Quantifying the temperature effects of Paris-compliant livestock trajectories

And why a rapid global protein-transition is our most desirable option

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Abstract

The food system emits one third of anthropogenic greenhouse gas (GHG) emissions and is projected to contribute 0.9 °C to end-of-century warming. It is also a primary source of methane; a powerful short-lived climate forcer (SLCF) and the second-most important GHG. Most food system methane emissions result from livestock production and is biogenic (part of the short carbon cycle). As such, livestock emission reductions can actively lower surface temperatures. Despite this, the livestock sector's current commitments do not meet the IPCC's 2035 global emissions reduction target. Here, we use the reduced-complexity climate model MAGICC to show that reduction trajectories identified by expert-elicitation for a livestock sector compliant with the Paris Agreement would avoid up to 0.42 °C warming by 2100. Specifically, a reduction in methane emission contributes 76.6% to this cooling in 2050 (of a total of 0.17 °C). Climate studies typically report emissions using GWP100, which underestimates the warming potential of SLCFs in the short term. We assess various climate metrics' performance relative to MAGICC outcomes, and find better performance for target-aligned time horizons (for both 1.5 °C and 2.0 °C). Our findings reinforce the scientific consensus that reductions in livestock emissions are unavoidable in meeting targets and developing climate policy.

Introduction

The food system is currently responsible for a third of anthropogenic greenhouse gas (GHG) emissions (Crippa et al., 2021) and is projected to grow to more than 50% by the end of the century (Ivanovich et al., 2023), endangering the 1.5 °C and perhaps even 2.0 °C temperature goals (Clark et al., 2020). Concurrently, food production is at risk from extreme weather events driven by climate change (Mbow et al., 2019). Despite this, efforts to reduce emissions have focused mainly on the energy sector, and countries have been hesitant to include significant reductions in food system emissions in their National Determined Contributions (NDCs) (Olczak et al., 2023). This is partly due to food security fears, along with economic implications, political backlash, and pressure from the industry lobby (The Changing Markets Foundation, 2024). Yet, to reach Paris Agreement temperature goals anthropogenic GHG emissions must be abated significantly and rapidly across all sectors.

Methane (CH_4) is the second-most abundant GHG after carbon dioxide (CO_2), and a short-lived climate forcer (SLCF). Unlike fossil methane, biogenic (*non-fossil*) methane is part of the short carbon cycle, so emissions do not increase the carbon stocks and heat trapped in the atmosphere. The agricultural sector is currently responsible for 44% of global anthropogenic methane emissions, primarily from livestock (33% of total methane emissions) (Saunois et al., 2020). Livestock emissions caused 0.19 °C of warming compared to preindustrial levels in 2010, to which methane contributed 61% (0.13 °C) (Reisinger & Clark, 2018). Models suggest that livestock emissions can contribute up to 0.55 °C of warming by 2100 (Ivanovich et al., 2023). As such, a rapid, global phase-out of livestock through dietary change can actively reduce temperatures on Earth. Analogous to controversial geoengineering techniques, but without their considerable risks, uncertainties, and investments (Fawzy et al., 2020; Lawrence et al., 2018). Substantial additional benefits include: decreased loss of (rain-)forests, amelioration of water scarcity, prevention of biodiversity loss, a lower risk of zoonotic pandemics, and a healthier population (Dalin & Outhwaite, 2019; Hayek, 2022; Rosenzweig et al., 2020; Springmann et al., 2016).

The food system's climate impacts can be quantified using life cycle analyses on individual food products combined with global consumption data (Poore & Nemecek, 2018). Once disaggregated by GHG species, the resulting emissions can be used to create alternative GHG-trajectories for climate models. This allows quantifying the temperature impact of specific mitigation measures, e.g. targeting methane intensive foods (Ivanovich et al., 2023). Globally, animal products provide just 37% of the protein and 18% of the calories consumed by humans, yet their production occupies 83% of agricultural land (Poore & Nemecek, 2018) and causes twice the GHG emissions associated with plant-based foods (Xu et al., 2021). This discrepancy means that a complete phaseout of animal protein from current diets would avoid 0.20 – 0.44 °C of warming by 2100 (Ivanovich et al., 2023). The prominent role of reducing ruminant meat and dairy consumption becomes increasingly obvious, as these products contribute 90% of the total climate benefits of a protein transition towards plant-based diets (Eisen & Brown, 2022).

Studies proposing dietary change to mitigate food-system (methane) emissions generally compare the climate impact of current diets to a sustainable and healthy alternative (e.g. the EAT-Lancet diet (Willett et al., 2019)). However, these studies rarely consider a complete phaseout of animal protein, stating adoption obstacles which preclude more substantial livestock reductions (Clark et al., 2020; Ivanovich et al., 2023; Reisinger & Clark, 2018). Estimates of the impact of livestock phase-outs generally use arbitrary timelines unconnected to climate targets. Harwatt et al. (2024) addressed this gap, surveying over 200 leading experts about the magnitude and urgency of reducing global livestock emissions. They developed five trajectories with peak livestock emissions in 2025, and subsequent reductions of up to 61% in 2036, yielding a *Paris-compliant* livestock sector.

Reduction targets for SLCF emissions like methane, are often reported using climate metrics which equate to carbon dioxide's warming potential (CO2-eq). However, the curves of atmospheric concentration, radiative forcing, and temperature change following emissions of different GHGs have distinct trajectories (Figure 1). This is true even if two GHGs have the same global warming potential (GWP) value. The real-world warming effect of GHG emissions cannot be captured by climate metrics alone (Figure 2). Additionally, the chosen time horizon and computation method heavily influences outcomes when equating SLCFs to carbon dioxide. Thus, selecting a metric to represent study outcomes inherently is a value judgement (Pierrehumbert, 2014). Although GWP is the *de facto* standard climate metric, it has distinct shortcomings. Firstly, the arbitrarily chosen fixed time horizon makes GWP100 unfit to calculate warming equivalency for years of interest, e.g. policy goals at t(g), especially when further removed from t = 100 years (Abernethy & Jackson, 2022). Secondly, GWP does not account for differences in warming mechanics between carbon dioxide and SLCFs, as it assumes a pulse of emissions at t = 0. This is unproblematic for carbon dioxide because its atmospheric lifetime is in the order of millennia, and the temperature change it causes is approximately linear with cumulative emissions. In contrast, the warming effect of SLCFs like methane are better captured using their rate of change relative to ongoing emissions (Lynch et al., 2020). Thus computing GWP for SLCFs can lead to large and significant inaccuracies (Pierrehumbert, 2014). Finally, GWP is a metric based on radiative-forcing, which is the precursor of temperature change. Given that climate goals are expressed in degrees Celsius, using a metric with the same unit would increase clarity (Balcombe et al., 2018).

As climate metrics simplify science communication and reporting for non-experts such as policy makers and the general public, newly devised metrics improve on GWP100's SLCF representation (see also, SI: Literature study): Instead of an arbitrary time horizon, those in $GWP_{1.5°C}$ and $GWP_{2.0°C}$ coincide with likely crossing years of the Paris Agreement temperature goals (Abernethy & Jackson, 2022). Another alternative, GWP*, compares a pulse of CO2 emissions to a rate of change in ongoing SLCF emissions, to account for the different effects of accumulating emissions over time (Allen et al., 2018; Lynch et al., 2020; M. A. Smith et al., 2021; P. Smith et al., 2021). Since each has different strengths and shortcomings, Balcombe et al. (2018) advise authors to choose the metric depending on the communication goal. In methane-dominated sectors, GWP100 consistently underestimates methane's temperature impact compared to a climate model. While GWP20 and GWP* outperform GWP100, this performance depends both on the metric and the evaluation year(Cohen-Shields et al., 2023).

Here, we explore the temperature impacts of a global phase-out of livestock products consumption. To do this, we create discrete food system emissions trajectories, based on recent global consumption data which project business-as-usual (BAU) and alternative mitigation pathways until 2100. In the latter, we reduce livestock emissions to levels compliant with the Paris Agreement 1.5 °C warming goal (Harwatt et al., 2024), and apply either immediate or gradual phase-outs. We use MAGICC, a reduced-complexity climate model (Meinshausen et al., 2011, 2020), to calculate their warming effects. We also express the emission reductions in various climate metrics, and compare the results from these different methods for two reasons. First, to study the differences caused by the inclusion of non-CO_2 SLCFs in CO_2-equivalents, compared to modelled outcomes. Second, to assess the implications of using climate metrics in science communication designed to aid policy making towards the Paris Agreement climate goals.

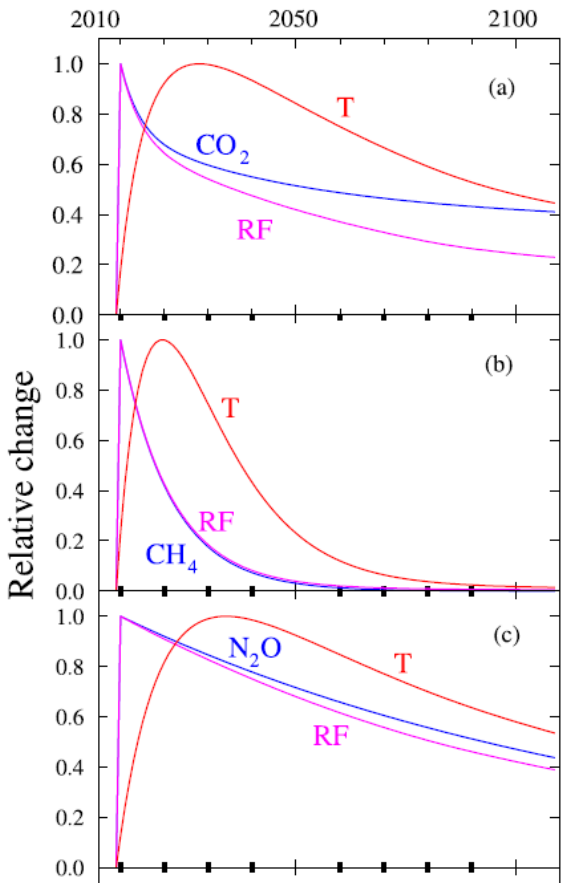

Figure 1: Pulse emissions in 2010 of a) CO2, b) CH4, and c) N2O, have different progressions of atmospheric concentration (blue, GHG), radiative forcing (RF), and temperature (T). Figure source: Kirschbaum (2014, Figure 3).

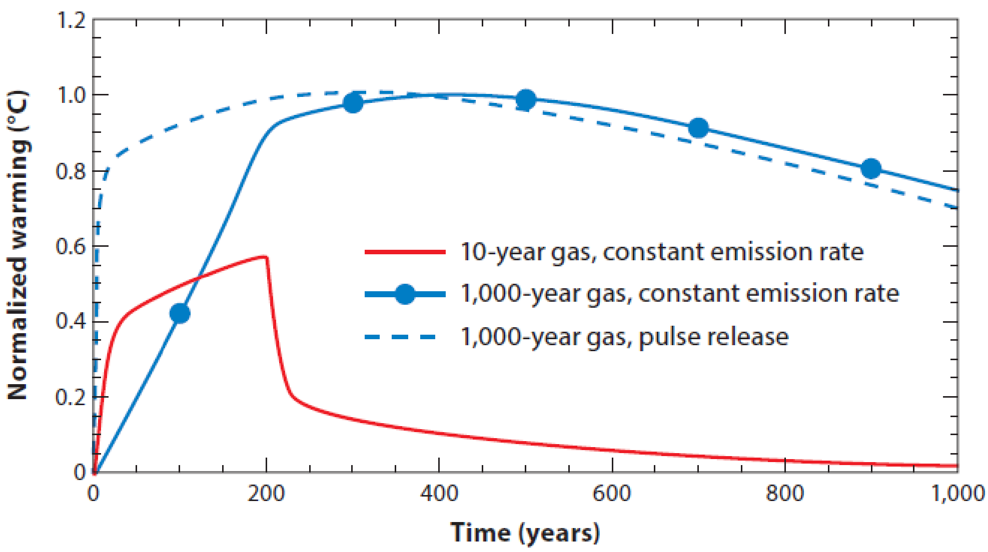

Figure 2: Comparison of the warming effect of gases with different lifetimes but the same GWP100 value. '10-year gas' denotes a 10-year atmospheric lifetime. The pulse emission is instant at year 0, while the constant emissions last from year 0 until 200. Figure source: Pierrehumbert (2014, Figure 7).

Methods

Here, we quantify the potential avoided warming to the end of the century of a global livestock emissions phaseout, and analyse the cooling contribution of methane. We investigate three scenarios: A business-as-usual scenario for emission and temperature references, and two mitigation scenarios in which livestock emissions reductions are immediate or follow expert-elicited timelines from Harwatt et al. (2024). We create matching trajectories of CH4, N2O, and CO2 based on the recent food-system emissions database by Ivanovich et al. (2023) with disaggregated emission values per GHG species and food-item. In each scenario, we deduct the corresponding annual emissions from livestock-associated food-items. We scale the reductions and remaining emissions based on the SSP2 population growth projection (*AR6 Scenario Explorer and Database*, n.d.; K.C. & Lutz, 2017). Other food demand fluctuations are outside the scope of this study.

After establishing the emission trajectories, we use the reduced-complexity climate model MAGICC7 to calculate the temperature impact by GHG species from animal foods. This approach has been used in other work (Eisen & Brown, 2022; Ivanovich et al., 2023; Reisinger & Clark, 2018). We also assess the performance of various climate metrics (GWP100, GWP20, etc.) to match the modelled cooling contributions of methane. For this purpose, we convert the cumulative emissions of each GHG species into CO2-equivalent climate metrics. Since the selected metrics express a warming potential (e.g. CO2-eq) and MAGICC outputs a temperature change (K), the two are not directly comparable. We therefore express methane's contribution to the total warming effect as a unitless ratio for each scenario, allowing a one-to-one comparison of metrics to model outcomes. This approach was previously used to assess metric performance on sector-wide (methane) emissions (Cohen-Shields et al., 2023).

We obtain baseline 2015 and 2020 levels for CH4, N2O, and CO2 food-system emissions from a study into the entire food system (Ivanovich et al., 2023). They provide data for the years 2010 and 2020, so we interpolate values for 2015 (see Table 1 for 2020 total food system GHG emissions). The database synthesizes annual food-system emissions based on life cycle analyses (LCA) and recent consumption and production figures. The disaggregated GHG species emissions per food item allows for the construction of alternative emission trajectories, and for the assessment of fluctuating consumption patterns with a climate model. Future food consumption patterns are highly uncertain as myriad socio-economic factors influence dietary trends (Sans & Combris, 2015). Studying and predicting these trends is well outside the scope of this study. We therefore assume current (2024) and future consumption to follow constant 2020 dietary patterns, and scale emissions proportionally to population change.

Table 1: Food system GHG emissions per category in 2020, in parentheses the percentage of total food system emissions. Adapted from: Ivanovich et al. (2023).

Food group \ GHG	*CH4 [Mt/a]*	*N2O [Mt/a]*	*CO2 [Mt/a]*
Food system, total	243.9	10.9	5711.5
Ruminant meat	95.5 (39.2%)	1.9 (17.4%)	387.5 (6.8%)
Dairy	52.0 (21.3%)	1.4 (12.8%)	495.4 (8.7%)
Non-ruminant meat (incl. eggs)	17.0 (7.0%)	2.8 (25.7%)	1203.3 (21.1%)

We quantify mitigation outcomes against BAU, which assumes no mitigation-measure induced livestock reductions. Each scenario follows the SSP2 'Middle of the road' population growth projection (Fricko et al., 2017; K.C. & Lutz, 2017; Riahi et al., 2017). Other studies either use a middle of the road projection (Clark et al. (2020) use the UN's 'medium fertility' pathway) or a high-population projection to illustrate the maximum potential mitigation effects (Ivanovich et al. (2023) and Reisinger & Clark (2018) use RCP8.5). The mitigation scenarios' 2025 – 2100 trajectories are based on a common set of assumptions. The underlying premise is a global dietary shift away from methane-intensive foods. In this case, all emissions associated with livestock. A replacement diet which would ensure equal food production in terms of caloric and nutritional value during a livestock products phaseout, is beyond the scope of this study. In the mitigation trajectories, the peak-livestock (2025) and mitigation-start (2026) years are dictated by the expert-elicited "greenhouse gas emissions trajectories for the global livestock sector" from Harwatt et al. (2024, p. 14).

Next, we create the immediate reduction trajectories (Figure 3). We quantify the three GHG species' global emissions per food-group in 2020 (Table 1), and scale with projected population growth to obtain their 2025 values. We use sub-scenarios to sequentially deduct emissions associated with ruminant-meat, dairy, and non-ruminant meat from the food system's BAU trajectories. This approach details the incremental effects of livestock products phaseouts. As this scenario concerns a full phase-out of livestock products from 2026 onwards, only the remaining non-livestock emissions are influenced by population growth during 2026 - 2100.

In contrast to the immediate-reduction trajectories, the expert elicitation trajectories (Figure 3 and Figure 4) follow a gradual reduction timeline of global livestock emissions based on Harwatt et al., (2024). The expert-survey resulted in five phase-out trajectories with peak-livestock in 2025 and thereafter reduced by 61% until 2036. This is one year after the targeted IPCC 2035 global emission reductions goal compared to 2019 levels, which would align the livestock sector with the Paris Agreement. The report's trajectories differ only in the timeline of the reductions: the *steady decline* trajectory proposes a linear progression, while the *(far) front-loaded* trajectories hypothesise at least 50% of emission reductions in the first five years, and the *(far) back-loaded* scenarios require at least 50% of the reductions in the last five years (Table 2). A majority of experts preferred the front-loaded scenarios, whereas a small minority opted for back-loaded scenarios. Since the expert-trajectories do not expand beyond 2036, we assume linear decline until a complete phaseout is reached in 2044 (the 0-livestock year). We apply these percentage-reduction trajectories to BAU livestock emissions, and obtain the expert-reduction trajectories expressed in GHG emissions per annum (SI: GHG_trajectories.xlsx).

Table 2: Overview of the expert-elicitation livestock trajectories, until the end-goal of 61% reduction in 2036. Adapted from: Harwatt et al. (2024).

Scenario: Trajectory	*Progression*	*Number of respondents*
Far front loaded	At least 75% of end-goal achieved within 5 years after peak emissions.	n=46
Front loaded	At least 50% of end-goal achieved within 5 years after peak emissions.	n=59
Steady decline	Even reduction between peak and end-goal.	n=59
Back loaded	At most 50% of end-goal achieved within 5 years before end-goal.	n=5
Far back loaded	At most 75% of end-goal achieved within 5 years before end-goal.	n=4

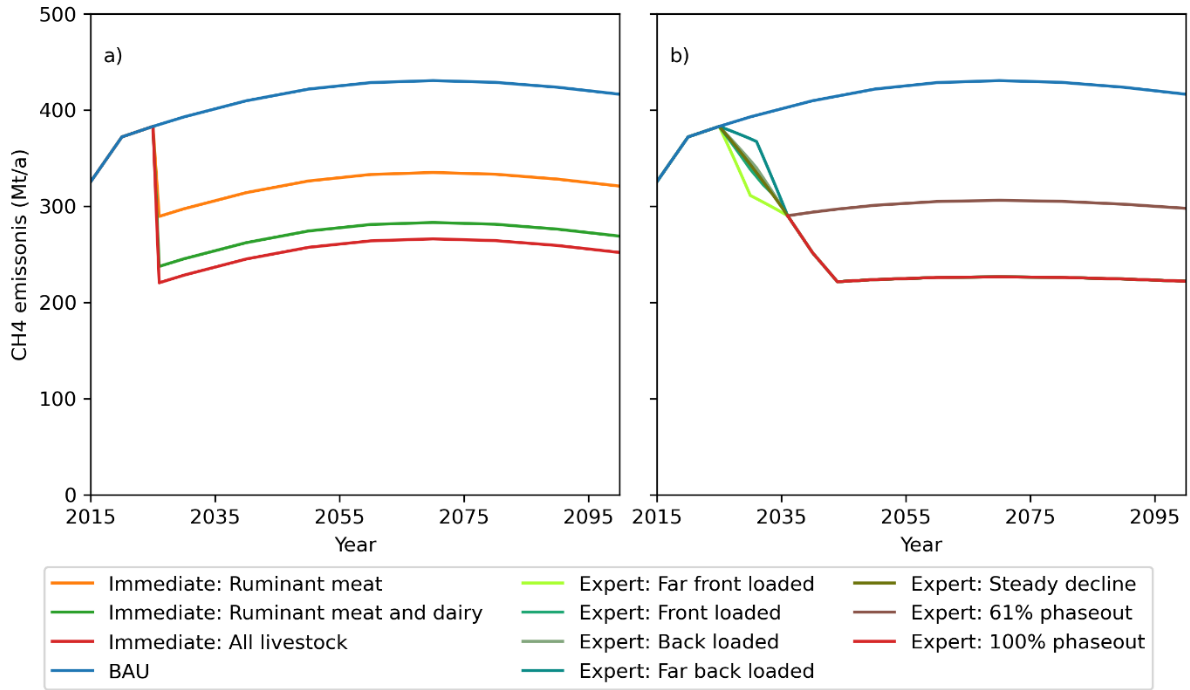

Figure 3: BAU and (a) immediate reduction trajectories and (b) expert-elicitation trajectories, for CH4 and with a projected population growth according to SSP2.

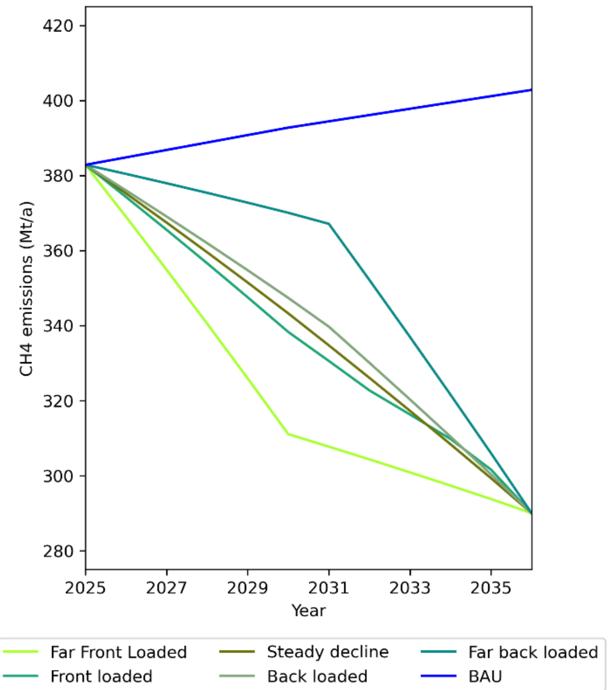

Figure 4: Detail of the expert-elicitation CH4 trajectories (2020 - 2036).

We use MAGGIC7, a reduced-complexity (simple) carbon cycle climate model used in IPCC Assessment Reports, to model the GHG trajectories' impact on global temperatures through to 2100 (*MAGICC7 - Live.Magicc.Org*, n.d.; Meinshausen et al., 2011, 2020). A simple model has no internal variability and their workings and parametrizations are calibrated to complex climate models (see Figure 5). This makes them a useful tool to acquire robust data on small perturbations in GHG emissions like in mitigation scenarios (Ocko et al., 2018). MAGGIC's calibration provides reliable data of climate outcomes following methane emission abatements (Meinshausen et al., 2011; Ocko et al., 2018), making it applicable to research sector wide (Cohen-Shields et al., 2023; Ocko et al., 2018) and food-system specific (Ivanovich et al., 2023; Reisinger & Clark, 2018) methane-focussed mitigation scenarios.

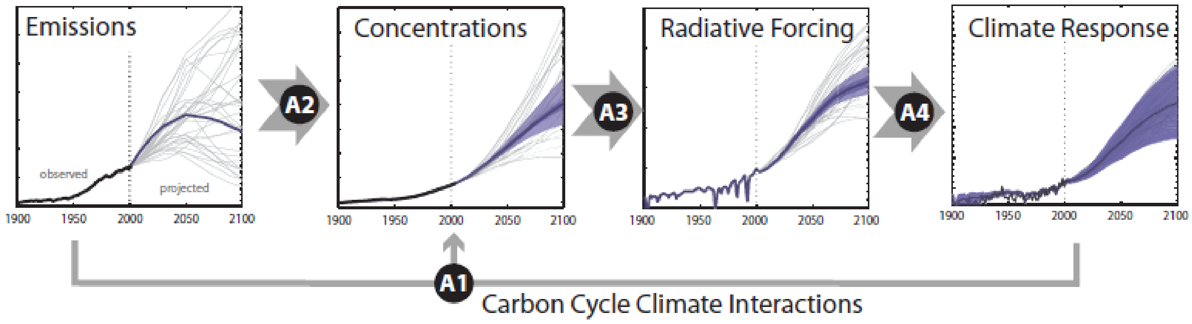

Figure 5: The MAGICC calculation process, source: Meinshausen et al. (2011, Figure A1).

We use MAGICC's SSP2 template for GHG emissions from 2015 – 2100. MAGICC templates employ a 10-year spacing, which we adjust to our scenarios' temporal resolution (SI: GHG_trajectories.xlsx). Values of non-analysed GHG-species have been filled through linear interpolation. The aforementioned food-system trajectories per GHG species replace the corresponding default trajectory. MAGICC distinguishes CO2 from two main sources: from agriculture, forestry, and other land use (AFOLU), and from fossil and industrial processes. Here, we assume CO2 from fossil and industrial sources to remain constant over time (as base level emissions), and exclusively result from non-food system sources. We assume CO2 from AFOLU activities to be exclusively food-system emissions, which negates non-food system AFOLU emissions. However, as we do not assess sector-wide emissions and outcomes are relative to BAU, this does not significantly influence the results. We make similar assumptions for fossil methane. The assumption of baseline emissions for non-food system fossil CO2 and CH4 has distinct benefits in this experiment. It filters out the effects from mitigation measures in other sectors otherwise aggregated into one value, which lacks granularity and could count food-system mitigations twice.

We use MAGICC's probabilistic setup, also used in IPCC reporting. In this configuration, MAGICC draws 100 models with distinct parameter sets (reduced from 600 for IPCC publications due to server load balancing) from a set of 82.500 models (Meinshausen et al., 2009). It then runs the 100 models with the inserted GHG trajectories, and presents the corresponding median climate response, i.e. temperature change. Within each sub-scenario, we run MAGICC five times: First, to assess the impact per individual GHG species CH4, N2O, CO2 and next, to include the combined effects of CH4 and N2O, and CH4, N2O, and CO2. This process provides insights into the contribution of each GHG species and food group. We assume that the difference in warming between BAU and each mitigation scenario, is the result of their specific mitigation measure (everything else remaining equal).

Quantifying the climate impacts of GHG emissions through modelling is the preferred method, as models output radiative forcing or temperature (change) over time. However, the use of climate metrics is abundant in studies and science communication, especially to non-expert audiences. This practise leads to a misrepresentation of methane's climate impact as no metric is deemed without shortcomings (Pierrehumbert, 2014). Here, we assess the performance of climate metrics relative to MAGICC outcomes from the (alternative) food system emission trajectories. For each scenario, we convert the GHG species' cumulative avoided emissions from the mitigation start (2026) into a CO2-equivalent climate metric. However, the metrics and MAGICC outcomes are expressed in different units. We follow Cohen-Shields et al. (2023), and convert the respective outcomes into unitless ratios which express methane's relative contribution to avoided warming in the evaluation year (equations (1) and (2)). We then determine which climate metrics most closely mimic MAGICC outcomes. These are preferable when communicating the food system's climate impact and mitigation strategies, to achieve the Paris Agreement temperature goals.

$$MAGICC: CH4\ contribution\ (t) = \frac{\Delta T_{CH4}(t)}{\sum \Delta T_{CH4}(t) + \Delta T_{N2O}(t) + \Delta T_{CO2}(t)} \quad (1)$$

$$Metrics\ (e.g.\ GWP): CH4\ contribution\ (t) = \frac{\mathrm{GWP}(\mathrm{E}_{CH4}, t)}{\sum \mathrm{GWP}(\mathrm{E}_{CH4}, t) + \mathrm{GWP}(\mathrm{E}_{N2O}, t) + E_{CO2}(t)} \quad (2)$$

We assess GWP100, GWP20, GWP (Allen et al., 2018; Lynch et al., 2020; M. A. Smith et al., 2021), and $GWP_{x.x\ °C}$ (Abernethy & Jackson, 2022) (see also SI: Literature study). $GWP_{x.x\ °C}$ applies a time horizon dictated by the years remaining until the temperature targets of the Paris Agreement are most likely breached: $GWP_{1.5°C}$ and $GWP_{2.0°C}$. We use atmospheric lifetimes and GWP values of methane and N2O from the IPCC's AR6 report (Forster et al., 2021) (*

Table 3). When metrics values for N2O are not available in literature, we express its impact using GWP100 instead (following Cohen-Shields et al. (2023). For $GWP_{x.x\ °C}$ we use the methane values proposed by (Abernethy & Jackson, 2022) (

Table 4). To calculate GWP*, we apply Cohen-Shields et al.'s (2023) modification of the method by M. A. Smith et al. (2021) (Equation (3)). This version excludes historic emissions occurring before the mitigation start, which increased GWP*'s performance when matching methane's potency relative to MAGICC's outcomes. Here, we update the GWP* equation with GWP values from AR6 (Equation (4)). Since the food system's methane emissions are biogenic, the biogenic values for the climate metrics are used whenever possible. We evaluate methane's contribution to avoided warming by mid-century (2050) and end-of-century (2100).

$$E^*(t) = 128 \times E_{CH4}(t) - 120 \times E_{CH4}(t-20) \quad (3)$$

$$E^*(t) = 122 \times E_{CH4}(t) - 115 \times E_{CH4}(t-20) \quad (4)$$

Table 3: CH4 and N2O lifetime, GWP values, adapted from Forster et al. (2021, table 7.15)

	Lifetime [years]	*GWP100*	*GWP20*
Fossil CH4	11.8	27.0	82.5
Biogenic CH4	11.8	29.8	79.7
N2O	109	130	273

Table 4: Metrics with goal-defined time horizons (relative to 2021), adapted from: Abernethy & Jackson (2022)

	Timeframe [years]	*End year*	*CH4 value*	*GWP100 under-estimation*
$GWP_{1.5°C}$	24	2045	75	63 %
$GWP_{2.0°C}$	58	2079	42	35 %

Results

A complete phaseout of livestock emissions following the expert-elicited reduction trajectories from Harwatt et al., (2024) avoids up to 0.42 °C of warming by 2100. By 2050, only 6 years after the 0-livestock year (2044) and 25 years after peak-livestock, the trajectory avoids 0.17 °C of warming. 70.3% of the avoided warming in 2100 is due to reduced biogenic methane emissions (Figure 6a). In this scenario $GWP_{2.0°C}$ estimated methane's contribution (65%) most closely to MAGICC (70%), while GWP100's underestimation makes it the least accurate (Figure 6b). After an immediate phaseout of livestock products in 2026, 74% of the end-of-century avoided warming benefit is attributable to eliminating ruminant meat and dairy products (the remaining being other meat and dairy products).

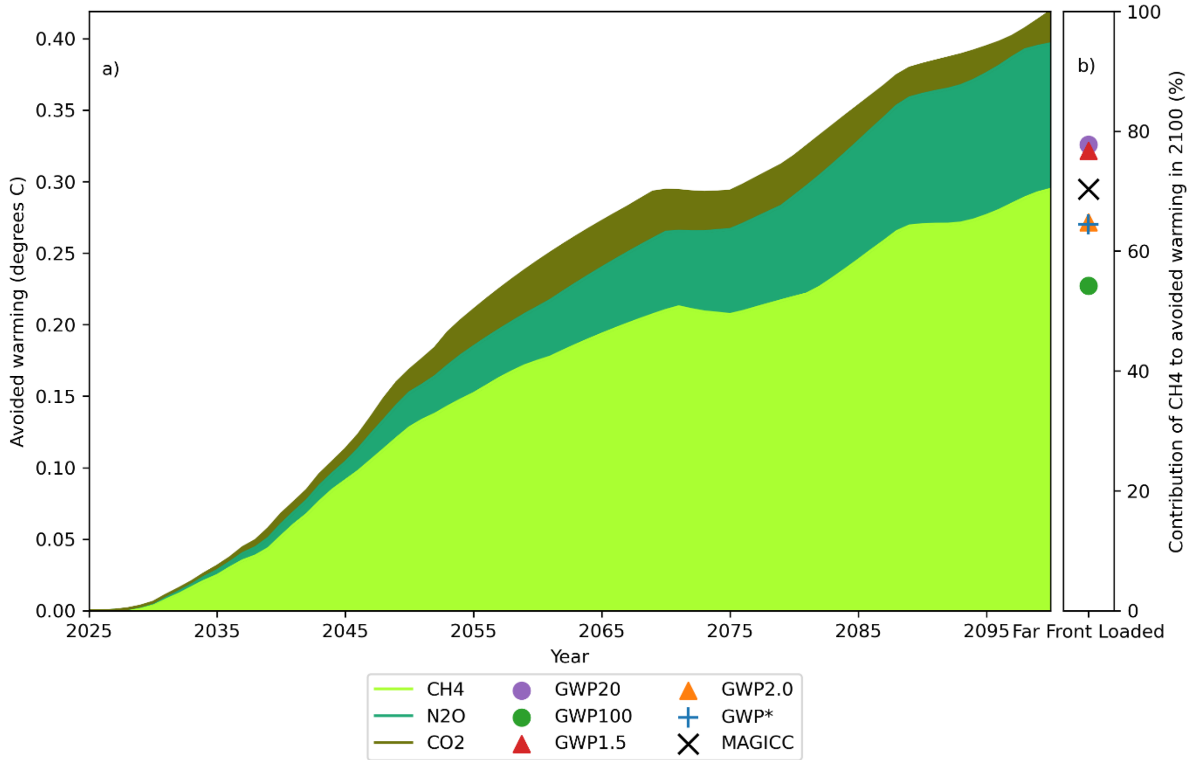

Figure 6: Outcomes of the expert-elicited 'Far Front Loaded' 100% livestock-reduction trajectory: a) Avoided warming until 2100, separated by GHG species. b) Metrics performance relative to MAGICC in estimating methane's contribution to avoided warming in 2100. The total avoided warming by 2100 in (a) coincides with 100% on the y-axis in (b).

CH4 emissions in the expert-elicitation scenarios are reduced to 40% of BAU levels, while emissions of N2O are reduced to 50%, and CO2 to 68%. We applied the experts' annual percentage-reductions to BAU emissions in the same year instead of 2025 (peak-livestock) levels. Consequently, a 100% reduction implies 0-livestock, and increased livestock production from population growth is restricted during the phaseout. However, this phase-out (2026 – 2044) coincides with the period of largest population growth (SI Figure 1). Thus, the expert 100%-reduction trajectories cumulatively emit less GHGs than the immediate-reduction scenario on which they are based (see Table 5 and SI Figure 2 -SI Figure 7).

We found that trajectories which included only methane from food-system sources, reduce net radiative forcing. Reducing concentrations of CH4 and N2O increase methane's warming potency because their radiative forcing varies nonlinearly with abundance, and they compete in overlapping absorption spectrums (Byrne & Goldblatt, 2014; Ramaswamy et al., 2001). It is important to consider this effect on temperature change when mitigating methane emissions (Reisinger & Clark, 2018). However, methane-mitigation efforts in other sectors is outside this study's scope, so we include a baseline of methane emissions in each trajectory to balance this effect. The baseline emissions are assumed from non food-system fossil sources, and unaffected by population growth. A baseline for N2O was not included, because its atmospheric concentration and radiative forcing vary less than an SLCF's from (reduced) emissions.

Table 5: Cumulative emissions (2026-2100) of biogenic CH4, N2O, and CO2 from AFOLU activities, per scenario. Where [1] indicates immediate reduction trajectories and [2] the expert-elicited reduction trajectories, for which the percentage-phaseout is also indicated.

Scenario	*CH4 [Gt]*	*N2O [Mt]*	*CO2 [Gt]*
Business as usual	21.8	975.2	511.0
Ruminant meat[1]	14.7	832.7	481.9
Ruminant meat and dairy[1]	10.8	727.7	444.8
All livestock[1]	9.5	518.8	354.5
Far front loaded – 61%[2]	13.2	656.7	401.8
Front loaded – 61%[2]	13.4	662.5	403.8
Steady decline – 61%[2]	13.4	663.2	404.1
Back loaded – 61%[2]	13.4	664.2	404.4
Far back loaded – 61%[2]	13.6	669.8	406.3
Far front loaded – 100%[2]	8.5	481.5	341.8
Front loaded – 100%[2]	8.6	487.3	343.8
Steady decline – 100%[2]	8.7	488.1	344.0
Back loaded – 100%[2]	8.7	489.1	344.4
Far back loaded – 100%[2]	8.8	489.0	346.3

The expert-elicitation trajectories avoid 0.41 – 0.42 °C of warming by 2100. The differences between these scenarios' outcomes are increasingly small towards 2100 (Figure 7 and Figure 8), as their trajectories only differ until 2036. Consequently, the far front loaded trajectory results in 0.017 °C more avoided warming by 2050 than the far back loaded trajectory; a small but noteworthy difference in this short period. By 2100, the expert-reduction scenarios avoid more warming than immediately reduced livestock emissions, due to this study's assumptions. However, by 2050 an immediate phaseout reduces temperatures 0.058 °C more than a full phaseout in the least-urgent expert trajectory (see overview in Table 6). This further emphasizes the urgency of mitigating (livestock) methane emissions.

We explored scenarios with an immediate, 2026 livestock phaseout by food group. Phasing out ruminant meat would avoid 0.17 °C of warming by 2100, and 0.27 °C when combined with dairy. These methane-intensive food groups drive most of the livestock-associated cooling: 78% in 2050 and 74% in 2100. Methane reductions alone contribute over 80% to the avoided warming in 2100 (Figure 9). By 2050, a period of twice methane's atmospheric lifetime following the 2026 phase-out, its effect is even larger, at 86% for ruminant meat. Due to population growth and the delayed effects of reduced N2O and CO2 emissions, avoided warming increases until 2100. However, methane's much larger cooling contribution establishes within 20 years (Figure 10).

Every avoided-warming plot exhibits visible perturbations post-2065, which follow the same pattern for each scenario and GHG species. This is a likely consequence of the population trend which affects the underlying emissions and atmospheric concentrations differently.

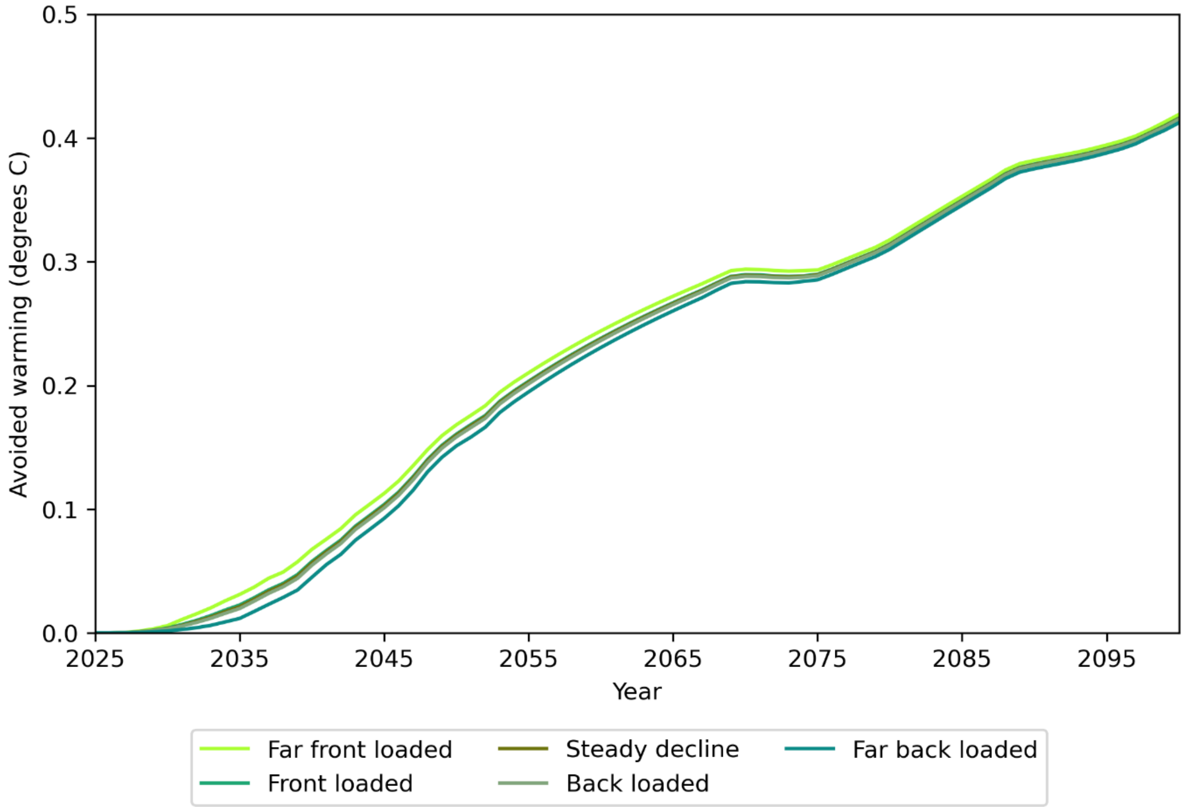

Figure 7: Total avoided warming following the expert-elicited 100% livestock-reduction trajectories.

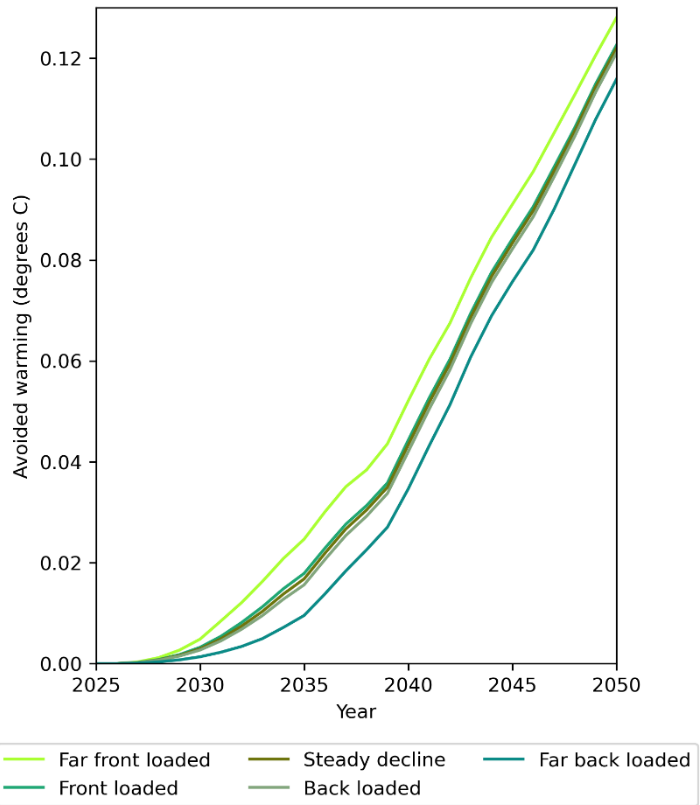

Figure 8: Detail (2025-2050) of avoided warming attributable to reduced methane emissions in each 100% livestock-reduction scenario.

Table 6: Avoided warming (ΔT) compared to BAU, from reduced total emissions (CH4, N2O, and CO2) per scenario. The percentage of avoided warming attributable to CH4 is included. Here [1] indicates immediate reduction trajectories and [2] the expert-elicited reduction trajectories, for which the percentage-phaseout is also indicated.

Scenario	*ΔT(2050) [°C]*	*CH4 [%]*	*ΔT(2100) [°C]*	*CH4 [%]*
Ruminant meat[1]	-0.098	86.8	-0.168	81.4
Ruminant meat and dairy[1]	-0.163	83.5	-0.270	81.2
All livestock[1]	-0.209	73.9	-0.364	67.7
Far front loaded – 61%[2]	-0.123	73.9	-0.259	67.9
Front loaded – 61%[2]	-0.115	74.0	-0.257	68.2
Steady decline – 61%[2]	-0.114	74.0	-0.256	68.3
Back loaded – 61%[2]	-0.113	74.0	-0.256	68.3
Far back loaded – 61%[2]	-0.106	74.1	-0.254	68.6
Far front loaded – 100%[2]	-0.168	76.1	-0.419	70.3
Front loaded – 100%[2]	-0.161	76.3	-0.416	70.6
Steady decline – 100%[2]	-0.160	76.3	-0.416	70.6
Back loaded – 100%[2]	-0.158	76.4	-0.415	70.7
Far back loaded – 100%[2]	-0.151	76.6	-0.412	70.9

We assess the climate metrics' methane-valuation relative to MAGICC outcomes in 2050 (Figure 11) and 2100 (Figure 12). $GWP_{1.5°C}$ performs closest to MAGICC in 2050, as the time horizon of 24 years coincides exactly with the mitigation start in 2026 until observation in 2050. The $GWP_{1.5°C}$ and $GWP_{2.0°C}$ values used in this study were not re-computed to account for the time passed since the publication of Abernethy & Jackson (2022). By 2100, GWP* and $GWP_{2.0°C}$ perform best in the expert-reduction scenarios, and $GWP_{2.0°C}$ in the immediate-reduction scenarios. Both metrics perform better as the considered sector is increasingly methane intensive with lower non-SLCF emissions (see Figure 12, immediate reduction scenarios). For $GWP_{2.0°C}$ the differences are smaller in 2100, which is closer to its time horizon (SI Figure 15). Although GWP* accounts for the rate of change in SLCF emissions over 20 years, the implicit time horizon between the mitigation start and observation year influences its performance: GWP* slightly overestimates methane's contribution to avoided warming in 2050, but underestimates by 2100. Static-timeframe metrics' methane valuations differ negligibly between observation years (see also SI: GHG_trajectories.xlsx), and their performance depends on MAGICC outcomes. In 2100, the metrics with relatively shorter time horizons (GWP20 and $GWP_{1.5°C}$) overestimate the contribution of methane, where the corresponding metrics with longer time horizons (GWP100 and $GWP_{2.0°C}$) result in underestimation. GWP100 underestimates the potency of methane the most across all scenarios and observation years. As in 2100, the performance differences are small, metric selection depends on the context of the study, and the preference of the scientist to over- or underrepresent methane's heat-trapping capacity.

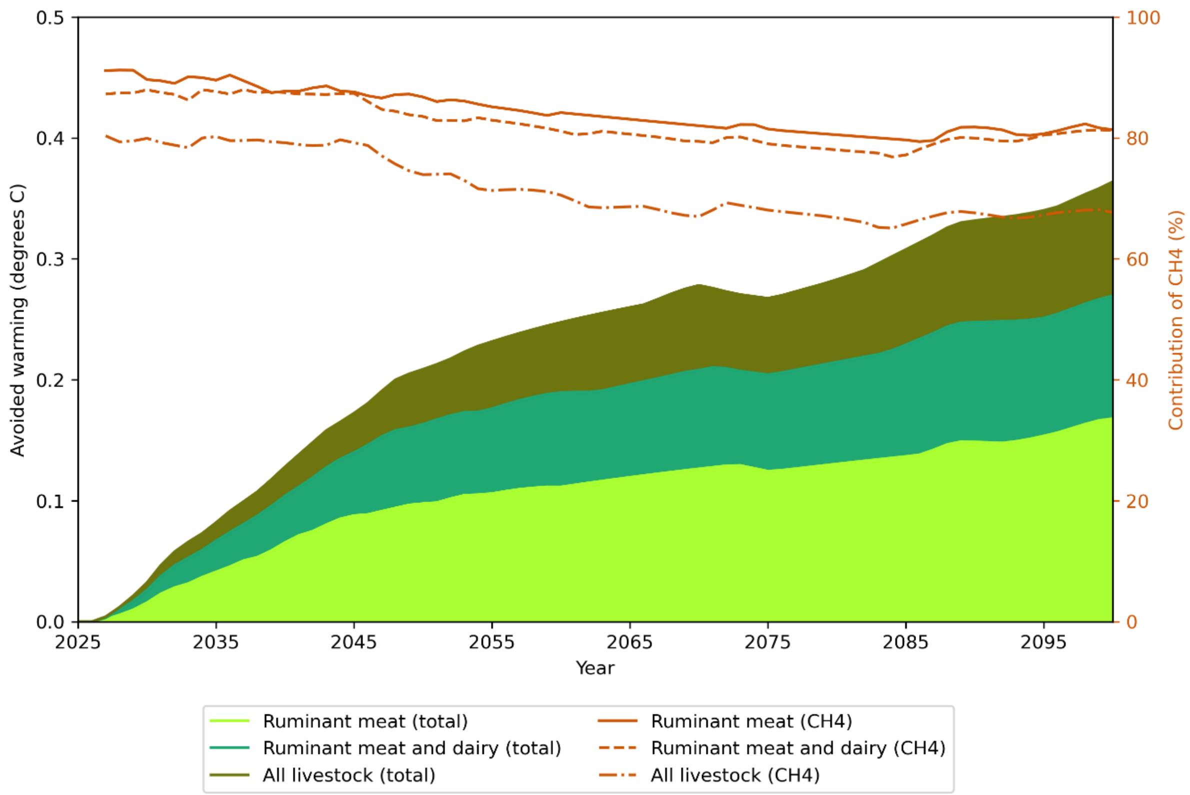

Figure 9: Total avoided warming due to an immediate phaseout of livestock food groups in 2026, and the corresponding contribution of methane.

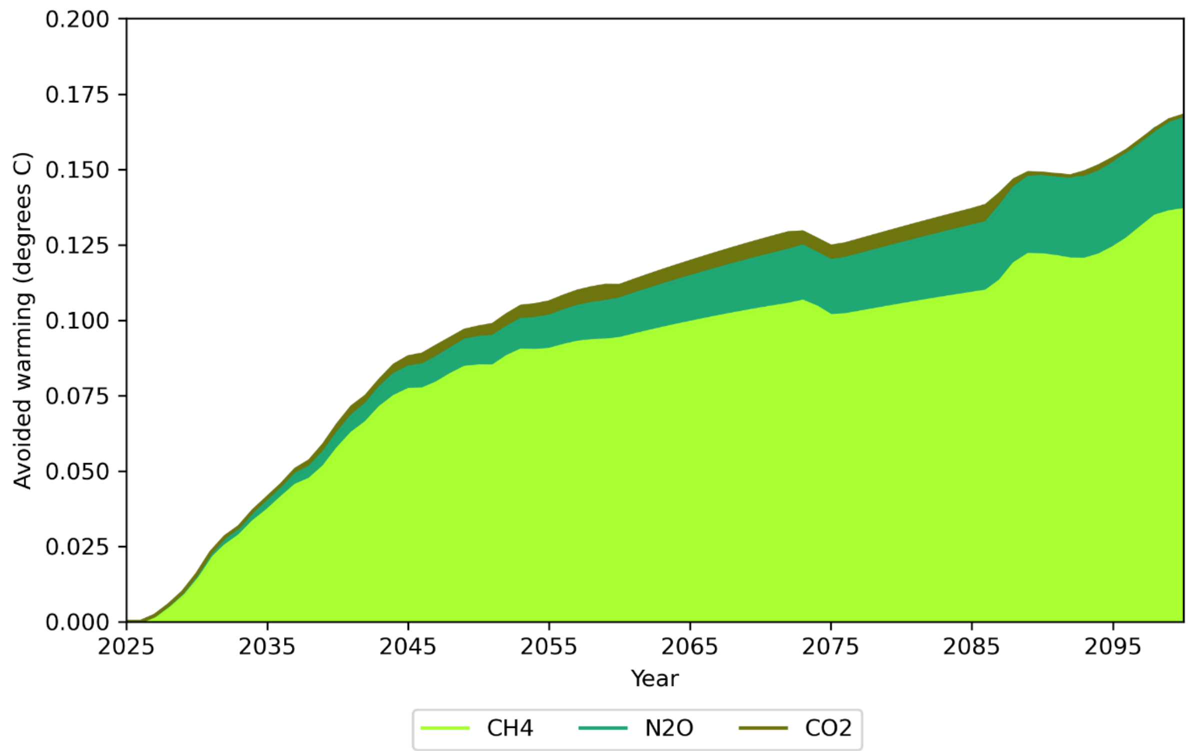

Figure 10: Avoided warming from emissions following the immediate phaseout of ruminant beef in 2026, separated by GHG species.

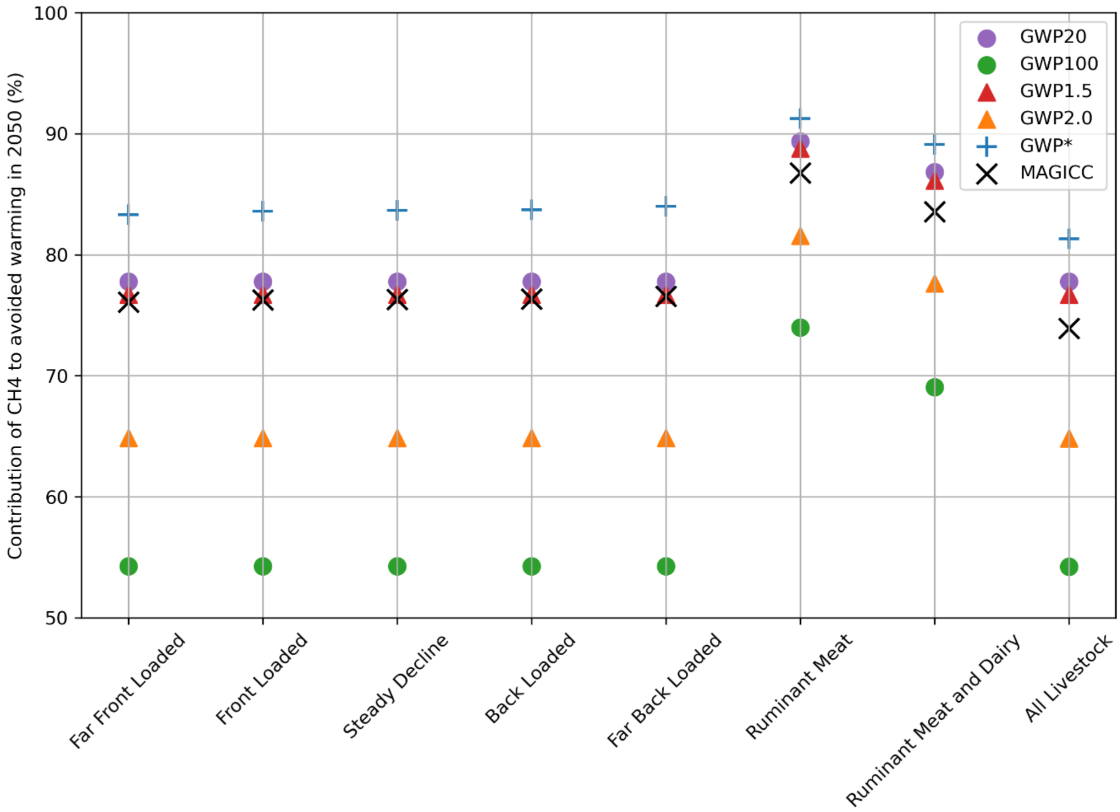

Figure 11: Climate metrics' and MAGICC outcomes of methane's contribution to avoided warming in 2050 per livestock reduction scenario (including population growth.

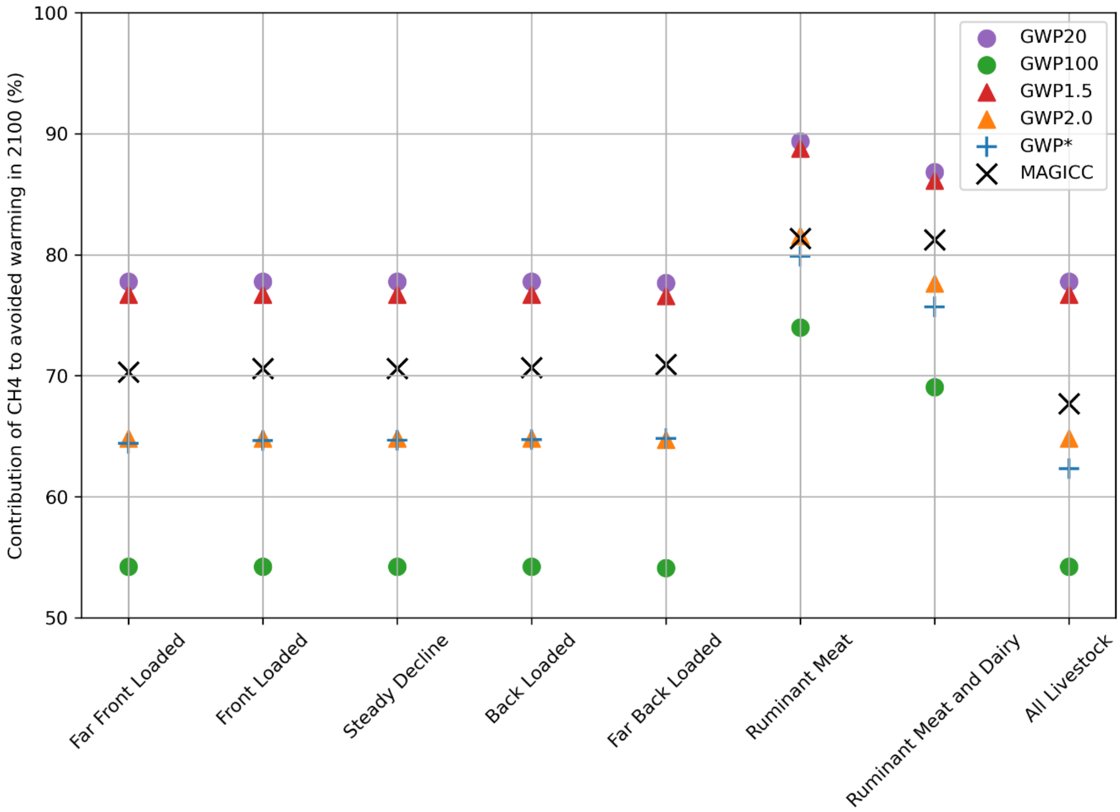

Figure 12: Climate metrics' VS MAGICC outcomes of methane's contribution to avoided warming in 2100 per livestock reduction scenario (including population growth).

Discussion

We quantified livestock emission reduction trajectories from an expert survey in Harwatt et al. (2024), which put the livestock sector in line with IPCC-prescribed reductions in other sectors and the Paris Agreement's temperature goals. This approach differs from that used in other studies where food system and livestock emissions are mitigated by an intervention's maximum technical capacity or arbitrary adoption rates (Eisen & Brown, 2022; Ivanovich et al., 2023; Reisinger & Clark, 2018). The trajectories continue with the same trend until 0-livestock is reached in 2044. This phase-out reduces warming by 0.17 °C (comprising of 76.1% CH4) in 2050 and 0.41 °C (70.3% CH4) in 2100. The considerable and rapid cooling effect of the avoided biogenic methane emissions demonstrates that (livestock) reductions can lower (peak) temperatures (Reisinger & Clark, 2018). These findings challenge the IPCC's scepticism about the political and social capacity and appetite for agricultural methane and nitrous oxide reductions in its AR6 (WGIII contribution). Which then necessitates the inclusion of various carbon dioxide removal (CDR) technologies in all of its 1.5 degree (overshoot) pathways (Intergovernmental Panel On Climate Change (IPCC), 2023; Prütz et al., 2023).

We reiterate the potential of a protein transition in reducing emissions and global temperatures. The immediate reduction trajectory shows that 78% (in 2050) and 74% (in 2100) of the temperature benefits result from ruminant meat and dairy alone. The remaining carbon budgets from 2024, with a 50% likelihood of staying under 1.5 °C and 2.0 °C warming, are 275 Gt CO2-eq and 1150 Gt CO2-eq, respectively. This means the 1.5 °C threshold will be breached within 7 years if emissions continue on 2023 levels (Friedlingstein et al., 2023), 14 years before the crossing year 2045 applied in $GWP_{1.5°C}$ (Abernethy & Jackson, 2022). The expert-reduction trajectories avoid up to 98.3 Gt CO2-eq and 397 Gt CO2-eq of methane by 2050 and 2100 respectively, deferring target temperatures by years.

We have shown that a complete phaseout of livestock products is desirable, but recognise that this target is optimistic without a societal paradigm shift. As such, we also evaluated a partial adoption of the expert-elicited trajectories. Here, we imposed no additional reductions beyond the original 61% in 2036 (SI Figure 11 - SI Figure 14). These partial phase-outs avoid notably fewer emissions (Table 5) and warming compared to a full phase-out (Table 6). Until 2100, these trajectories emit up to 4.8 Gt more CH4, and cause 0.160 °C (38.2%) more warming. The near-term is more important to avoid breaching temperature thresholds, but by 2050 the partial phaseout avoids just 0.123 °C of warming: 26.8% less than a full phaseout (Figure 13). While the 61%-phaseout trajectories remain Paris Agreement-compliant, it is still preferable to implement additional livestock-reduction targets after 2036.

The climate benefits of reducing the emission of biogenic methane should not be undervalued by using climate metrics incompatible with the considered mitigation effort and time horizon. In the context of aligning the food system with Paris Agreement temperature goals, we recommend reporting methane's warming potential using $GWP_{1.5°C}$ or $GWP_{2.0°C}$, as they perform closest to modelled outcomes. However, this would require periodic recalculation, as the time until temperature targets decreases or is reassessed. In use cases without a specific time horizon, GWP* is a better fit as the metric is designed with SLCFs in mind and was also close to modelled outcomes. However, caution is advisable, as invested stakeholders have misused it to ignore perpetual warming from ongoing methane emissions (Donnison & Murphy-Bokern, 2024). When applied correctly, GWP* can (in a single metric) communicate SLCF abatements' increasing urgency, e.g. when mitigation commitments are postponed.

The IPCC recognises that metric choice impacts the communicated message, but states that more research is needed into choosing an appropriate metric. Thus, it continues to use GWP100 in their reporting to make the abatement efforts of various GHGs comparable (Forster et al., 2021; Intergovernmental Panel On Climate Change (IPCC), 2023). As we have shown, methane abatements expressed in GWP100 undervalue their effect towards short- and middle term temperature targets in the Paris Agreement. Conversely, using e.g. $GWP_{1.5°C}$ or GWP* more closely describes methane's warming contribution, with CO2-equivalent values 26% (midpoint, range: 23% – 29%) higher than otherwise reported with GWP100 (Figure 11, Far front loaded scenario). This also emphasizes methane-mitigation efforts' efficacy and desirability, which can move governments to prefer reducing 'hard-to-abate' SLCF-emissions over CDR technologies.

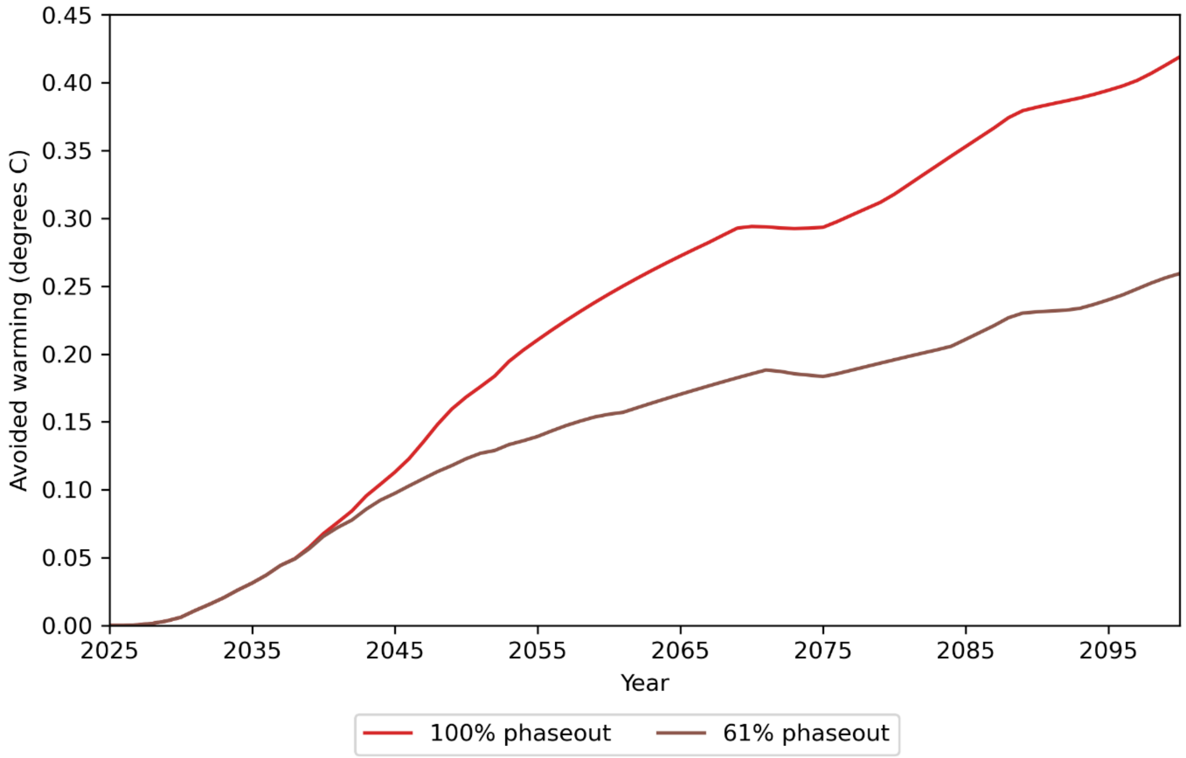

Figure 13: Total avoided warming following the far front loaded expert-elicited trajectories with 61% and 100% phaseouts post-2036. The 100% phaseout is complete in 2044.

IPCC AR6 1.5 °C (overshoot-) and 2.0 °C pathways all employ some level of CDR; first relying on afforestation and reforestation (A/R), and from 2050 on novel CDR technologies like bioenergy with carbon capture and storage (BECCS) and direct-air carbon capture and storage (DACCS) (Ganti et al., 2024). The use of CDR in models can create a dependency that delays fossil phase-out, further increasing necessary CDR volumes in a self-fulfilling modelling exercise (Anderson & Peters, 2016; Lenzi et al., 2018). However, the BECCS land-use requirement could be "larger than the current best-guess estimate on the global extent of all forests" (Creutzig et al., 2021, p. 511), with corresponding water, energy, food security, and biodiversity pressures (Creutzig et al., 2021; Hansen et al., 2017). DACCS has a land footprint two orders of magnitude smaller than BECCS (Creutzig et al., 2019), but consumes three times its energy (Fawzy et al., 2020). Both technologies must scale up at an unprecedented pace (up to 80 times in 50 years (Fawzy et al., 2020)), while storage may be limited (Lane et al., 2021; Lawrence et al., 2018). Prolonged fossil emissions while betting on the viability and efficacy of CDR technologies, defers the climate crisis' burden to future generations (Hansen et al., 2017; Lenzi et al., 2018). Swift emission reduction through demand-side management (i.e. dietary change) is thus preferable over the implicit risks, investments, deployment period, and ethics of CDR (see SI: Literature study).

We also highlight that a radical reduction of livestock emissions is necessary and unavoidable to reach climate goals. The expert-reduction trajectories can be met with a diverse portfolio of mitigation measures, including production intensification and technological innovation. These can aid reaching near-term reduction targets, but rapid dietary change is more effective without impacting animal welfare (Harwatt et al., 2024; Rosenzweig et al., 2020). This conflicts with the vested interests of the livestock industry. Their anti-reduction rhetoric contains fraudulent climate neutrality claims, and is legitimised in (sponsored) publications (Donnison & Murphy-Bokern, 2024; The Changing Markets Foundation, 2024). Despite the challenges, it is essential to devise an implementation strategy for the expert-elicited livestock trajectories. As such, governments should issue a clear statement of intent, and allocate adequate funding during the agricultural transition (Harwatt et al., 2024).

There are several parameters and assumptions of our study that could be changed. Firstly, we assume non food-system emissions are constant, thus we effectively use a dynamic value for methane's radiative efficiency which may not be representative of future conditions. However, these future conditions are difficult to predict. Secondly, we use a food system emissions database by Ivanovich et al. (2023) and find current emissions by scaling with population change. Other studies find similar emissions, thus changing sources or quantifying recent emissions ourselves based on LCAs and consumption data would result in similar outcomes. Third, we assume no changes in meat-consumption patterns, where Sans & Combris (2015) project a 70% increase for animal products, and 90% for ruminant-meat by 2050. If we adjust the BAU conditions accordingly, we would find much more avoided warming. Fourth, we assume a middle-of-the-road population projection (SSP2). Again, changing this assumption to a high-fertility estimate (e.g. SSP3) would increase the avoided warming due to a livestock phaseout. In all these cases, our main conclusions remain intact.

Land-use change (LUC) emissions are driven by increasing demand for meat, so emissions cease when net livestock-consumption decreases. We reduce LUC emissions by the same percentage as livestock, because they are not separately reported in Ivanovich et al. (2023). As such, we underestimate the avoided warming following a livestock phaseout. Phasing out animal protein from global diets means these foods need to be replaced by plant-based alternatives, whose emission and land use footprints are significantly lower (Poore & Nemecek, 2018; Xu et al., 2021). Not accounting for this does not meaningfully influence this study's results. Also, we do not consider carbon sequestration on former pastures and feed land, but this can double the climate benefits following a global protein transition (Eisen & Brown, 2022; Sun et al., 2022). This study aims to quantify the avoided warming in this century, primarily due to methane, following expert-elicited livestock reduction trajectories. We did not account for (mitigated) emissions in other sectors, thus the combined effects of sector-wide emissions is not described in this study (see also SI: Discussion).

Future work could add the potential carbon sequestration benefits to the expert trajectories presented here. The temperature effects thereof should be studied as part of a complete climate mitigation portfolio which limits anthropogenic warming to 1.5 °C. Doing so would reduce uncertainty about methane's concentration-dependent warming efficiency, and show the real-world cooling-contribution of abating livestock emissions. Numerous obstacles complicate reducing locked-in livestock emissions through dietary change (Rosenzweig et al., 2020). We increased ambition by proposing a full livestock phaseout, but even non-Paris-compliant reductions targets are deemed unrealistic (e.g. Reisinger & Clark (2018)). Therefore, the expert-elicited reduction trajectories for livestock emissions by Harwatt et al. (2024) should be followed by feasibility and implementation studies.

Conclusion

We used recent food-system emissions data to quantify the first expert-elicited reduction trajectories for the global livestock sector, extending them to a complete phase-out by 2044. We used the climate model MAGICC to find their temperature impact, and assessed various climate metrics' methane-valuation performances.

We found that these trajectories could prevent 0.42 °C of warming by 2100. 40% (0.17 °C) of which is reached by 2050, only 6 years after livestock emissions have been completely phased out. Avoided methane emissions alone account for 98.3 Gt CO2-eq in 2050 and 397 Gt CO2-eq in 2100, rapidly lowering (peak) temperatures. The climate benefits of a livestock phaseout are primarily from ruminant-meat and dairy reductions (74%). We also found that $GWP_{1.5°C}$ and $GWP_{2.0°C}$ perform best for temperature-targeted mitigation, while GWP* performs well for non-specific timeframes.

Our findings underscore that significant emission reduction efforts in the livestock sector should be included in climate mitigation portfolios. Swift and radical change aligns the livestock sector with the IPCC's global reduction targets, and decreases the reliance on risky novel CDR technologies. Future research is needed to quantify the yet unknown cooling dynamics of the expert-elicited livestock trajectories. Especially when combined with carbon sequestration on freed-up agricultural land, or included in a sector-wide climate mitigation portfolio. Policy tools should be developed to transition towards plant-based diets: by far the most effective instrument to limit the food system's impact on global temperatures.

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Supplementary information

Literature study

Food system emissions

Numerous (recent) studies have estimated current food system emissions. The results vary due to differing methodologies, (temporal variation in) source data, and boundary conditions. The IPCC state the food system emits 10.8 – 19.1 Gt CO_2-eq/yr (Mbow et al., 2019). While Crippa et al. (2021) and Tubiello et al. (2021) found the food system emits one third, Poore & Nemecek (2018) a quarter, and Rosenzweig et al. (2020) 21 - 37% of anthropogenic GHGs. These studies include post- and preproduction, on-farm emissions, energy use, and LULUC when quantifying food system emissions. All but Poore and Nemecek include waste. Overall, food system emissions have increased over time, while (the share of) total LULUC and per capita emissions have decreased due to increased efficiency. These large emission and warming contributions mean that mitigation measures in the food system can and should play important roles towards curbing overall emissions and global warming. Far-reaching mitigation measures in the food system would increase the carbon budget (the volume of 'available' GHG emissions until temperature goals are exceeded (Friedlingstein et al., 2022)), available for unavoidable emissions, without breaching temperature goals.

Future food system emission trajectories are estimated based on various population and consumption projections, and subjected to mitigation scenarios to quantify potential emissions and (avoided) warming. Following current consumption and population trends, the contribution of food system emissions preclude staying below the 1.5 and potentially the 2.0 °C warming goals, even if reduction goals in the fossil energy sector are met (Clark et al., 2020; Ivanovich et al., 2023; Reisinger & Clark, 2018). Ivanovich et al. (2023) project that methane-intensive foods (ruminant meat and dairy, and rice) will be responsible for up to 75% of the 0.9 °C food system caused warming by 2100, with nearly 60% directly attributable to methane. The above papers assume a business-as-usual (BAU) level of meat and dairy consumption in their trajectories. However, meat-demand is projected to increase following historic trends, due to changing consumption patterns and increased prosperity (Henchion et al., 2021; OECD & FAO, 2021; Sans & Combris, 2015), making the results in those studies underestimates.

Animal products and livestock

The consumption of animal products is responsible for 58% of food system emissions (Poore & Nemecek, 2018; Xu et al., 2021). The disproportionate share of livestock emissions is widely described and accepted: Animal products only supply 37% of proteins and 18% of calories in the human diet (Poore & Nemecek, 2018) while their emissions share (58%) is twice that of plant-based foods (29%) (Xu et al., 2021). Livestock's feed and pastureland necessities are major drivers of land use and land use change (LULUC). In 2015, LULUC caused 32% of food system GHG emissions when expressed in CO2-eq (Crippa et al., 2021), mainly CO2 from forest clearing activities. By 2100, livestock emissions from meat and dairy are projected to contribute 0.20 – 0.44 °C warming according to Ivanovich et al. (2023), who account for emissions due to LUC, animal feed and the supply chain. Reisinger & Clark (2018) only consider direct non-CO2 livestock emissions (CH4 and N2O) and find 0.27 °C. Ruminant meat alone would cause 0.14 – 0.45 °C of warming (Ivanovich et al., 2023; Pierrehumbert & Eshel, 2015). 90% of avoided warming following a complete animal agriculture phaseout would be attributable to eliminating ruminant meat and dairy, and 71% to only cow meat and dairy because of their high methane intensities (Eisen & Brown, 2022). A recent report by Harwatt et al. (2024) has for the first time published global livestock emission trajectories based on expert elicitation (>200 respondents), which are necessary to reach the Paris Agreement climate goals. A majority of experts advise: 1. Reaching peak livestock emissions in 2025 followed by 50% reductions within 5 years, up to 61% in 2036. 2. A dietary shift is most effective to curb livestock emissions, while technological innovation and production intensification are less effective. 3. High- and middle-income countries should immediately start reductions, with low-income countries following shortly.

Rice
Rice is the third largest food-system source of biogenic methane, after livestock and food waste (Saunois et al., 2020). As a food group, it's the second emitter after ruminant-meat, and before dairy (Ivanovich et al., 2023). The anaerobic circumstances responsible for methane emissions are created by flooding rice paddies unnecessarily long. Significant emission reductions can be achieved by periodically draining paddies, without loss of yield. P. Smith et al. (2021) report 8-10 Mt/yr CH_4 potential reductions from production management. This mitigation measure relies on farmers' compliance instead of unreliable, complicated, or ineffective technologies.

Replacement diets
Considering replacement diets is a methodical necessity when comparing (partial) food phaseouts associated with dietary shifts, as the benefits are not 'free'. Three main strategies are applied in literature: First, applying sustainable diet recommendations from other literature, e.g. the EAT-Lancet diet (Willett et al., 2019) used by Sun et al. (2022), or the Harvard medical school used by Ivanovich et al. (2023). This method does not allow a complete phaseout of animal products as these guidelines still include low quantities. Second, quantifying the protein and caloric intake that needs replacing, and substitute this by plant-based alternatives, commonly pulses, e.g. Eisen & Brown (2022). And third, when animal feed is outside the direct scope of a study, researchers may choose to include the replacement diet in a sensitivity analysis of their work without actual application/quantification of its environmental footprint. Arguing that vastly more resources are needed to produce animal feed than food for direct human consumption, resulting in underestimated but valid results.

Methane and SLCFs
Methane (CH_4) is the second-most abundant anthropogenic GHG after CO_2 and much more potent at trapping heat. It is an SLCF (a GHG with a lifetime of hours to years, significantly less than CO_2's atmospheric lifetime of centuries to millennia) with an atmospheric lifetime of 11.8 years (Forster et al., 2021) and a half-life of 9 years (Eisen & Brown, 2022), before breaking apart into predominantly CO_2 (SI Table 1). Biogenic methane denotes that its carbon atom is part of the short carbon cycle, as opposed to the long carbon cycle (e.g. stored for millions of years in fossilised remains). This property means that fluxes of biogenic methane do not disturb the long carbon cycle's equilibrium, or add to atmospheric CO_2 stocks upon reacting to CO_2. Ruminants, rice paddies and waste are important food system sources of biogenic methane. Methanogenesis in ruminants occurs under anaerobic conditions through enteric fermentation and decomposition of manure (Saunois et al., 2020; P. Smith et al., 2021). Much less methane is formed when manure decomposes under aerobic conditions (e.g. when handled as a solid instead of a liquid) (Saunois et al., 2020). The animals act as catalysts and exacerbate global warming by converting carbon stored in plants after photosynthesis of atmospheric CO_2 to CH_4, which is released to the atmosphere again. In rice production, anaerobic conditions created by flooding of rice paddies for extended periods of time cause methanogenesis by microorganisms (Saunois et al., 2020; P. Smith et al., 2021). The heat trapping and atmospheric lifetime properties of methane make curbing emissions essential to reach temperature goals.

Climate metrics - Background
The properties of SLCFs and reporting conventions of emissions and warming complicate effective policy making. Climate metrics allow for consistent reporting and can replace climate modelling when calculating warming from BAU or mitigation scenarios. The most commonly used metric, GWP, equates the warming from pulses of non-CO_2 GHG emissions to CO_2-equivalents (CO_2-eq) over a chosen timespan, (Balcombe et al., 2018; Pierrehumbert, 2014). GWP is highly dependent on the time horizon and poorly quantifies the temperature effects of SLCFs (Lynch et al., 2020). The default timeframe was originally and arbitrarily chosen as 100 years in the Kyoto agreement from 1997 at COP 3, and thereafter criticised (Abernethy & Jackson, 2022; Pierrehumbert, 2014). To address the shortcomings

of GWP, new metrics including GWP*, GTP, and metrics with goal-defined temporal scopes ($GWP_{x.x^oC}$) have been introduced. GTP is an end-point metric quantifying temperature variation (Pierrehumbert, 2014; Shine et al., 2005), GWP* more accurately quantifies SLCF effects because it considers emission rates of change instead of pulses, producing CO2 warming-equivalents (CO2-we) instead of CO2-eq (Allen et al., 2018; Lynch et al., 2020; M. A. Smith et al., 2021; P. Smith et al., 2021), and $GWP_{x.x^oC}$ makes GWP suitable for considering temperature and temporal targets (Abernethy & Jackson, 2022). SI Table 1 and Table 4 show the metrics' properties for methane. No metric fully solves GWP's issues, and all have their shortcomings and ambiguity when used to interpret the climate impacts of SLCFs (Pierrehumbert, 2014). Balcombe et al. (2018) advise to match metric(s) to the goal of communication and communicate the time horizon, optionally supplemented with climate model outcomes (which are more reliable due to their continuous calculations during the considered timespan). Pierrehumbert (2014) states that climate metrics are generally not necessary to communicate findings, and qualitative descriptions are better suited to convey nuances in the results. Cohen-Shields et al. (2023) have compared climate impacts of CO2- and CH4-dominated sectors using a climate model and various metrics. They find that, compared to GWP100, GWP20 and GWP* (without historic emissions) show better agreement with modelled outcomes until 2100. Accuracy decreases when the observation year and the metric's time horizon are further apart.

Climate metrics – Commonly used metrics and their characteristics

GWP100 & GWP20

GWP's commonly used time horizons are 100 and 20 years. A GHG's radiative forcing relative to CO2 is integrated over the chosen timeframe. GWP does not quantify temperature change at the end of the time horizon, but averages radiative forcing during it, making GWP best suited for radiative forcing targets. Coordinating the timeframe with the goal of the calculation and GHGs involved is crucial (Balcombe et al., 2018; Pierrehumbert, 2014).

GTP

Global Temperature Change Potential (GTP), expresses the temperature variation at the endpoint of the selected timeframe , due to a pulse emission at t=0 (Pierrehumbert, 2014; Shine et al., 2005). The latter initially proposed two GTP metrics: GTP_p for pulse emissions and GTP_s for emissions sustained during the time horizon, but GTP_p is commonly used to consider temperature goals.

GWP*

Allen et al. (2018) introduced GWP* to improve the quantification of SLCF's climate impact. GWP* considers an SLCF's rate of change instead of a pulse emission, which is more accurate to describe their warming impact. Where GWP denotes a CO2-equivalent (CO2-eq), GWP* denotes a CO2 warming-equivalent (CO2-we). The positive effects on distinguishing the properties and impacts of long- and short-lived climate forcers are demonstrated in Lynch et al. (2020), and improved calculation methods explained in M. A. Smith et al. (2021), used in Cohen-Shields et al. (2023). They find that neglecting historic emissions before the intervention year, isolating the future emissions of interest, result in most closely resembling model outcomes. In the same context, the drawback that GWP* requires data on historical emissions is negated. A method to apply GWP* on agricultural methane emissions is explained and applied in P. Smith et al. (2021).

Metrics with goal-specific time horizons.

GWP and GTP cannot be reliably applied towards temperature goals fixed in time, like those in the Paris agreement. Abernethy & Jackson (2022) propose adaptations of these metrics with timeframes aligning with the 1.5 and 2.0 °C warming. Ten integrated assessment models (IAMs) calculated IPCC warming target pathways to obtain the temperature goal years. Metric properties for methane can be found in Table 4. The authors estimate that the Paris Agreement's 1.5 and 2 °C goals will be met in 2045 and 2079, which they recommend as end-years. This implies the need to recalculate the timeframe and metrics when performing analyses in intermediate years. During this time, the relative importance of individual GHGs may shift due to lifetime and radiative efficiency.

Climate metrics - Use of metrics in communication and modelling comparison
Metrics can be used in science communication to make results simple and comparable. Pierrehumbert (2014) states that authors should be wary that metrics outcomes' ambiguity and assumptions might not be interpreted correctly by the intended audience, and advises to give qualitative interpretations instead of relying on metrics in climate futures reports in most cases. Balcombe et al. (2018) recommend to choose metrics representing methane impacts based on three situations: 1. Short term and locally scoped research should use one metric and distinguish individual GHG contributions. 2. Multi-year technology assessment should use a static metric with short and longer timespans. 3. Long-term pathways should use short and long term pathways, and consider the use of climate modelling. They state that added value from dynamic metrics may be limited. Cohen-Shields et al. (2023) calculate future sectoral contributions to climate change. They conclude that while modelling climate impacts also involves uncertainties and imperfections, they offer more sophisticated considerations than simplified metrics. Their study compares modelled outcomes (using the MAGICC climate model) to the climate metrics GWP100, GWP20, and GWP*, to assess their differences and performance. For GWP* they use methods by M. A. Smith et al. (2021). GWP20 and GWP* outperform GWP100 in model agreement until 2100. Regardless of the metric used, larger differences between the chosen metric time horizon and the model evaluation year, introduce more disagreement between metric and modelled outcomes.

Climate metrics – Values
SI Table 1: CH4 and N2O lifetime, metric values, adapted from Forster et al. (2021, table 7.15), and supplemented with Abernethy & Jackson (2022)

	Lifetime [years]	*GWP 100*	*GWP 20*	*GTP-100*	*GTP-50*	*$GWP_{1.5°C}$*	*$GWP_{2.0°C}$*
Fossil CH4	11.8	27.0	82.5	7.5	13.2	75	42
Biogenic CH4	11.8	29.8	79.7	4.7	10.4	-	-
N2O	109	130	273	233	290	-	-

The case for dietary change to achieve a protein transition and avoid global warming
Animal products have higher protein and caloric densities than plant-based foods, but the feed-to-food conversion is inefficient: the average efficiency ratio for animal products is 9%, and for beef 3% (Shepon et al., 2016). Xu et al. (2021) estimate (with carbon content as the functional unit) the ratio of food grown for human consumption to that for animal feed is 1:3, illustrating the disproportionate cost of consuming animal products. Even if feed crops are not suitable for human consumption, their production uses resources. A protein transition reduces GHG emissions and global temperatures, while providing food security for a growing population. Positive impacts include improved human health (Willett et al., 2019) and animal welfare (Scherer et al., 2019), and decreasing deforestation (Rosenzweig et al., 2020), biodiversity loss, water scarcity (Dalin & Outhwaite, 2019), acidification, eutrophication (Poore & Nemecek, 2018), antibiotic resistance, spread of zoonotic diseases, and pandemics (Hayek, 2022). It also frees up space: Physically from grazing and feed crop lands, which can lead to a *double climate dividend* through carbon sequestration (Eisen & Brown, 2022; Hayek et al., 2021; Sun et al., 2022), or bioenergy and carbon capture storage (BECCS) without the need for cropland expansion upon rewilding (Rueda et al., 2024). And conceptually, in the carbon budget,

lowering reliance on risky geoengineering technologies and enabling the continued use of essential technologies for which reliable alternatives not yet exist.

Emission reductions are significant even from partial adoptions of plant-based diets (Poore & Nemecek, 2018), like vegetarian and flexitarian diets (Scarborough et al., 2023). Beef's environmental pressures vary by production system (Pierrehumbert & Eshel, 2015). However, not eating beef has a much more positive climate impact than eating efficiently raised beef (Clark & Tilman, 2017).

Two main forms of technological innovations to mitigate direct and indirect methane emissions from livestock exist: decreasing methane from enteric fermentation (e.g. through feed), and from manure management (e.g. methane inhibitors) (Arndt et al., 2022). These are frequently analysed as mitigation measures because of their theoretic emission savings and perceived necessity (Arndt et al., 2022; Clark & Tilman, 2017; Herrero et al., 2016; Rosenzweig et al., 2020; P. Smith et al., 2021). Governments favour technological innovation over dietary change in policies and NDCs (*Global Methane Pledge*, n.d.) as it means sustaining economic activity with minimal impact on consumer freedom. But their efficacy is contested and dietary change is deemed most effective and necessary (Harwatt et al., 2024; Hayek & Miller, 2021; Rasmussen et al., 2018; Rosenzweig et al., 2020). Artificial beef currently has a high CO2 intensity and is not a sustainable alternative to avoid warming (Lynch & Pierrehumbert, 2019).

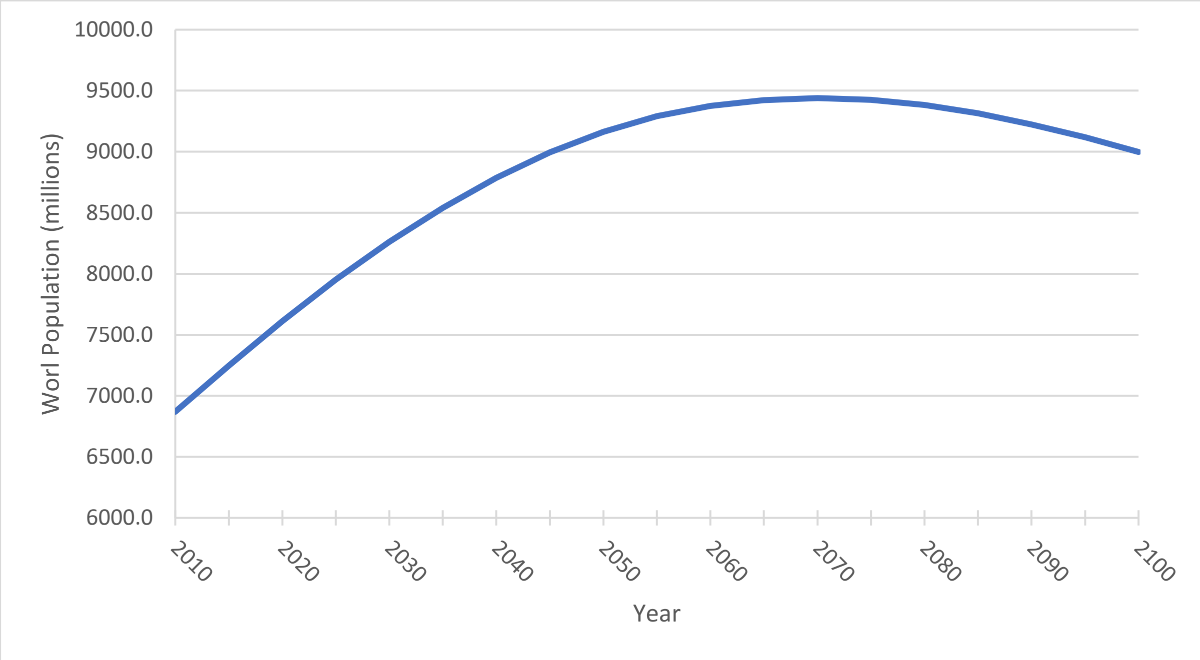
Current per capita consumption of animal products is highest and on unhealthy levels in developed nations (Arndt et al., 2022), while the impacts are predominantly felt in developing countries (Hong et al., 2022; Pinero, 2022). A dietary change based on the 'best-available-food' strategy (Harwatt et al., 2020) allows for partial adoption in the few low-income regions that do not currently have viable alternatives for livestock. For instance in pastoralist communities for whom animals are not just a food source. A rapid and full phaseout of animal products should be the goal for climate, sustainability, and ethical reasons, and due implementation places the largest burden on the countries that have historically profited the most from anthropogenic GHG emissions.

Methods

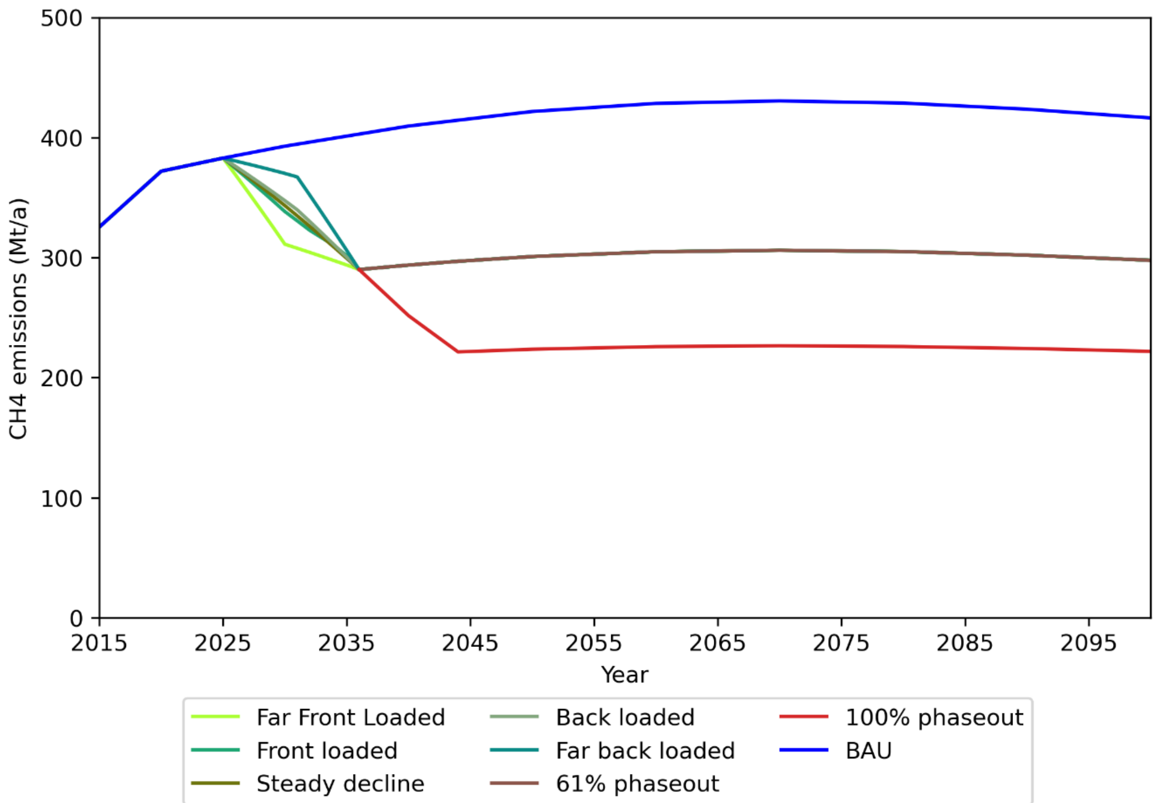
MAGICC modelling: Baseline fossil CO2 and CH4 emissions

The baseline GHG emission values were applied at 2015, 2020, and 2024 during the establishment of historic and current emissions. CO2 emissions from fossil fuels and industry are from the Global Carbon Budget (Friedlingstein et al., 2023). For 2015 (35,700.0 Mt/a) and 2020 (34,100.0 Mt/a) exact findings for those years were used. For 2024, we used data from 2023, the nearest year for which a carbon budget was published: 36,300.0 Mt/a. For methane emissions from fossil fuel production we refer to the Global Methane Budget (Saunois et al., 2020). We use the 2008-2017 average value of methane from fossil fuel production using their bottom-up approach: 128 Mt/a. In the trajectory, this value is applied to all years since no additional details are available.

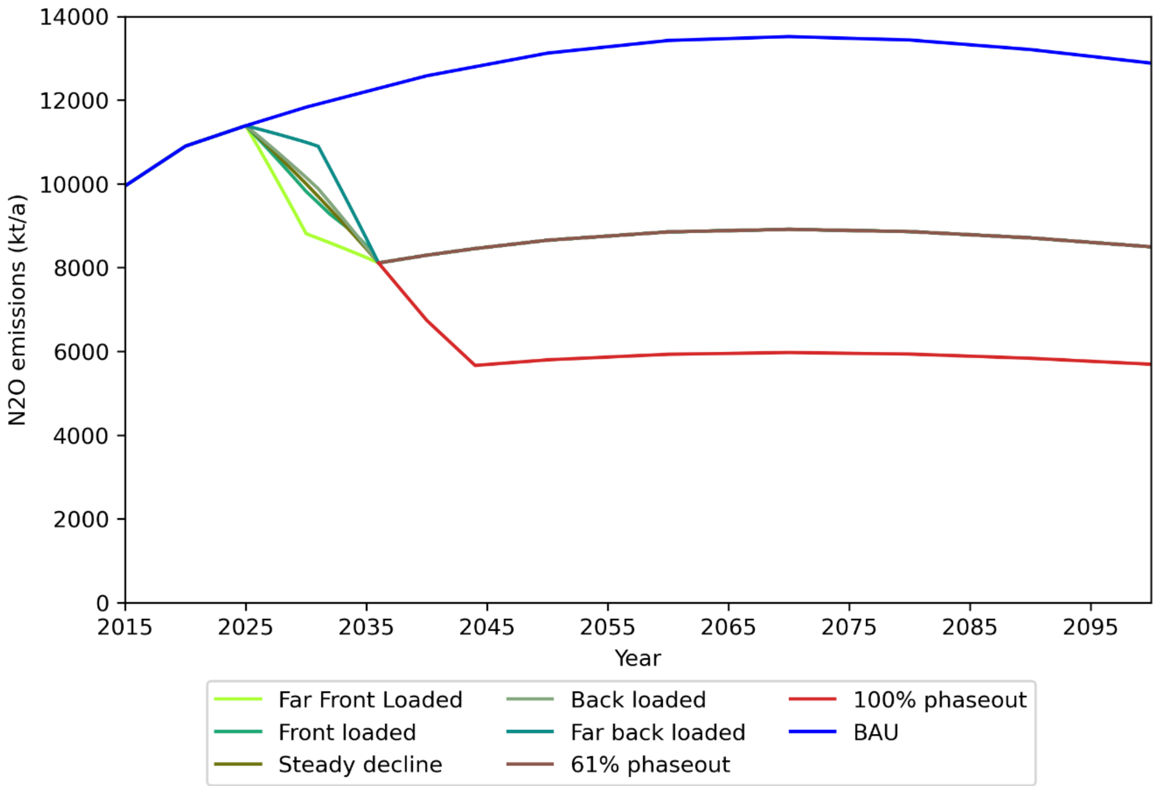
Results



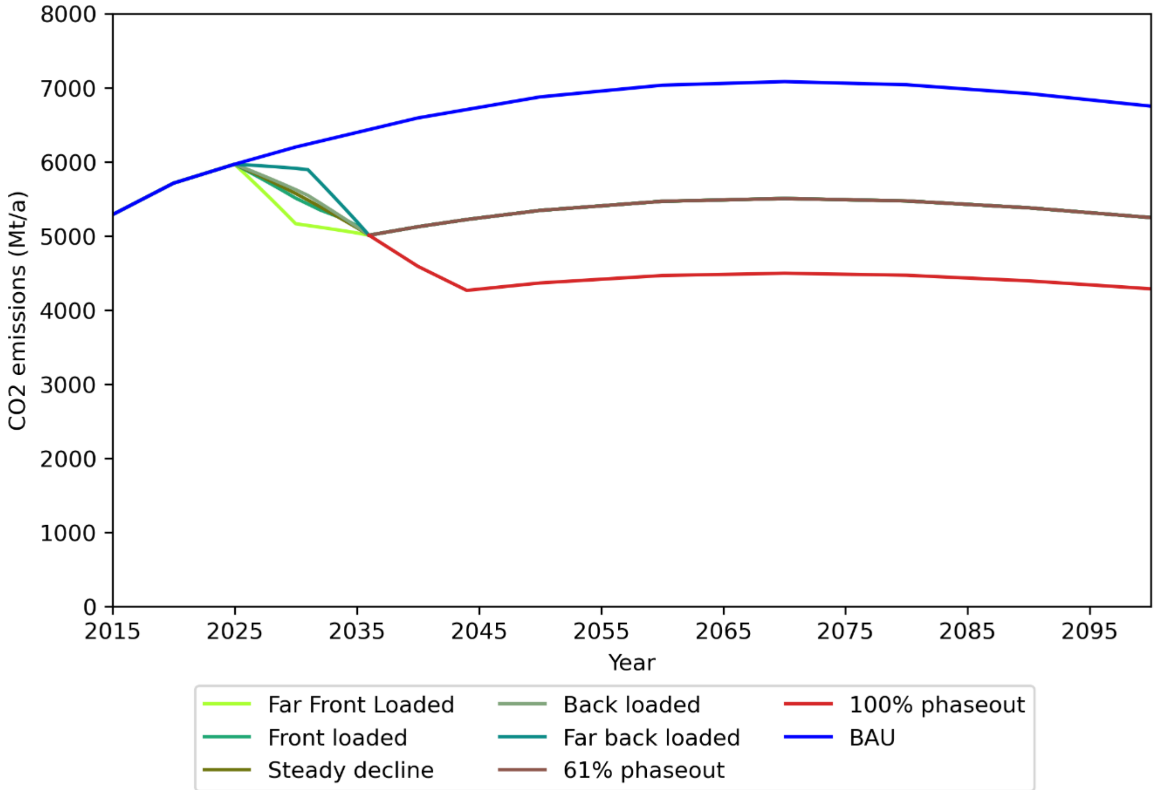
SI Figure 1: Global population projection according to SSP2, source: (AR6 Scenario Explorer and Database, *n.d.)*



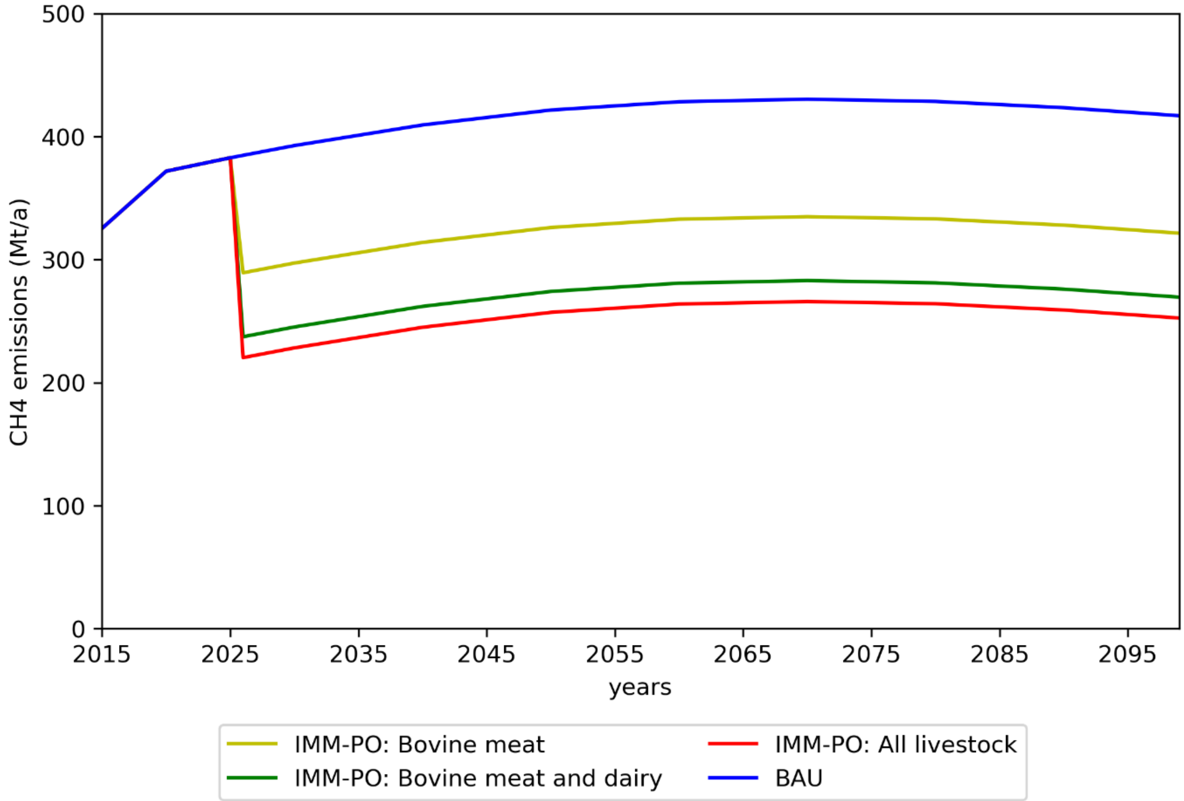
SI Figure 2: Expert-elicitation livestock-reduction trajectories for CH4.



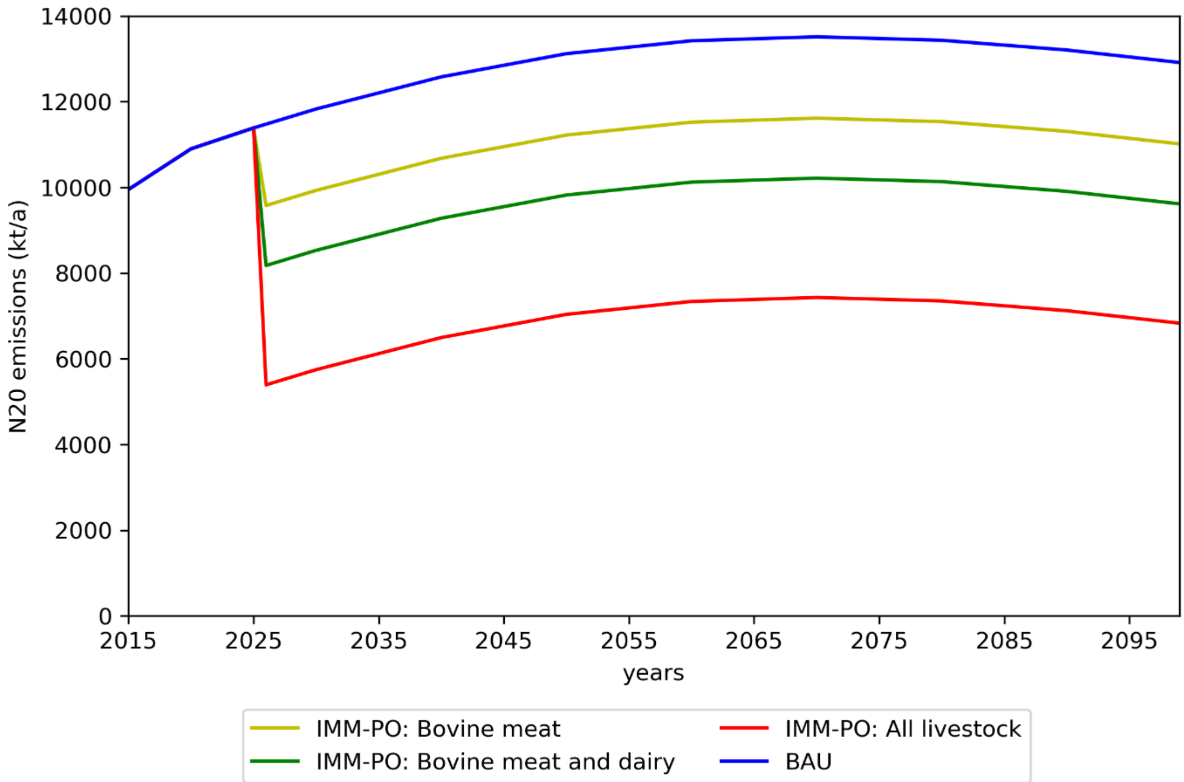
SI Figure 3: Expert-elicitation livestock-reduction trajectories for N2O.



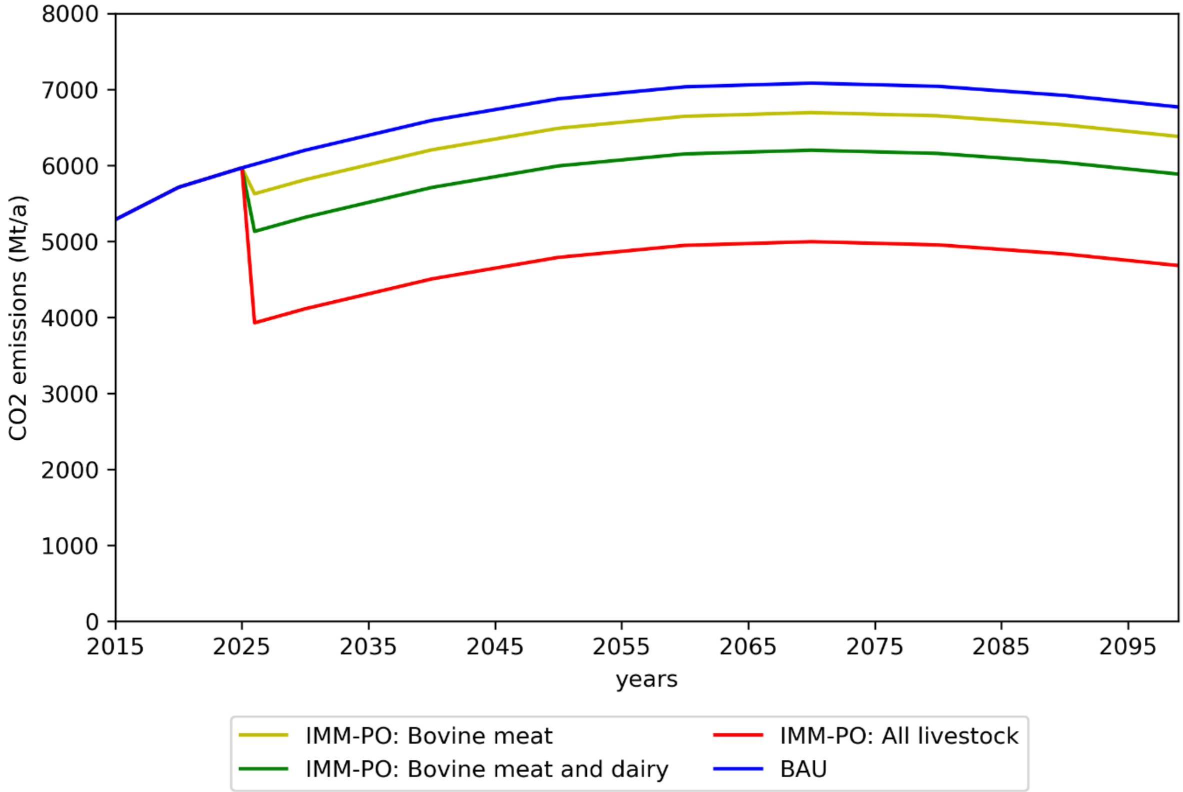
SI Figure 4: Expert-elicitation livestock-reduction trajectories for CO2.



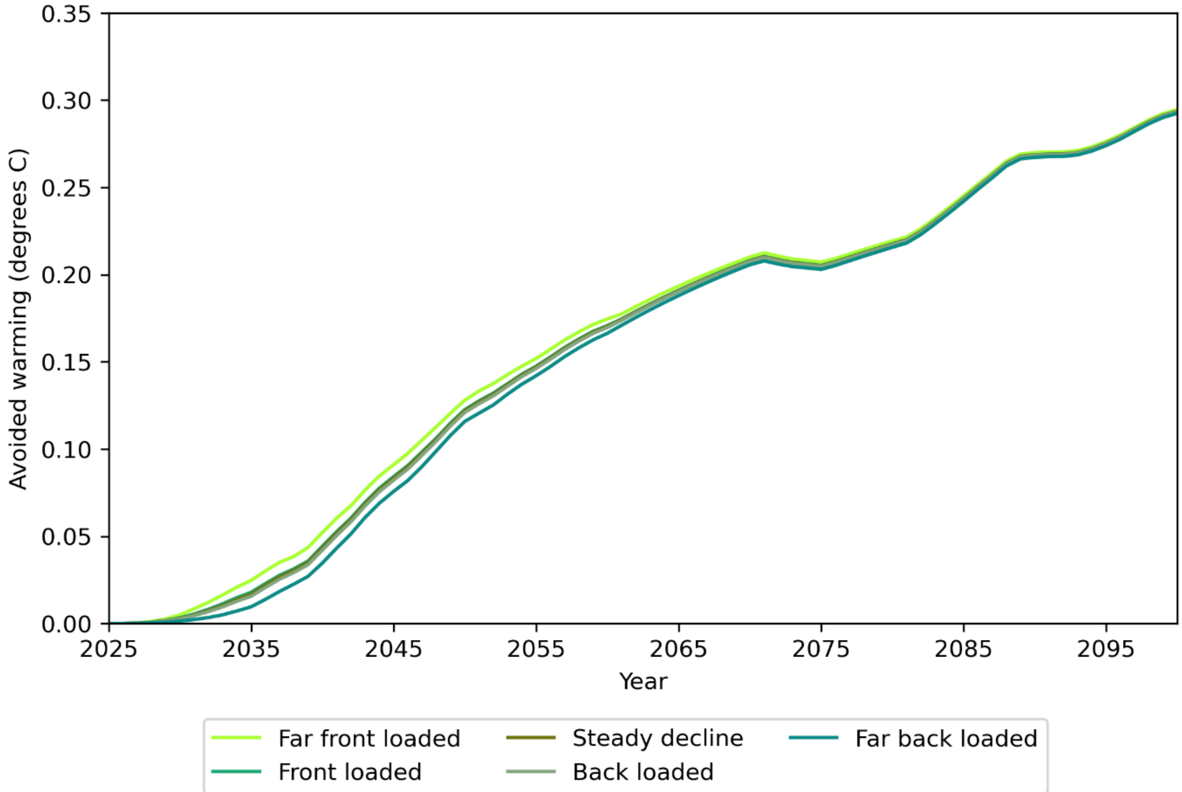
SI Figure 5: Immediate reduction trajectories for CH4.



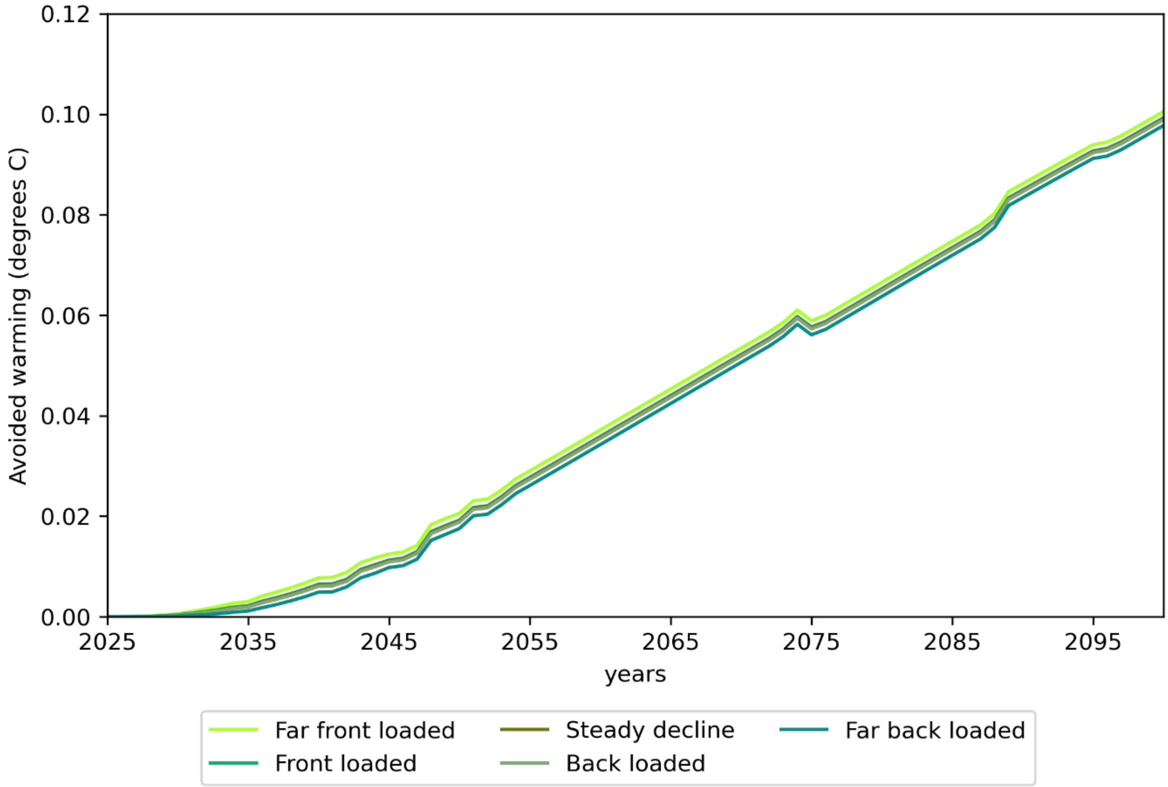
SI Figure 6: Immediate reduction trajectories for N2O.



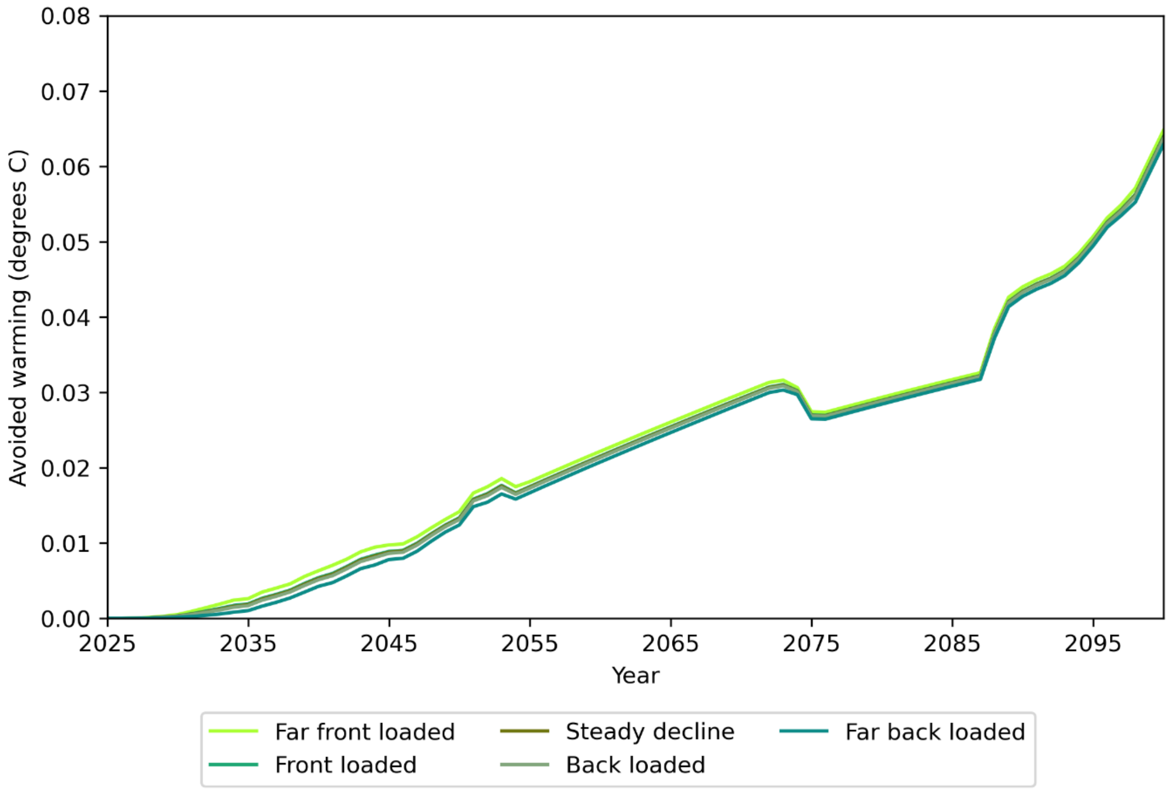
SI Figure 7: Immediate reduction trajectories for CO2.



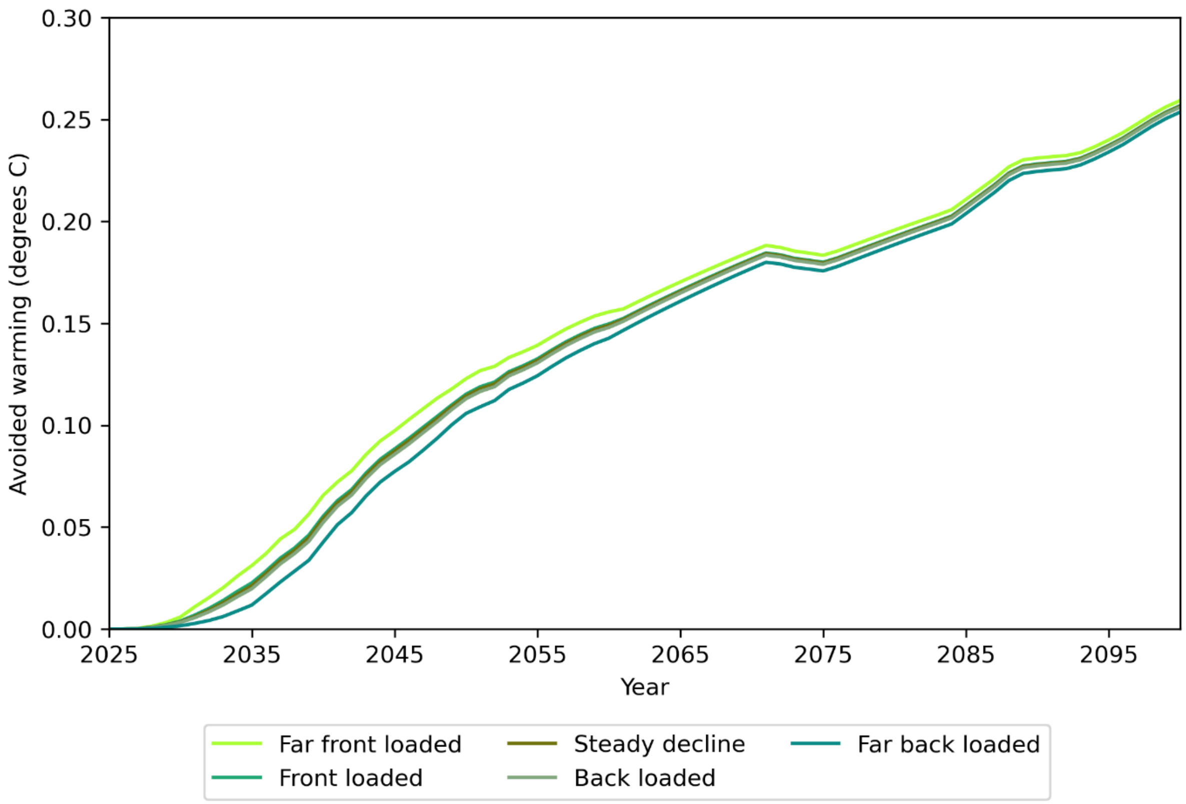
SI Figure 8: Avoided warming attributable to CH4 in the expert-elicited 100% livestock-reduction trajectories.



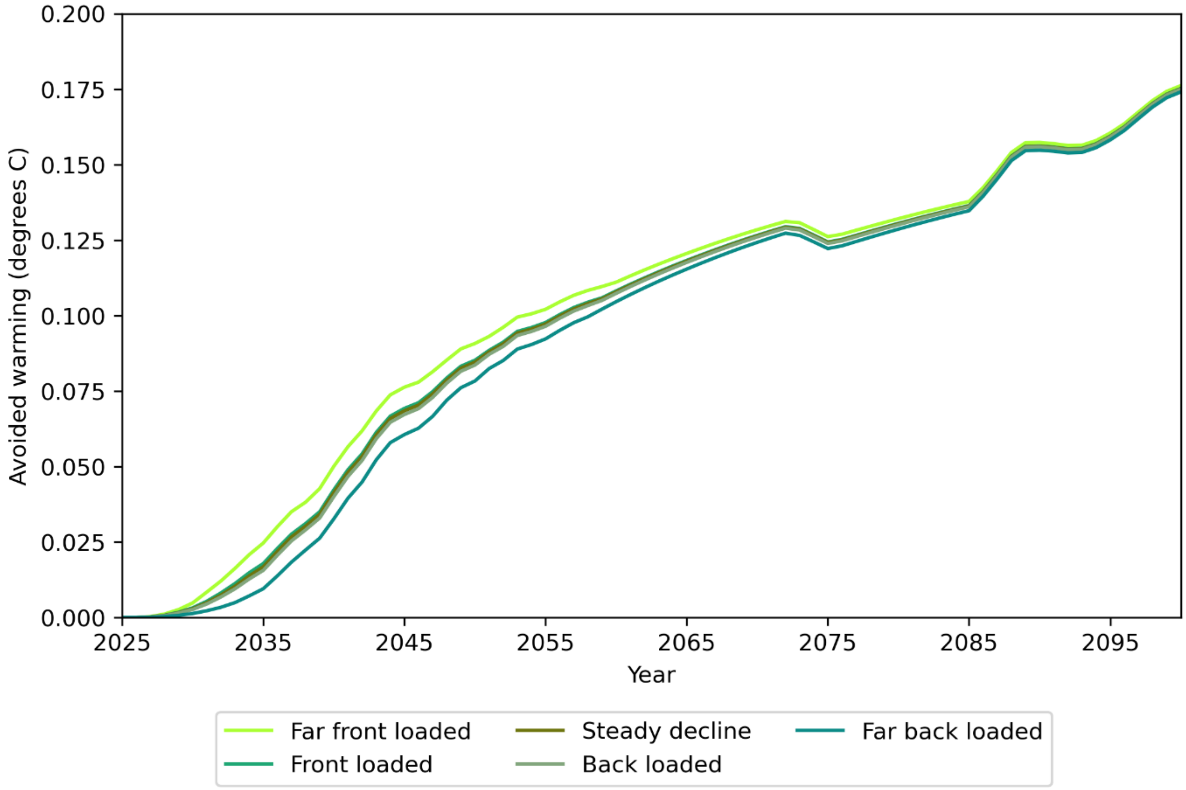
SI Figure 9: Avoided warming attributable to N2O in the expert-elicited 100% livestock-reduction trajectories.



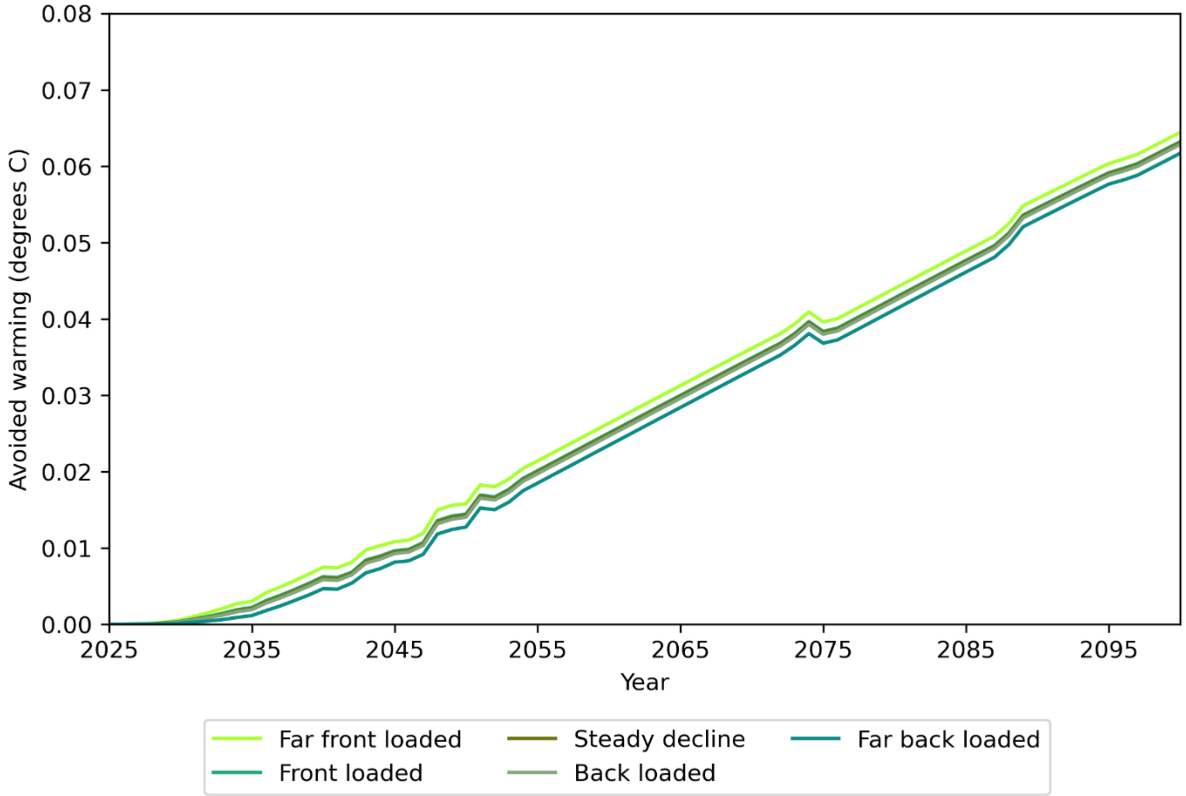
SI Figure 10: Avoided warming attributable to CO2 in the expert-elicited 100% livestock-reduction trajectories.



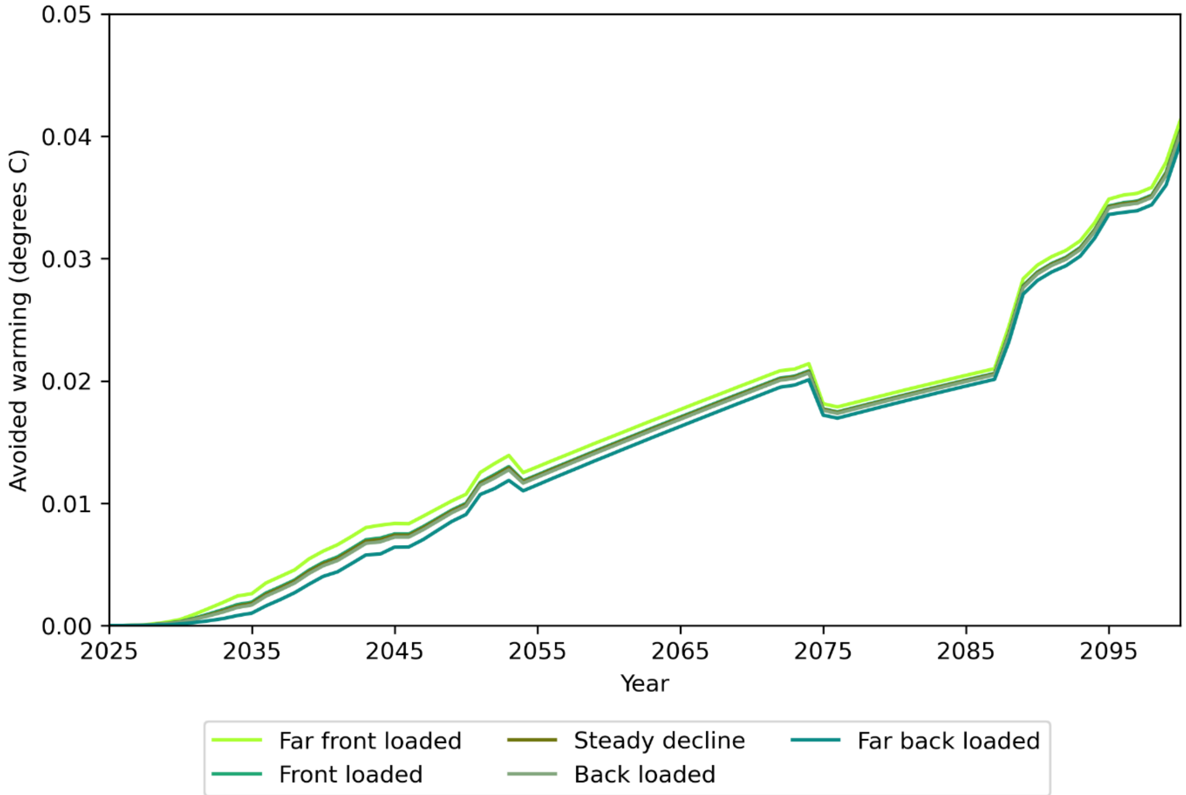
SI Figure 11: Total avoided warming in the expert-elicited 61% livestock-reduction trajectories.



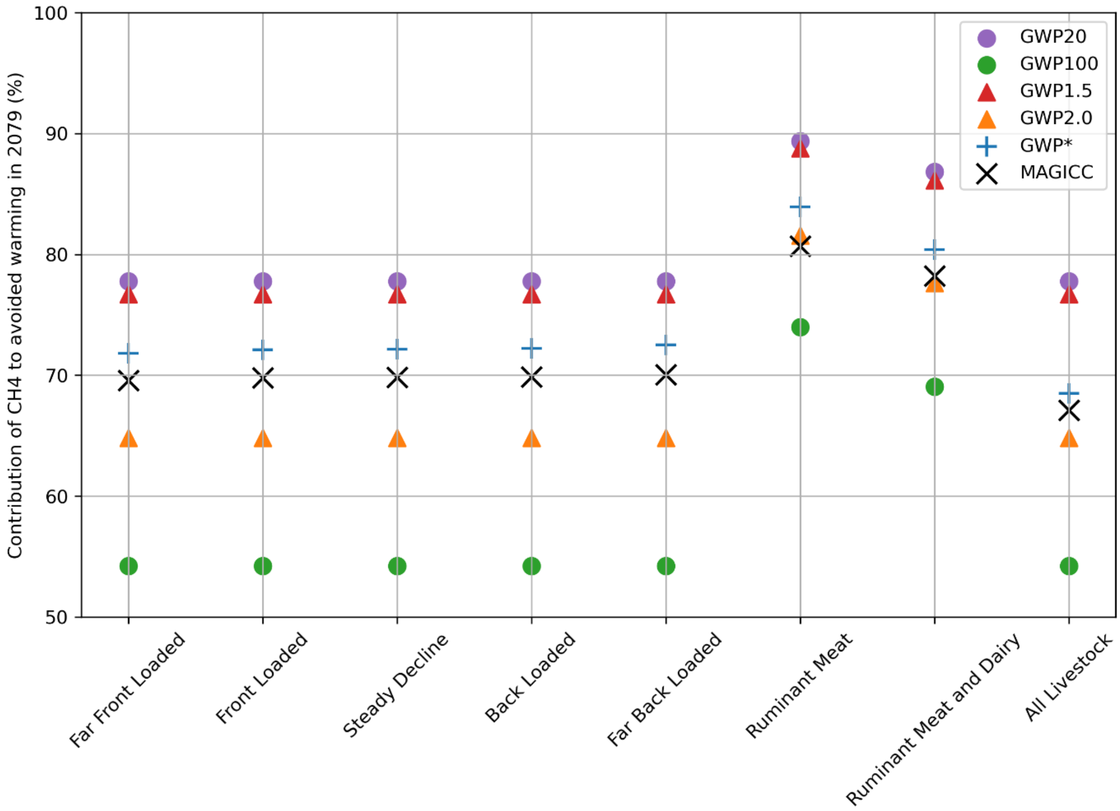
SI Figure 12: Avoided warming attributable to CH4 in the expert-elicited 61% livestock-reduction trajectories.



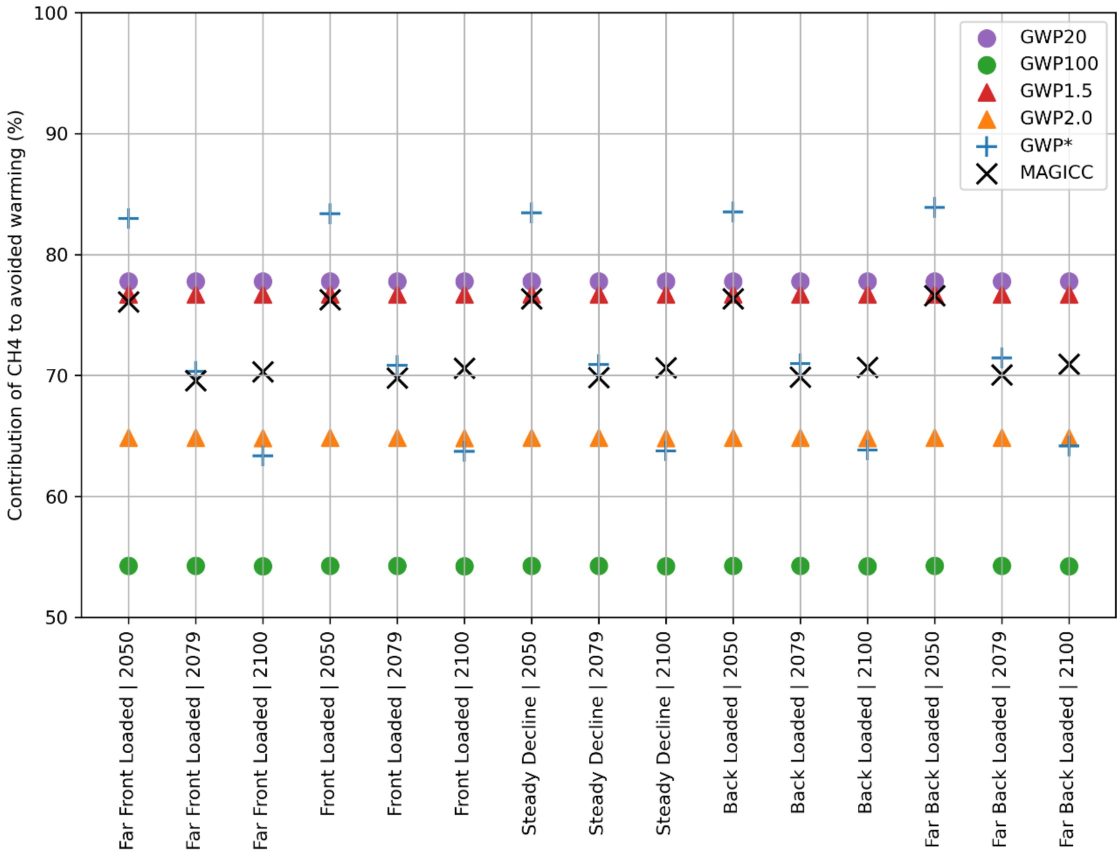
SI Figure 13: Avoided warming attributable to N2O in the expert-elicited 61% livestock-reduction trajectories.



SI Figure 14: Avoided warming attributable to CO2 in the expert-elicited 61% livestock-reduction trajectories.



SI Figure 15: Climate metrics' and MAGICC outcomes of methane's contribution to avoided warming in 2079 per livestock reduction scenario (expert-reduction scenarios use 100% phaseout).



SI Figure 16: Metric performance for the expert-elicitation trajectories with a 61% reduction, for 2050, 2079, and 2100.

Discussion

Sensitivity analysis

Modelling choices and model uncertainty

Since this study compares the outcomes of various scenarios with identical setups, barring the GHG trajectories of CO2, CH4, and N2O, the outcomes are not influenced by varying model settings. The results are also not expected to be significantly influenced by unexpected and untrue model behaviour, since the methane mitigation modelling-capabilities of MAGICC have been verified, and MAGICC is shown to produce similar results as more sophisticated climate models (Meinshausen et al., 2011; Ocko et al., 2018). Comparability to other studies' outcomes is ensured by the usage of the standard MAGICC settings also used in IPCC publications, and generally applied in literature when assessing methane mitigation options (see SI: Literature review).

Methane's radiative efficacy

The warming capacity of any GHG is dependent on (initial) atmospheric concentrations, and the much lower concentration of methane compared to carbon dioxide explains their difference in radiative efficiency (Pierrehumbert, 2014). Methane's very short atmospheric lifetime and the assumed rapid emission reductions in this study lead to quickly changing atmospheric methane concentrations. This exposes potential uncertainty since the radiative efficacy of methane decreases with higher concentrations of both CH4 and N2O (Ramaswamy et al., 2001). Avoided warming from the mitigation measures presented in this study is thus influenced not only by the rate of change in methane emissions from livestock and other food system sources, but also the methane emissions from other sectors and natural sources. Efforts to curb methane emissions in other sectors and their effects are outside the scope of this study, and we have chosen to represent these methane emissions as constant baseline emissions nullifying the effect when intercomparing each scenario's outcome.

However, the avoided warming from reducing the food system's methane footprint would decrease if the fossil fuel industry and waste management sectors drastically reduce their methane emissions as pledged in NDCs (Nationally Determined Contributions) (*Global Methane Pledge*, n.d.), and assumed in several IPCC pathways (Intergovernmental Panel on Climate Change (IPCC), 2022). An example from literature of the impact thereof is presented by Reisinger & Clark (2018). They show that livestock methane emissions cause less end-of-century warming (0.14 °C) in the BAU high-emissions scenario (RCP8.5), compared to 0.18 °C in the sector-wide mitigations scenario (RCP2.6) in which they reduced livestock emissions by 40%. In a more stringent mitigation scenario they reduced livestock emissions by another 50% compared to the previous 40%, and found the warming contribution to be lower than under BAU conditions.

Current and future food system and livestock emissions:

Several assumptions about current and future food system emissions could influence this study's outcome. We used food system emissions based on recent values and yearly intensities found by Ivanovich et al. (2023), because: 1. The findings are recent and they build and expand upon existing knowledge, 2. the detail in their database with yearly emissions per food group and disaggregated GHG was practical to apply to trajectories based on dietary change scenarios. 3. Using food system emissions data from one study, ensures that the magnitude of total food system emissions is in concordance with the livestock emissions being reduced. Other studies that quantified food system and livestock emissions, applied different methodologies and do not have these benefits. Most findings are in general agreement when accounting for the different boundary conditions of each study, (see the food system emissions from literature overview in the SI: 'GHG_Trajectories.xlsx', and e.g. the SI in Ivanovich et al. (2023)). The spread in findings means selecting a different source can influence the magnitude of this study's results. Observing the various emission values used in literature to quantify the food system's warming contribution, the order of magnitude of (avoided) warming is expected to stay the same. Selecting a different principal source for food system and livestock emissions would thus not void the principal findings and conclusions of this study.

The magnitude of future livestock emissions will be the result of demand (which is uncertain) and technological advancements (which are mitigation interventions). In the BAU and expert-reduction scenarios (in which the livestock phaseout is not immediate) we assumed the demand for livestock products to be influenced only by population growth, and negate a demand increase from changing consumer preferences. This is unlikely and a significant underestimate, as demand for animal products is projected to increase globally by up to 20.9% by 2050 (Henchion et al., 2021), and much higher estimates exist (Eisen & Brown (2022; Ivanovich et al. (2023) cite 70% and 90% more meat demand in 2050). The findings of this study when using conservative animal-food consumption numbers are thus an underestimate. The influence of technological advancements as mitigation measures is not explicitly considered in this study. Mitigation efforts are not considered by design in the BAU and immediate-reduction scenarios, while in the expert-reduction scenarios a dietary change is assumed but the trajectories can theoretically be achieved by a diverse mitigation portfolio. This means that accounting for technological advancement and demand would not alter the findings presented in this study.

Limitations

Carbon sequestration

The potential climate benefits of utilizing freed up pasture- and feed crop lands following declining demand for animal products to sequester carbon are vast (Hayek et al., 2021; Rueda et al., 2024; Sun et al., 2022). The impact of negative emissions from rewilding are outside the scope of this study, but Hayek et al.(2021) estimated 547 (358 to 743) $GtCO_2$ to be sequestered following a dietary shift from the BAU to a plant-based diet. To illustrate this magnitude; in 2023 the remaining carbon budgets to have a 50% chance of achieving 1.5 °C and 2.0 °C were 275 and 1170 Gt CO_2 (Friedlingstein et al., 2023). In Eisen & Brown's (2022) study quantifying the merit of a complete phaseout of livestock products, they used the high boundary and assumed a natural rewilding process over 30 years on land that became available. Expressed in radiative forcing, the biomass recovery approximately doubles the end-of-century reduction effect of phasing out livestock's direct GHG emissions. While the outcome is dependent on the assumed reforestation timespan and the sequestration potential, this secondary effect of a protein transition would free up significant space in the carbon budget to achieve the Paris Agreement temperature goals.

LUC: handling of emission reductions

LUC emissions are included in this study's source data from Ivanovich et al. (2023), and are reduced proportionally to the livestock phaseout in the each scenario. However, LUC is a symptom of increasing demand for livestock products, and the study's underlying premise is an invariant demand for animal products except due to population growth. So LUC emissions should be zero from the time of the mitigation start in scenarios not accounting for population growth, instead of a proportional reduction over time. It was not possible to infer and subtract the proportion of livestock LUC emissions from within the same source as Ivanovich et al. (2023) disaggregated GHG emissions in their database, but did not separate land use and land use change emissions. Since the underlying data from Poore & Nemecek (2018) also includes energy use and supply chain emissions, the assumption that LUC constitutes all CO_2 emissions from livestock does not hold. Other publications have quantified livestock LUC emissions (Clark et al., 2020; Crippa et al., 2021; Rosenzweig et al., 2020), but this study uses only Ivanovich et al. (2023) emissions data to quantify reductions in each GHG trajectory, and it would not be accurate to apply findings from other sources. Since methane reductions contribute the most to avoided warming until 2100, this study's conclusions would not be different if the mitigation trajectories assumed LUC CO_2 emissions were zero after the peak-livestock year.

Replacement diets

This study has not devised a replacement diet to replace animal protein and calories with plant-based equivalents. Doing so would increase the accuracy of the outcomes, but the outcomes wouldn't be significantly different. The emission footprint of plant-based alternative is very small compared to animal products (Xu et al., 2021), and the land it requires to grow is a fraction of the land previously used for feed: Poore & Nemecek (2018) find that a shift from the 2009-2011 average diet, to a plant-based diet would reduce food system land use by 76%. When modelling a dietary change towards the (low in animal-product consumption) EAT-Lancet diet in high-income nations, Sun et al. (2022) find a necessary increase of only 0.01 GtCO2eq/yr to replace the animal proteins with plant-based equivalents. This is an order of magnitude smaller than the avoided emissions from animal product consumption (0.75 GtCO2eq/yr).

Partial adoption rates

The primary aim of this study was to quantify the maximum avoided warming from a dietary shift following expert-elicited livestock phaseout trajectories, which is compared to the maximum potential of an immediate phaseout of livestock products. As such, partial adoption rates were not considered in-depth. Other studies have compared the various climate impact of vegetarian, vegan, and sustainable and healthy diets like the EAT-Lancet diet, e.g. Springmann et al. (2020). Here, the phaseout trajectories dictate adoption rates. The results of this study confirmed findings by Eisen & Brown (2022) and Ivanovich et al. (2023) that a phaseout of beef and dairy contribute the most to avoided warming. This suggests that partial adoptions could achieve the majority of the cooling benefits. For maximum efficiency, the partial adoptions should focus on the highest emitting food groups and consumers; most reductions should be made first by high-income nations (Harwatt et al., 2024).