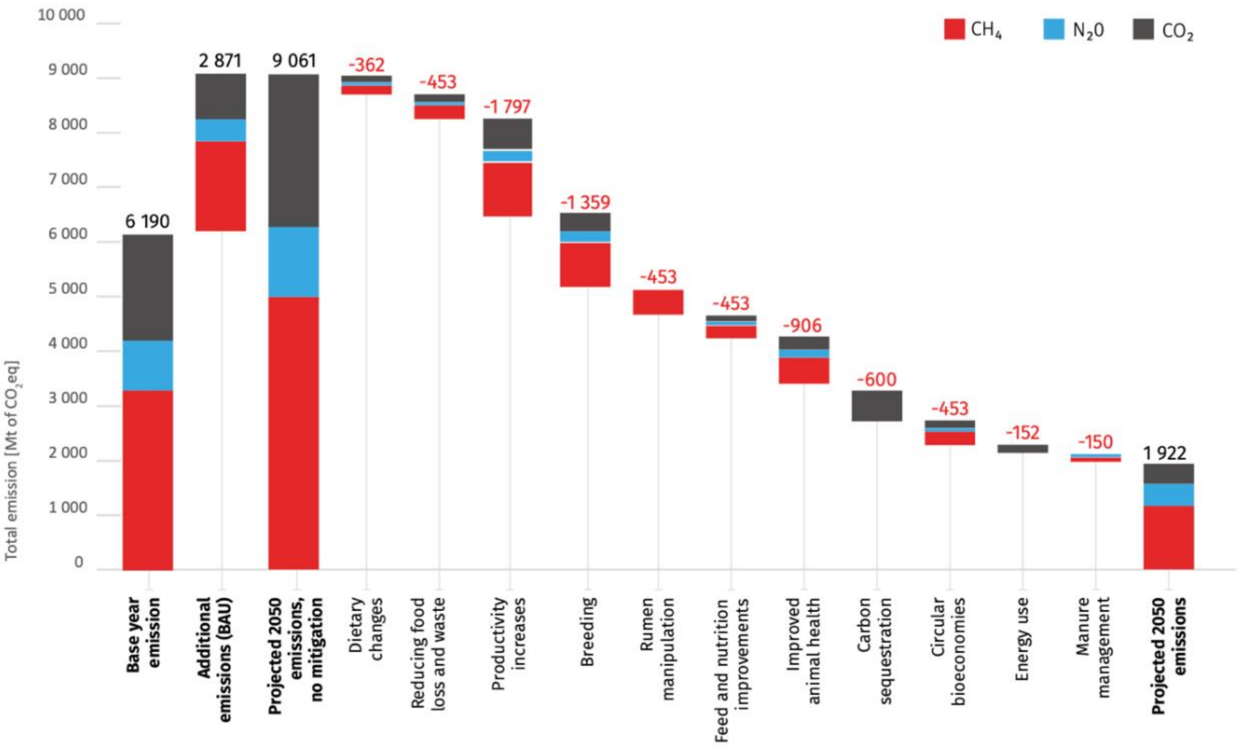

FIGURE 22: BASE YEAR (2015) AND PROJECTED GHG EMISSIONS FROM LIVESTOCK AS A WATERFALL CHART, WITH A RANGE OF MITIGAITON MEASURES APPLIED, FOR THE POTENTIAL REDUCTION IN EMISSIONS BY 2050. DATA FROM FAO PATHWAYS TOWARDS LOWER EMISSIONS, 2023 REPORT[162].

- There is huge scope to sustainably manage the livestock agricultural industry to reduce methane emissions through the adaptation of existing systems for higher productivity gains[162]. This includes making improvements in productivity, herd health, selective breeding, feeding regimes and supplementation, manure management, and animal health and welfare outcomes. Figure 22 shows global analysis data from a comprehensive literature review on the FAO's 2023 report 'Pathways towards lower emissions' of GHG mitigation methods which can be employed within the livestock sector.

- A significant portion of methane emissions can be reduced on farms through mitigation strategies, many of which can be implemented now with minimal extra costs – and indeed potential economic and animal health and welfare benefits. For instance, the FAO estimates that improvements in productivity can mitigate over 1,700 $MtCO_2e$ greenhouse gas emissions by 2050[163]. Given the responsibility of the veterinarian in improving animal health on farms and their crucial relationship with farmers, the role of the veterinary industry in this area is vital.
    - Global analysis may not be reflective of results from individual production systems but functions to illustrate the concept of the employment of GHG mitigation strategies within the sector. The authors note that some mitigation strategies may not be mutually exclusive from each other, which poses a challenge for a clear delineation as some emissions are possibly being double counted[163].

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[162] FAO. 2023. *Pathways towards lower emissions – A global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems.* Rome https://doi.org/10.4060/cc9029en

  - Enhancing the health status of herds and flocks through endemic disease control strategies can increase productivity and reduce GHG emission intensity. It has been suggested that implementing disease control measures including improving nutrition, biosecurity, vaccination and colostrum management could reduce GHG emissions from the cattle sector by 6% in the UK[113]. Furthermore, there is considerable opportunity to improve vaccination uptake, which is often well below 50% in eligible herds[118], through government-led initiatives and funding following the Agricultural Act 2020.
  - Feed additives that reduce methane production from ruminal archaea are another effective mitigation strategy. In December 2023, the FSA approved 3-Nitrooxypropanol for use in cattle which has been shown to reduce methane emissions from dairy cows by 30% without affecting feed intake or productivity[133]. Similarly, reducing the ratio of concentrates in feed, increasing the legume content and the addition of lipids in feed can all shift ruminal VFA production towards propionate and therefore reduce enterically produced methane under certain conditions[61]. Importantly, the results of these strategies can be highly variable and a tailored approach may be required for practicable implementation on farm.
  - Since methane production is a heritable trait, selective breeding can be used to breed naturally low-emitting animals - a strategy already being utilised in New Zealand and the Netherlands. Furthermore, there is potential in developing vaccines against ruminal methanogens which could stimulate the immune system to produce antibodies that suppress methanogen activity in the rumen. This is a developing field with significant research from the Bezos Earth Fund funding projects at the Royal Veterinary College and the Pirbright institute to assess the viability of this methane mitigation strategy.
  - With regard to manure management, the implementation of centralised anaerobic digestors, storing manure outside during the winter and promoting aerobic conditions when applying the slurry to soils can all be used to reduce methane associated with manure storage and application.

- The livestock sector continues, and will continue, to be a significant emitter of GHG emissions, in part due to the inherent nature of livestock production and their role in the biogenic carbon cycle, and in part due to predicated population increases and demand for animal protein. Current land management, production and management systems need to modernise and adapt to more sustainable systems, whilst still prioritising productivity and efficiency.

- Mitigation strategies will need to be implemented on a case-by-case basis, depending on the suitability (cost-effectiveness, methane mitigation potential and economic benefits) for each production system due to the vast heterogenicity within the livestock sector. Studies have shown that GHG emissions vary significantly depending on factors such as animal breed, species, production system (extensive, intensive, or mixed), diet, nutrition, animal health, and climate. Additionally, since the livestock sector impacts biodiversity, soil quality, animal health and welfare, public health, employment, and the rural economy, mitigation strategies must be contextualised within this broader range of variables when weighing up the costs and benefits and therefore the overall employability of each mitigation method.

- Overall, the UK must guard against destroying the indigenous livestock industry which is relatively environmentally efficient with the consequence of inevitably importing more meat and dairy produced with poorer environmental efficiency in order to reach net zero faster.

Miscellaneous References[163], [164], [165], [166], [167], [168], [169], [170], [171], [172], [173], [174], [175], [176], [177], [178], [179], [180], [181]

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