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Animal board invited review: Opportunities and challenges in using GWP* to report the impact of ruminant livestock on global temperature change

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A R T I C L E I N F O

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A B S T R A C T

Ruminant livestock is a large contributor of CH_4 emissions globally. Assessing how this CH_4 and other greenhouse gases **(GHG)** from livestock contribute to anthropogenic climate change is key to understanding their role in achieving any temperature targets. The climate impacts of livestock, as well as other sectors or products/services, are generally expressed as CO_2-equivalents using 100-year Global Warming Potentials **(GWP_{100})**. However, the GWP_{100} cannot be used to translate emission pathways of short-lived climate pollutants **(SLCPs)** emissions to their temperature outcomes. A key limitation of handling long- and short-lived gases in the same manner is revealed in the context of any potential temperature stabilisation goals: to achieve this outcome, emissions of long-lived gases must decline to net-zero, but this is not the case for SLCPs. A recent alternative metric, **GWP*** (so-called 'GWP-star'), has been proposed to overcome these concerns. GWP* allows for simple appraisals of warming over time for emission series of different GHGs that may not be obvious if using pulse-emission metrics (i.e. GWP_{100}). In this article, we explore some of the strengths and limitations of GWP* for reporting the contribution of ruminant livestock systems to global temperature change. A number of case studies are used to illustrate the potential use of the GWP* metric to, for example, understand the current contribution of different ruminant livestock production systems to global warming, appraise how different production systems or mitigations compare (having a temporal element), and seeing how possible emission pathways driven by changes in production, emissions intensity and gas composition show different impacts over time. We suggest that for some contexts, particularly if trying to directly infer contributions to additional warming, GWP* or similar approaches can provide important insight that would not be gained from conventional GWP_{100} reporting.

Implications

Ruminant livestock are a major contributor to global CH_4 emissions, and consequently to global warming. Greenhouse gas emissions are generally expressed as CO_2-equivalents using 100-year Global Warming Potentials, but this metric cannot be used to infer any particular temperature impacts, because it cannot capture the dynamics of how changing emissions of short-lived gases, i.e. CH_4, result in changing global temperature. This article explores an alternative metric called Global Warming Potential Star, outlining how it operates and can provide insight into the contribution of CH_4-dominated activities, such as ruminant production, to global temperature changes.

Introduction

As part of the global effort to avoid dangerous climate change, the Paris Climate Agreement sets out a global framework to limit global warming to well below 2 °C and pursue efforts to limit it to 1.5 °C compared with pre-industrial levels (UNFCCC, 2015). This

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will require rapid reductions of global CO_2 emissions to and potentially below net-zero, mainly from fossil fuel use, but the global food system including livestock is also expected to play an important role in achieving this target through large-scale greenhouse gas **(GHG)** emissions reduction and providing opportunities for C sequestration (Clark et al., 2020).

The climate impacts of livestock, as well as other sectors or products/services, are commonly expressed using emission metrics reporting 'CO_2-equivalent' **(CO_2-e)** emissions. For example, national GHG emissions inventories, sectoral GHG emissions or product 'carbon footprints' are generally reported as 'CO_2-equivalent' quantities using 100-year Global Warming Potentials **(GWP_{100})**.

The GWP is defined as the integrated radiative forcing (atmospheric energy imbalance that leads to global warming) resulting from a pulse emission of a given GHG, relative to an emission of the same mass of CO_2. The GWP_{100} takes a period of 100 years following either emission from which to compare the integrated forcing. The Intergovernmental Panel on Climate Change (**IPCC**) 5th Assessment Report suggests the GWP could therefore be interpreted as "an index of the total energy added to the climate system by a component in question relative to that added by CO_2" (Myhre et al., 2013).

Despite this apparently intuitive construction, and the long history of use of the GWP_{100} as an emission metric, there is an equally long-standing discussion of its limitations, especially in relation to characterising the climate impacts of short-lived climate pollutants **(SLCPs)** such as CH_4 (e.g., Shine, 2009; Allen et al., 2016; Ocko et al., 2017). A fundamental challenge, particularly in the context of overarching temperature-based climate goals, is that time series of emissions reported using the GWP_{100} cannot be translated to temperature outcomes for various points in time.

As the GWP is based on radiative forcing impact integrated across the whole time-horizon used, the dynamic detail of how forcing changes within this period is lost. Consequently, the forcing, or resulting temperature change, at any particular time cannot be determined. This obscuring of the temporal evolution of climate impacts also imposes a fundamental barrier in understanding how different sequences of emissions contribute to any overall climate impacts.

To determine the current contribution to elevated temperature from any given activity, or simply understand how overall global temperature change has been driven by total global emissions, we need to know what GHGs have previously been emitted and the climate impacts exerted. These impacts decline over time at gas-specific rates according to the various atmospheric removal processes that apply to each gas. Future temperature changes similarly depend on the time-varying impacts of past, present and future emissions.

For CO_2, the extremely long-term persistence of a significant fraction of emissions, coupled with the timescales of the global temperature response, mean that emissions of CO_2 cause relatively stable additions to overall global warming for at least centuries to millennia (Solomon et al., 2010; Pierrehumbert, 2014). Consequently, each CO_2 emission can be thought of as raising temperatures in a straightforward, additive manner, and the warming contribution of a CO_2 emitter can be determined by simply summing all of their past CO_2 emissions to date.

For shorter-lived climate pollutants such as CH_4, however, emissions do not exert indefinite, cumulative impacts on temperature. Instead, their contribution to temperature increases wanes over time post-emission, in accordance with the natural atmospheric removal processes for the given gas. For N_2O, with an average atmospheric lifetime of around a century, the decay of temperature impact over time is still quite slow (though still much faster than for CO_2), and emissions can still be thought of as adding cumulatively to global temperature over timeframes within its atmospheric lifetime. For CH_4, with an average atmospheric lifetime of around a decade, a substantial fraction of its warming impacts are reversed relatively shortly after emission (within 4–5 decades less than 2% of the original emission remain), and its impacts are predominantly not cumulative.

One potential means of reporting the global warming impact of emitters which may allow a more direct link to climate outcomes, based directly on the physical dynamics noted above, is the radiative forcing **(RF)** climate footprint (Ridoutt and Huang, 2019; ISO, 2021 *under development*, Ridoutt, 2021a). The contribution to RF made by an organisation or industry is determined by summing the RF from current emissions with the RF from historical emissions that remain in the atmosphere, thus overcoming the problems in trying to use isolated pulse emissions with different time-dependent impacts to assign climate responsibility. As it is indicated in Ridoutt (2021a), organisations and industries could target to achieve no net addition to RF or even manage to reduce their RF, as appears to be happening in the Australian sheep meat sector (Ridoutt, 2021b).

Another recent alternative has been the appearance of **GWP*** (so-called 'GWP-star') (Allen et al., 2016; 2018; Cain et al., 2019; Smith et al., 2021). This new climate metric allows integrating short-lived gases in cumulative emission frameworks (Enting and Clisby, 2021). GWP* treats a change in the rate of SLCPs as directly equivalent to an individual emission of CO_2, sometimes called 'step-pulse' equivalence, with the 'step-change' in SLCP emission rates equated to an individual CO_2 pulse. This type of equivalence comes about because for short-lived gases, stable emission rates lead to stable concentrations (where emissions are balanced by natural removals), reflecting the long-term atmospheric persistence of an individual CO_2 release. Through this approach, GWP* allows for simple appraisals of warming over time for different GHG that are not obvious if using pulse-emission metrics (i.e. GWP_{100}). It can capture the differing temporal and legacy impacts of different emissions and relate emission trajectories more directly to climate outcomes, similarly to the RF footprint, but can be computed very easily (see below). GWP* reports different GHG emission pathways in terms of 'CO_2-warming equivalents', or CO_2-we.

It must be noted that 'CO_2-warming-equivalents', as provided by GWP*, are not the same quantity as reported using typical pulse-emission 'CO_2-equivalent' metrics such as the GWP_{100}. CO_2-warming-equivalents report a given non-CO_2 or multi-gas emissions pathway as the approximate CO_2 emissions series that would result in the same temperature change over time, relative to a reference level of warming caused by prior emissions up to the beginning of the time series that is being evaluated. They are thus distinct from conventional CO_2-e approaches that provide a single weighting to indicate the relative impact (as defined by the specific CO_2-e metric used) of emitting *vs* not emitting a given GHG, irrespective of how this impact may compare with respect to the warming caused by prior emissions.

We also highlight that there is a wider recognition of the potential for 'step-pulse' equivalence between CH_4 and CO_2 to overcome the limitations of conventional metrics: Lauder et al. (2013) present an early example of a fixed amount of CO_2 sequestration offsetting sustained CH_4 emissions (in an Australian livestock context), and more recently Collins et al. (2020) reported an alternative take (combined step-pulse metrics denoted the combined global warming potential and combined global temperature change potential) capturing similar principles to GWP*. Here, we focus on GWP* for being simple to compute and having received significant attention in parts of the agricultural community.

This manuscript provides a number of case-studies illustrating the use of GWP* to report how ruminant emission trajectories contribute to global temperature change, and explore a few examples of how and why GWP* represents a different approach to GWP_{100}. We build on these case-studies to discuss some potential implications, and finally note some current challenges and wider considerations surrounding concepts of 'CO_2-equivalence'.

Material and methods

Global Warming Potential Star as an emission metric and tool for estimation of global warming impact

The GWP* metric allows expressing all emissions (i.e. both long- and short-lived gases) in "CO_2-warming equivalents" **(CO_2-we)**, which in a common cumulative emission framework correlate well with the global temperature increase expected to result from the original emissions being reported (Cain et al., 2019).

Carbon dioxide emissions, by definition, do not require further conversion under any 'CO_2-equivalent' reporting system. For other longer-lived gases (also denoted as long-lived climate pollutants: **LLCPs**), such as N_2O, conventional application of GWP_{100} (i.e. standard reporting of "CO_2-e") works acceptably well in a cumulative emissions framework (at least until the end of the 21st century; further distinctions required for multi-century scenarios are discussed further below), and so can still be considered as reporting 'warming-equivalent' emissions.

For SLCPs (i. e., CH_4 emissions), the following equation is used to calculate GWP* (called the CO_2-we) at a particular year:

$$ECO_2\text{-we} = GWPH \times \{[0.75 \times (\Delta ESLCP/\Delta t) \times H] + [0.25 \times ESLCP]\}.$$

where ECO_2-we is the estimated CO_2-we, GWPH is the conventional global warming for CH_4 over time-horizon H (100 years), ΔESLCP is the change in CH_4 emission rate compared to the preceding Δt (20) years, ESLCP is the CH_4 emissions for the objective study year (Cain et al., 2019). We can note that a further refinement was made to the formula in Smith et al. (2021), but we chose to stick to this formula as GWP* metrics are used as this version has been illustrated more widely to date, and may be more familiar to a more agriculture-focussed readership. Smith et al. (2021)'s update has only a small impact on the results, so it should not affect the conclusions.

As can be inferred from the equation, changes in CH_4 emission rates are reported as a very large CO_2-we for the 20-year period following the change, and can be either positive or negative. This reflects the fact that CH_4 is a strong climate pollutant, but also that once a new emission rate is established, most of the resulting climate impacts are experienced rapidly. After this initial period, we already experience most of the warming that these ongoing CH_4 emissions will cause, owing to its short atmospheric lifespan, and so when ΔESLCP = 0 across the preceding 20-year period, the equation only reports a much smaller element to capture the longer-term warming contribution from the slow-climate response component to increased RF. We can lower CH_4 emissions to reverse much of the CH_4-induced warming experienced, having an analogous temperature impact to actively removing past CO_2 emissions, and hence reported as a negative CO_2-we. Through this simple approach, effectively treating each individual CH_4 emission as behaving like a large CO_2 release followed by an automatic CO_2 removal 20 years later, GWP* manages to capture the key differences in how short- vs long-lived gases contribute to changes in global temperature, as described above.

For a multi-gas appraisal, values of CO_2-we from CH_4 emissions can be then summed with any CO_2 emissions and GWP_{100} CO_2-e values from N_2O (or other long-lived gases) to give a total CO_2-we. Annual CO_2-we can then be summed each year in order to report cumulative CO_2-we and estimate overall warming contribution across the period of interest.

As noted above, cumulative CO_2 emissions show a linear relationship with the warming caused. This results in a simple coefficient known as **TCRE** (Transient Climate Response to cumulative C Emissions), which can be multiplied by cumulative CO_2 emissions to obtain an approximate estimate of temperature change due to the CO_2 burden experienced (Matthews et al., 2018). By extension, GWP* and the reported CO_2-we can also be multiplied by the TCRE and give a direct link between emissions and warming, by bringing all gases into a cumulative C framework. According to the latest IPCC report (IPCC, 2021), each Tt of cumulative CO_2 emissions is assessed to likely cause a 0.27 °C to 0.63 °C increase in global surface temperature with a best estimate of 0.45 °C. For this study, we used a TRCE of 0.4 K°/Tt CO_2 (following Lynch et al., 2020) to translate CO_2-we to warming, with the exception of case study one, where an independent climate modelling approach is used to directly model temperatures and confirm this simpler approach. As with the version of GWP* used, we keep a slightly older version for comparability with previous GWP* literature, and our intention is to provide a number of simple applications of the potential use of GWP* metrics rather than show the most exact temperature estimates or the uncertainties associated with the choice of TRCE values.

Case studies used to illustrate Global Warming Potential Star

We present a number of different case-studies highlighting insights that GWP* can provide for different contexts and application in relation to livestock production. For all case studies, we used GWP_{100} values from the fifth Assessment report (IPCC, 2013): CH_4 = 28 and N_2O = 265.

Case study 1. Warming dynamics of CH_4, CO_2 and N_2O, and impacts of foods with similar CO_2-equivalents (100-year Global Warming Potentials) footprints but with different gas compositions

This case-study presents the most idealised example to provide an initial illustration of the key principles explored in this paper. We used the case study by Lynch and Pierrehumbert (2019) where cultured or "lab-grown" meat is compared with beef meat in terms of climate impacts. For this paper, we select two of the footprints (one for beef and one for cultured meat) from the range presented in the original study. For beef, an emissions footprint of 0.9 kg CO_2, 1.2 kg CH_4 and 0.03 kg N_2O (42.45 kg total GWP_{100} CO_2-e) per kg bone-free beef was taken from Cederberg et al. (2009) as a representative Brazilian beef production system. Meanwhile, for cultured meat, Mattick et al. (2015) provided a mid-range estimate of 6.64 kg CO_2, 0.019 kg CH_4, and 0.0013 kg N_2O (7.5 kg total GWP_{100} CO_2-e) per kg cultured meat produced. The key difference here being that beef production is dominated by CH_4 and N_2O, with relatively little CO_2 (with this Brazilian case-study used as it was especially high in CH_4), while the lab-grown meat footprint is expected to be dominated by CO_2 result from energy use (with near-negligible amounts of CH_4 and N_2O from fossil CH_4 losses in the energy system and agricultural production of starch cell-scaffolding material, respectively). Two idealised consumption scenarios from the paper are presented, to show how either type of meat would contribute to global warming. The first shows the climate impacts of very high meat consumption (25 kg per year for a population of 10 billion) sustained at stable rates, with the emissions associated with either type of meat production as in the footprints noted above. The second reveals the impacts of reducing emissions (simply modelled as a decline in consumption) from this high level, after a period of 100 years.

In this paper, we use GWP* to show how reported CO_2-we emissions can capture the warming dynamics of different gases/types of the production system, and we compare them with the results obtained from climate modelling in Lynch and Pierrehumbert (2019). Lynch and Pierrehumbert (2019) ran their model for 1000 years to emphasise the legacies of different emissions, but here, we truncate to 500 years to highlight the key principles.

It should be noted that the individual case-study footprints (a speculative case-study for cultured meat and one of many beef production systems globally) are used to highlight the gas dynamics, and should not be taken as necessarily representative of overall or typical climate impacts of either system. The 500 years to illustrate gas dynamics are not tied to any particular calendar years, and in reality, we should expect increases in production efficiency for either type of food production and decreases in the C footprint per unit of energy (specially relevant to the cultured meat footprint).

Case study 2. Change in temperature contribution from ruminant production systems subject to decreasing production

For this exercise, we used the case study of sheep in Europe (1981–2018) and their corresponding direct GHG emissions. In order to estimate the relative temperature change contribution resulting from direct GHG emissions from sheep in Europe over the period 1981–2018, we first estimated direct annual CH_4 and N_2O emissions from the European sheep for the period 1961–2018 and 1981–2018, respectively. For the application of GWP* methodology on CH_4 for a time series starting from "n" year, we need to include the emission rates from the 20 years prior to the "n" year of additional warming analysis as explained in the GWP* section. The different sources considered were enteric CH_4, manure CH_4, N_2O from manure storage, grazing and manure application to soil and indirect N_2O from NH_3 and NO_x losses from housing, manure storage, grazing and manure application to soil. In order to carry out this study, we used the latest 2019 Refinement to the IPCC guidelines for National GHG inventories (Gavrilova et al., 2019) to derive GHG emissions per animal (emission factor) and, multiplied the calculated emission factor by the number of animals (activity data) from the FAOSTAT database to estimate total GHG emissions. From these CH_4 and N_2O emission data, we estimated the cumulative CO_2-we emissions and multiplied these by the TCRE to estimate additional warming (1981–2018) associated with these emissions, as described in the methods section. We also report the same CH_4 and N_2O pathways as the equivalent CO_2 emissions time series they would be reported as using the GWP_{100}, to contrast. We also show how these CO_2-equivalent emissions cumulatively and the associated warming over time that would be anticipated if they really were CO_2 emissions, to highlight the difference, but note that scaling by the TCRE to estimate temperature change resulting from cumulative equivalent emissions is not a valid use of the GWP_{100}.

Case study 3. Change in temperature contribution from ruminant production systems with increasing emissions

For this exercise, we used the case study of cattle in Brazil (1981–2018) and their corresponding CH_4 emissions. We used the FAOSTAT existing data on global CH_4 emissions from cattle for the period 1961–2018 (enteric fermentation: http://www.fao.org/faostat/en/#data/GE and manure management: http://www.fao.org/faostat/en/#data/GM). As case study 2, we report the cumulative CO_2-we and the resulting additional warming (1981–2018) associated with these emissions, as estimated using the TCRE. Similar to case study 2, we also present the GWP_{100} CO_2-equivalent emissions that would be reported for this CH_4 pathway, noting the same caveat.

Case study 4. Warming dynamics of a CH_4 mitigation strategy in industrialised countries

For this exercise, we used the case study of mitigation of CH_4 from manure storage in the Californian dairy cattle sector. The potential for GHG mitigation through manure anaerobic digestion could be high, especially in warmer regions (Pardo et al., 2017). In these cases, anaerobic digestion can contribute to mitigation targets by avoiding the release of substantial amounts of CH_4 from dairy lagoons, which is enhanced under mild-warm conditions, but also through the production of renewable energy from the biogas collected during digestion and post-digestion stages.

In California, digesters and alternative management methods other than digesters have been funded between 2014 and 2020 through the Dairy Digester Research and Development Program and the Alternative Magure Management Program, respectively.

To demonstrate the potential role of these mitigation programmes, we projected the CH_4 emissions from manure management in California between 2019 and 2030 and explored how these would be reported under GWP*, assuming either: (1) The livestock production practices remain the same as in 2018; or (2) starting from 2020, the annual CH_4 emission from manure management is reduced by 0.088 Mt CH_4 (2.46 Mt CO_2-e) resulting from the installed digesters and Alternative Magure Management Program.

Case study 5. Life cycle greenhouse gas emissions of a CH_4 mitigation measure

For this exercise, we used the case study of introducing feed supplements to reduce emissions from beef production in Australia, and how this might be reported in terms of CO_2-we per kg meat output. In 2018, the Australian beef cattle feedlot sector managed around 400 million head·days of production (number of cattle $\times$ days in feedlot) and based on the current growth trajectory, this is expected to increase to around 476 million head·days in 2030. With this scale of production, beef cattle feedlots are an important intervention point for GHG emissions reduction. While in feedlots, farmers have daily contact with their animals and the level of control over dietary intake is also high. As such, feed supplements that inhibit enteric CH_4 production are a promising option. This prospective case study evaluates the life cycle GHG emissions implications of a CH_4-inhibiting dietary supplement (*Asparagopsis* seaweed) in 2030 (Ridoutt et al., 2022). The seaweed supplement, having a carbon footprint of around 1 kg CO_2 per kg active ingredient (*unpublished data*), is assumed to be provided in daily doses sufficient to achieve an average of 80% reduction in enteric CH_4 emissions. By 2030, these supplements are assumed to be used widely throughout the industry. The modelling was based on methods described in Ridoutt (2021b).

Specifically, a disaggregated time series of GHG emissions was developed from historical data up to 2018. The emissions trajectories of individual gases were then linearly projected to 2030 under scenarios with and without CH_4-inhibiting feed supplement. CO_2-we is then reported for 2018 and 2030.

Case study 6. Differences in global temperature change contribution for different scenarios of future trends in meat production, emissions intensity and gas composition

For this exercise, we used as a baseline scenario the GHG emissions intensity **(EI)** for grassland-based cattle systems for the Sub-Saharan Africa region simulated by GLEAM (for year 2010) (intensityu), its respective meat production for the years 2000–2018 and the projected increase in cattle meat for sub-Saharan Africa until 2050 was interpolated using projections from FAOSTAT for 2030 and 2050. The relative contribution to the whole EI (in CO_2-e) of CH_4 is 66% and meat production from the grassland-based beef system were estimated at 2.5 Mt protein/yr for the year 2010 and increased up to 3.18 Mt protein/yr (2050). The exercise consisted in estimating the additional warming caused by projected meat consumption (2020–2050) under different scenarios of GHG mitigation based on reductions in CO_2-e using metrics of GWP_{100}. The different scenarios would assume three levels of mitigation ambition in terms of reduction of meat's EI (based on GWP_{100}) and were compared with a baseline assuming no change in EI. Scenarios involved: (i) moderate: up to 14% reduction of EI, (ii) ambitious: up to 24% reduction of EI and (iii) very ambitious: up to 36% reduction of EI. For each scenario, three levels of sub-scenarios were tested depending on the type of GHG species that GHG reduction was based on: LLG: based on reduction only of long-lived gases (N_2O and CO_2), all: based on half reduction of EI based on long-lived gases (N_2O and CO_2) and the other half in short-lived gases (CH_4) and SLG: based on reduction only of short-lived gases (CH_4). Additionally, we simulated that the EI reduction would be sustained in the 2020–2050 period or that EI reduction was fast introduced in the first 10 years (2020–2030) and then EI would remain unchanged (2030–2050). In total, 18 scenarios (other than the baseline one) were simulated testing combinations of three levels of mitigation ambitions (moderate: 14%, ambitious: 26%, very ambitious: 36%) × 3 specific GHG-based mitigation focus (only LLG, all GHG, only SLG) and two speeds of mitigation adoption (sustained and fast, followed by unchanged). The main questions of this case study were for the period 2020–2050: how much additional temperature increase would be caused by the different trajectories of GHG from Sub-Saharan grassland-based production beef under different EI reductions (based on GWP_{100}) but differing on GHG species focus of mitigation and speed of introduction of mitigation measures.

Results

Case study 1. Warming dynamics of CH_4, CO_2 and N_2O, and impacts of foods with similar CO_2-equivalents (100-year Global Warming Potentials) footprints but with different gas compositions

Reporting the GWP* cumulative CO_2-we for introducing and then sustaining the Brazilian cattle emissions indicates that there is large initial warming for establishing the new CH_4 source, which dominates the overall warming contribution, but stabilises at a lower rate of temperature increase after a few decades (Fig. 1A). Nitrous oxide and CO_2 exert cumulative effects over the longer-term, but CO_2 emissions here are small enough to be relatively marginal (noting that this system is considered as occurring on already established agricultural land, and so does not represent the C loss from initial deforestation). The dynamic warming contribution of the different gases, and their sum representing total warming, is reflected in the modelled warming (Fig. 1C, data taken directly from Lynch and Pierrehumbert, 2019). For cultured meat's fossil CO_2-dominated footprint, cumulative CO_2-we almost entirely indicates a linear rate of warming due to the ongoing CO_2 emissions (Fig. 1B), as also reflected in the modelled warming (Fig. 1D).

These dynamics, and the scale of the different emissions for these specific footprints, result in the level of warming caused by the beef system being approximately six times greater than that caused by the cultured meat after 100 years (similar to the relative difference in GWP_{100} footprints), but the difference lowers to being about two times after 500 years, for the scenario where high meat consumption is sustained at stable rates across the study period.

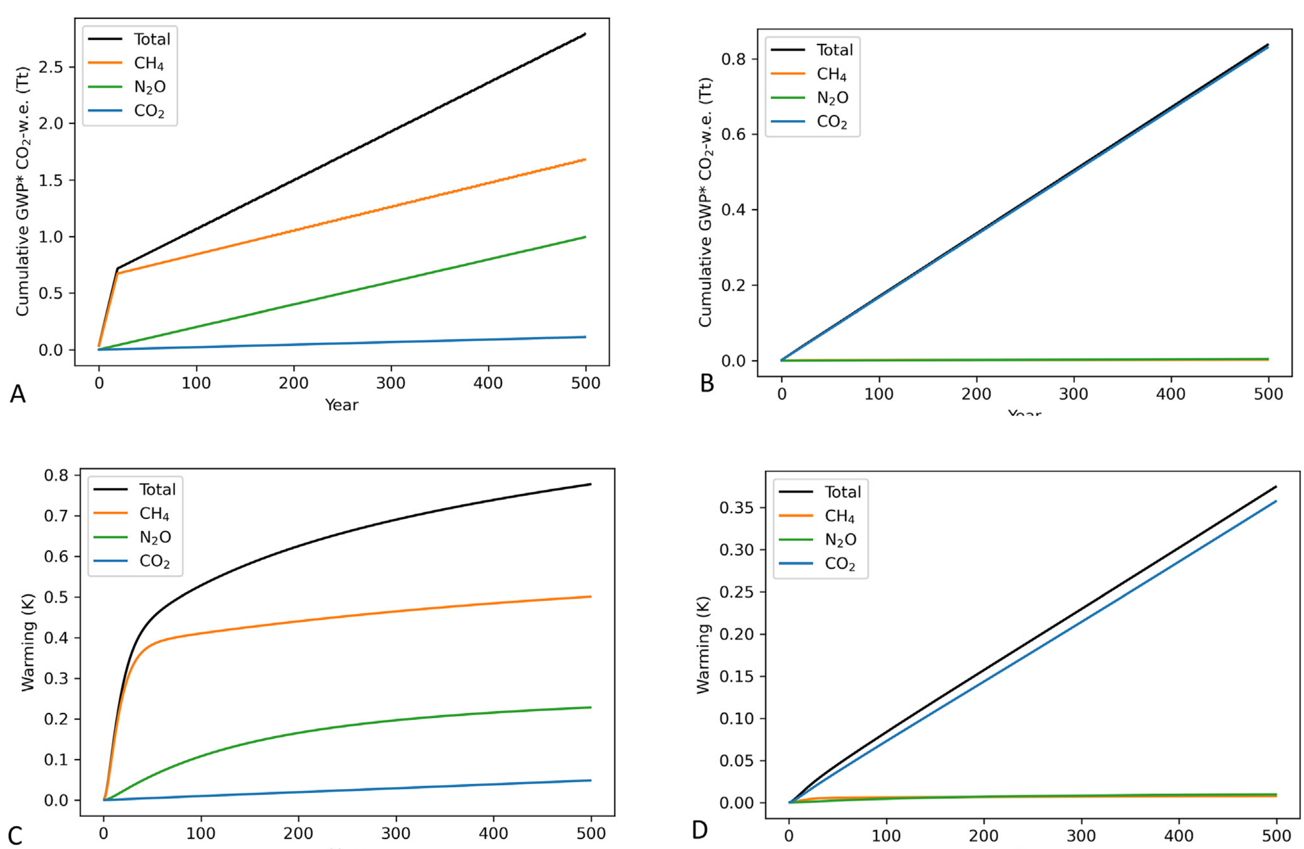

Fig. 1. Cumulative CO_2-we emissions for Brazilian beef (A) and speculative cultured meat (B) production and corresponding contribution to global warming (C and D, for the Brazilian and cultured systems, respectively) for sustained consumption at high rates. For further details on scenario design and climate modelling, see Lynch and Pierrehumbert (2019). Abbreviations: CO_2-we = CO_2-warming equivalents; GWP* = Global Warming Potential Star, Tt = terratonnes.

Thus highlighting a GWP_{100} footprint provides direct insight only into the specific timeframe as defined in the metric, and is scenario-specific: here, the proportional temperature change after 100 years is similar to the proportional difference in GWP_{100} footprints, as over the same time-horizons relative differences in GWP are close to relative temperature impacts of constant emission rates (Azar and Johansson, 2012), but this relationship does not hold for more complicated emission pathways (as illustrated for the scenarios showing a decline in consumption).

To illustrate the warming legacies of different emissions, the same study also presented an illustrative scenario where consumption of either type of meat is initially very high, as in the previous example, but after 100 years starts an exponential decline (with a time-constant of 50 years) towards no consumption.

Here, when CH_4 emissions start to decline, GWP* reports negative CO_2-we (Fig. 2A), so the cumulative CO_2-we reported for our CH_4 emission pathway from the beef system starts to reverse, while for CO_2-dominated cultured meat footprint, we can only stabilise total cumulative emissions at the point reached when we finally remove all ongoing emissions (Fig. 2B). Climate modelling confirms that we do indeed expect to see a reversal of warming when reducing/stopping CH_4 emissions (C), but not for CO_2 (D). Despite the cultured meat production having a much smaller $\mathbf{GWP_{100}}$ CO_2-e footprint, and both footprints following the same scenarios, in the very long term after phasing out either set of emissions, the eventual warming impact is smaller from the beef system.

Case study 2. Change in temperature contribution from ruminant production systems subject to decreasing production

Results show in Fig. 3 the CH_4 and N_2O annual emissions rates (1961–2019) (A) and aggregated CO_2-we and estimated temperature change relative to 1981 (B) associated with reducing direct CH_4 and N_2O emissions rates from European sheep systems (1981–2019). Results are also disaggregated for CH_4 and N_2O. Fig. 4 shows the same emissions as a CO_2-equivalent pathway reported using GWP_{100} annually (A) and cumulatively, alongside estimated temperature change (B) that would result from these emissions.

The GWP_{100} reported CO_2-equivalent emission rates are reduced by about half (from 72.2 Mt CO_2/yr to 34.8 Mt CO_2/yr) for the period 1981–2019 (Fig. 4A), but there is still a considerable increase in the cumulative total emissions, of around 2000 Mt CO_2-equivalent, which would imply considerable associated temperature increase over that period (almost 0.8 mK) (Fig. 4B) if they really were directly equivalent to CO_2 in every respect. Reductions in CH_4 and N_2O annual emission rates from European sheep systems mean that these non-CO_2 emissions end up making a lesser contribution to global temperature increase in 2019 at the start of the assessment period (about −0.8 mK) (Fig. 3B). This was caused by the reduction in CH_4 emission rates: as past emissions are continuously removed, bringing emissions down reduces the absolute warming caused. This dynamic would not be recognised if CH_4 was considered directly analogous to CO_2, where the impact

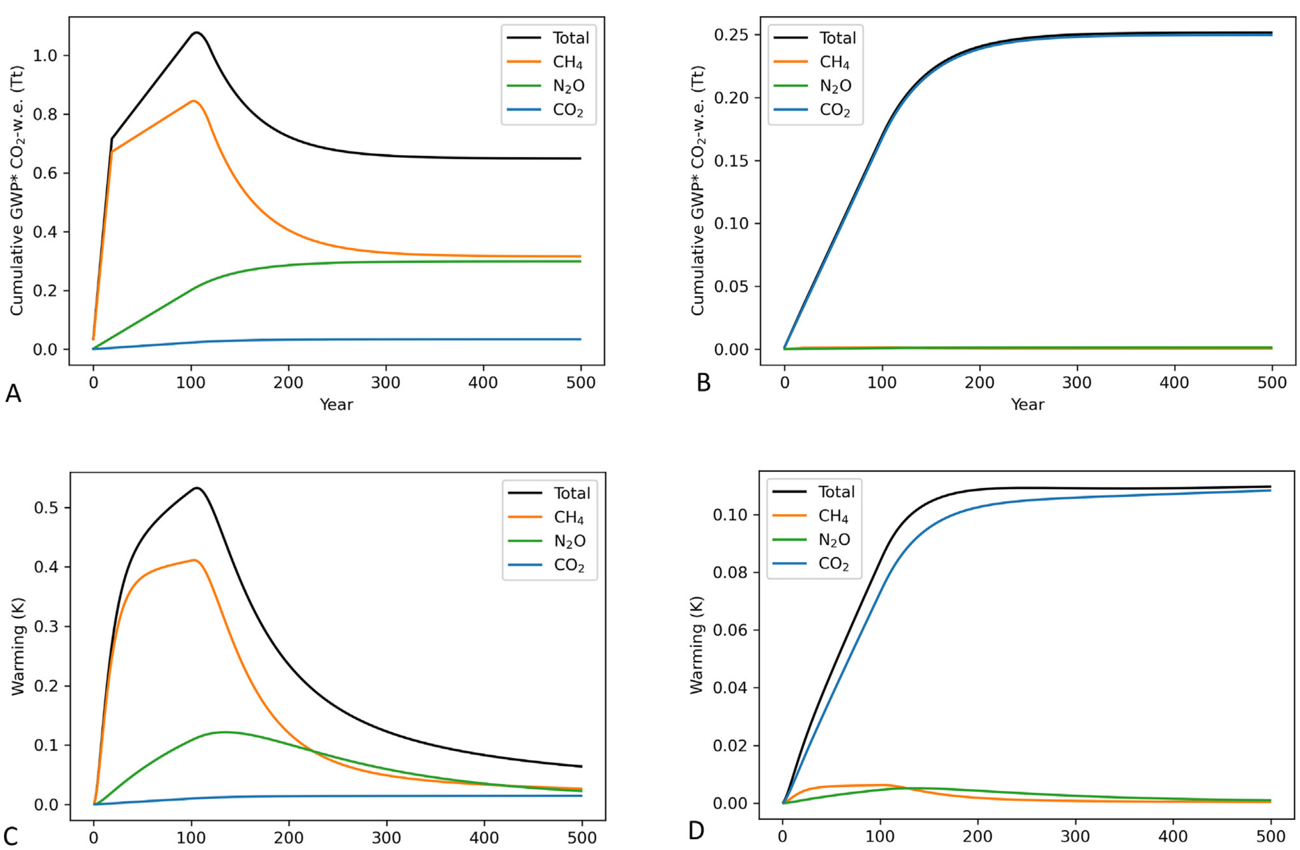

Fig. 2. Cumulative CO_2-we emissions for Brazilian beef (A) and speculative cultured meat (B) production and corresponding contribution to global warming (C and D, for the Brazilian and cultured systems, respectively) for consumption at high rates for the first 100 years, followed by an exponential decline towards no consumption. For further details on scenario design and climate modelling, see Lynch and Pierrehumbert (2019). Abbreviations: CO_2-we = CO_2-warming equivalents; GWP* = Global Warming Potential Star, Tt = terratonnes.

of any emission on global temperature increase is entirely additive, hence the different conclusions that would be drawn from the GWP_{100} reported pathway, as noted above.

Nitrous oxide emissions are also treated as having an additive effect, using GWP_{100} to report CO_2-we emissions, and hence infer relative temperature change, but given the much smaller CO_2-we quantities, the positive warming contribution of N_2O from sheep production were dwarfed by the downward impact of CH_4 on CO_2-we (Fig. 3B).

Case study 3. Change in temperature contribution from ruminant production systems with increasing emissions

Results show in Fig. 5 the CH_4 annual emissions rates (1961–2018) (A) and cumulative CO_2-we and estimated temperature change (B) associated with increasing direct CH_4 emissions rates from Brazilian cattle systems (1981–2018). Fig. 6 shows annual (A) and cumulative emissions, and associated temperature change estimate (B), from the same emissions pathway as would be reported as GWP_{100} CO_2-equivalent emissions.

The GWP_{100} CO_2-equivalent emissions increase from 202 to 348 Mt CO_2-e/yr for the period 1981–2019 (Fig. 6A) and their associated aggregated CO_2 emissions leads to about 10 900 Mt CO_2-e, which would imply considerable associated temperature in that period (about 4.4 mK) (Fig. 6B). In this case-study, however, the GWP* CO_2-warming-equivalents reported from increasing CH_4 rates from Brazilian cattle systems are even greater, with a cumulative total of just over 17,500 Mt CO_2-we (indicating further warming temperature increase since 1981 of about 7 mK) (Fig. 5B). This was caused by the large, rapid increase in CH_4 emission rates.

Case study 4. Warming dynamics of a CH_4 mitigation strategy in industrialised countries

Between 2010 and 2018, about 0.41–0.43 Mt CH_4 was emitted from livestock manure management in California every year (CDFA, 2020), equivalent to 13.8–14.7 Mt CO_2-e (Fig. 7A). For the same period, GWP* results showed a decrease from 26.8 to 22.9 Mt CO_2-we with a peak of 28.1 Mt CO_2-we in 2012 (Fig. 7A). The high CO_2-we emissions were due to the increasing CH_4 emissions from livestock manure, from 0.23 Mt in 1990 to 0.41 Mt in 2008, resulting from the increase in dairy cow population from 1.1 to 1.9 million head during the same period.

Between 2019 and 2030, while GWP_{100} results show a constant net emission of 10.9 Mt CO_2-e every year, annual GWP* results keep decreasing over time and fall below zero in 2022 (Fig. 7A). The negative warming-equivalent indicates that, in near future, the combined effects of the two mitigation programmes will start to reverse the temperature increases that resulted from the CH_4

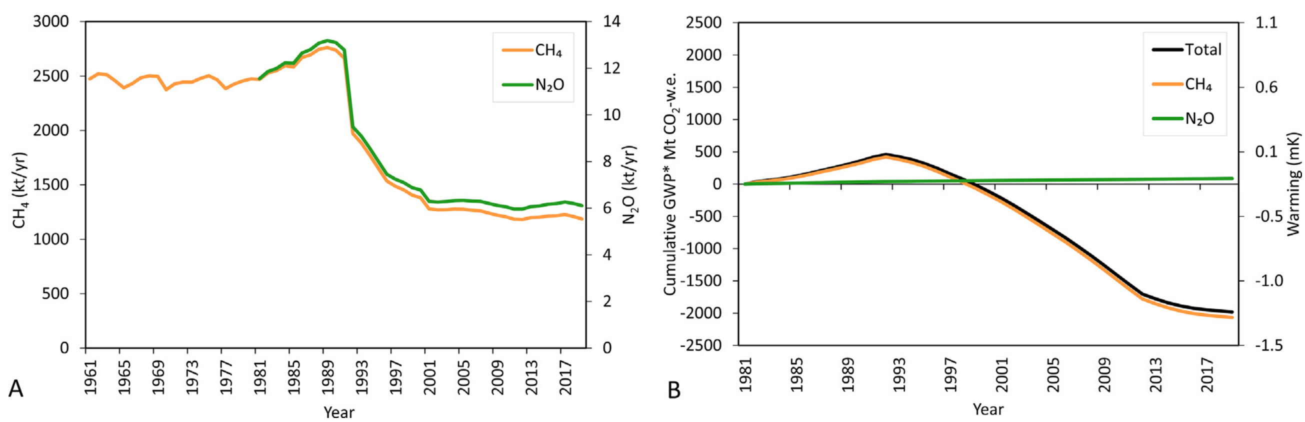

Fig. 3. Annual CH_4 and N_2O emission rates (kt/yr) (A) and corresponding cumulative warming emissions (Mt/yr) and additional warming (as estimated using GWP*) (B) from direct GHG from sheep in Europe for the 1981–2018 period. Orange line: CH_4 results only and grey line: N_2O results only. Black line (only in 3B): CH_4 + N_2O results for CO_2-we and additional warming. Abbreviations: GWP* = Global Warming Potential Star; GHGs = Greenhouse gases; CO_2-we = CO_2-warming equivalents.

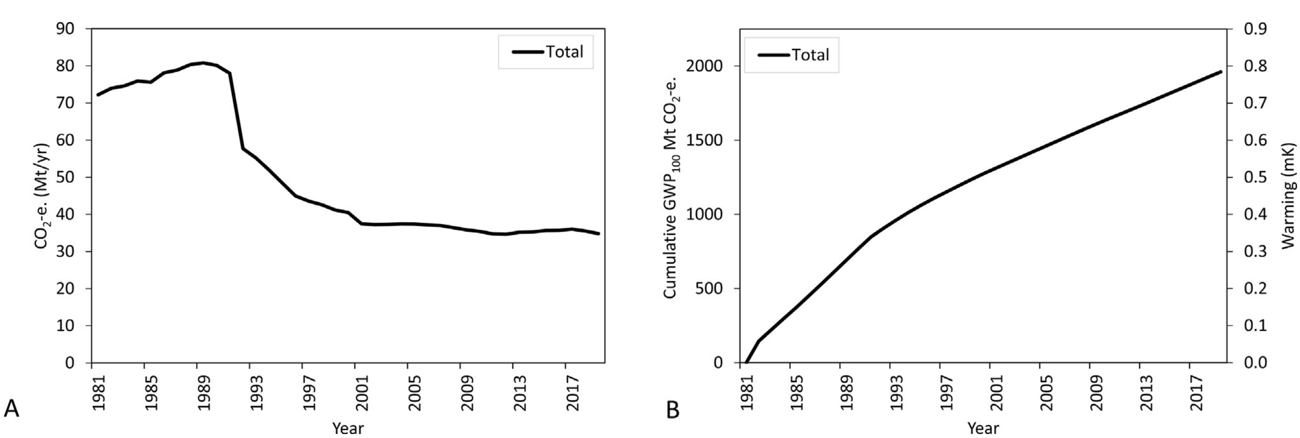

Fig. 4. Annual CO_2-e emission rates (Mt/yr) calculated from CH_4 and N_2O for sheep in Europe for the 1981–2018 period (in Fig. 3) (A) and corresponding cumulative CO_2-e emissions (Mt/yr) and the associated warming over time that would be anticipated if they really were CO_2 emissions (B). Note that scaling by the TCRE to estimate temperature change resulting from CO_2-e GWP_{100}-based as calculated here is not a valid use of the GWP_{100}. Abbreviations: CO_2-e = CO_2-equivalents; GWP_{100} = 100-year Global Warming Potentials; TCRE = Transient Climate Response to cumulative C Emissions.

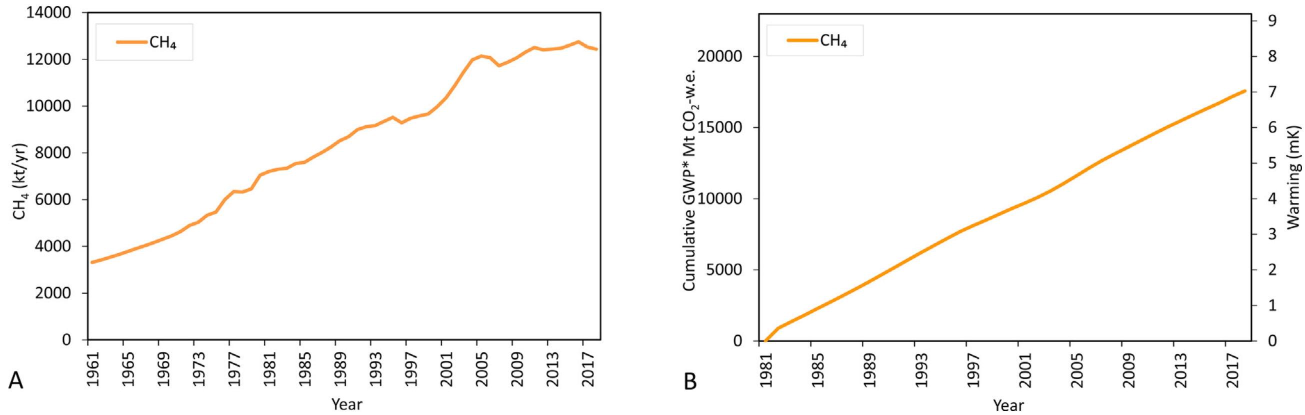

Fig. 5. Annual CH_4 emission rates (kt/yr) (A) and corresponding cumulative warming emissions (Mt/yr) and additional warming (as estimated using GWP*) (B) from CH_4 emissions from Brazilian cattle for the 1981–2018 period. Abbreviations: GWP* = Global Warming Potential Star; CO_2-we = CO_2-warming equivalents.

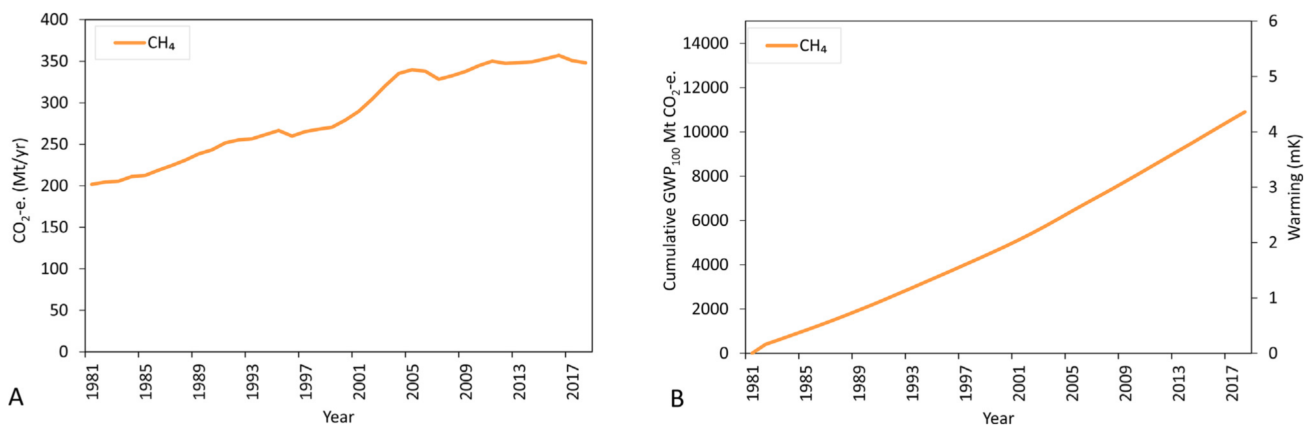

Fig. 6. Annual CO_2-e emission rates (Mt/yr) calculated from CH_4 emissions from Brazilian cattle for the 1981–2018 period (in Fig. 5) (A) and corresponding cumulative CO_2-equivalent emissions and the associated warming over time that would be anticipated if they really were CO_2 emissions (B). Note that scaling by the TCRE to estimate temperature change resulting from CO_2-e GWP_{100}-based as calculated here is not a valid use of the GWP_{100}. Abbreviations: CO_2-e = CO_2-equivalents; GWP_{100} = 100-year Global Warming Potentials; TCRE = Transient Climate Response to cumulative C Emissions.

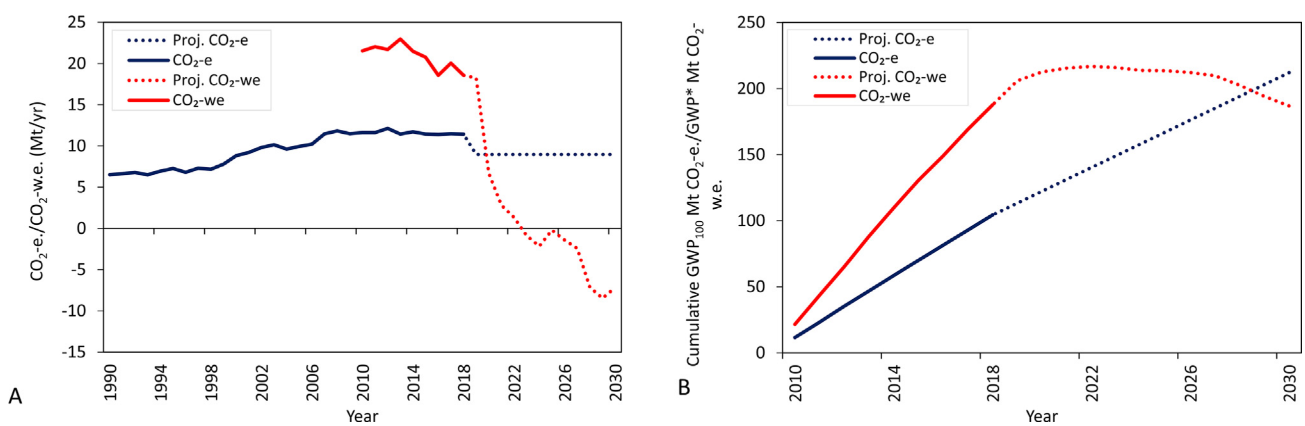

Fig. 7. Climate impacts of CH_4 from manure management in Californian dairy cattle sector (annual (A) vs. Cumulative (B) emissions). Blue and red solid lines represent GWP_{100} and GWP* of CH_4 emissions, respectively; blue and red dashed lines represent the projected GWP and GWP* results, respectively. Abbreviations: CO_2-e = CO_2-equivalents; CO_2-we = CO_2-warming equivalents; Proj = projected emission; GWP = Global Warming Potential; GWP* = Global Warming Potential Star; GWP_{100} = 100-year Global Warming Potentials.

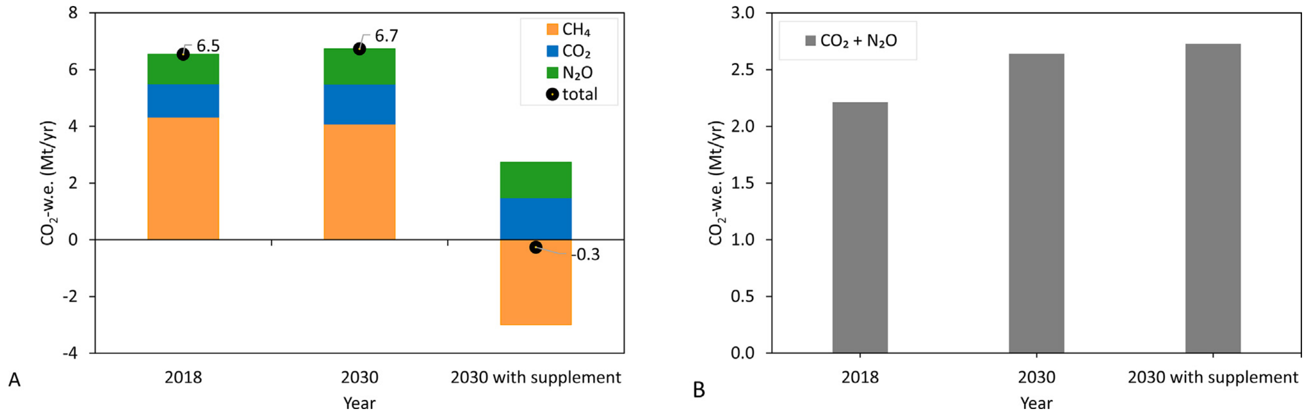

Fig. 8. Potential climate impact of feed supplementation with a CH_4-inhibiting supplement (*Asparagopsis* seaweed) in Australian beef cattle feedlots. A) Climate impact in 2018 compared with projected impact in 2030 with and without supplementation (Mt CO_2-we). B) Climate impact of long-lived climate forcers only (Mt CO_2-we). Abbreviation: CO_2-we = CO_2-warming equivalents.

emissions from livestock manure management in California increasing, and temperatures will decline from this peak.

The cumulative GWP* results increase at a rate twice as fast as GWP between 2010 and 2018. After hitting a plateau in 2019 and holding at elevated levels until 2025, they decreased to 192.3 Mt CO_2-we in 2030. Conversely, the cumulative GWP_{100} results show ongoing increases (Fig. 7B).

Case study 5. Life cycle greenhouse gas emissions of a CH_4 mitigation measure

In 2018, the climate footprint of Australian beef cattle feedlots amounted to a total of around 6.5 Mt CO_2-we when assessed using GWP* (Fig. 8A) – i.e. 2018s Australian feedlot cattle emissions caused additional warming equivalent to releasing 6.5 Mt CO_2. Methane emissions contributed around two-thirds of warming, with smaller contributions from CO_2 and N_2O emissions that arise mainly from feedlot operations and the production of crops used as feedlot rations.

Due to the expected increase in production in future years, the emissions (expressed as CO_2-we) are projected to increase marginally to around 6.7 Mt CO_2-we in 2030 (Fig. 8A). However, the utilisation of CH_4-inhibiting feed supplements has the potential to reduce the climate impact of feedlots dramatically, reaching a negative value of around −0.3 Mt CO_2-we in 2030, based on an assumed 80% efficacy and widespread adoption by this year (Fig. 8A).

That said, the emissions profile in 2030 indicates an increase in long-lived GHG emissions (CO_2 and N_2O) compared to 2018 due to some level of intensification (i.e. implying small reductions in CH_4 at the expense of increasing N_2O and CO_2 emissions intensity) and compared to the base case, without CH_4-inhibiting feed supplements (Fig. 8B). This case study highlights the potential for trade-offs, where CH_4 reductions are attained through interventions that increase emissions of CO_2 and/or N_2O, and there are dangers if longer-term climate implications are not also considered.

Case study 6. Differences in global temperature change contribution for different scenarios of future trends in meat production, emissions intensity and gas composition

The average EI for grassland-based cattle meat in the Sub-Saharan region has been estimated to be 0.56 t CO_2-e/kg protein in meat (GHG share: 66% CH_4, 33% N_2O and 1% CO_2) (Gerber et al., 2013). The evolution of the different GHG sources that comprise the total GHG emissions from grassland-based beef in the Sub-Saharan African region assuming that the IE remains unchanged for the period 2000–2050 is shown in Supplementary Fig. S1 (Baseline). For each scenario involving changes in EI, CH_4, N_2O and CO_2 share to the total EI and speed of introduction of IE reduction, the resulting total and per GHG-type emissions for 2000–2050 period are shown in Supplementary Figs. S2–S7. Reduction in EI at a sustained rate of up to 14, 26 and 36% in 2050 with respect to the baseline are shown in Figs. S2, S3 and S4, respectively. Reductions in EI at a fast rate up to 14, 26 or 36% in 2030 followed by an unchanged EI are shown in Figs. S5, S6 and S7, respectively. Each Figure shows GHG results when emission intensity reduction is caused by reducing only long-lived gases (a), both long-lived and short-lived GHG in equal parts (b) or by only short-lived gases (c). Supplementary Fig. S8 shows the changes in EI (expressed as CO_2-e/kg protein) of grassland-based beef in the Sub-Saharan African region for the three mitigation options (14, 26 and 36%) and speed introduction of mitigation in the period of study (2020–2050).

Temperature change (2020–2050) resulting from the emissions in the baseline and 18 mitigation scenarios is shown in Fig. 9.

The impact of GHG mitigation on reducing the additional temperature caused for the analysed period (2020–2050) is smaller (under the same CO_2-e reduction) when the GHG reduction is based on reductions of LLGs (e.g. N_2O or CO_2) than when it involves CH_4-based reductions (Fig. 9). In fact, if we look at the scenarios under sustained mitigation (Fig. 9A, C, E) and compare mitigation scenarios (orange: moderate, blue: ambitious and green: very ambitious, lines) with the baseline trajectory (red line: no mitigation) on the basis of the additional temperature results, whereas scenarios involving reductions in long-lived GHG only would lead to reductions in additional temperature caused of 9% (moderate), 16% (ambitious), 23% (very ambitious), scenarios involving only reductions in short-lived GHG (i.e. CH_4) led to reductions in additional temperature caused of 29% (moderate), 55% (ambitious) and 79% (very ambitious).

As expected, a faster introduction of a mitigation measure in an emissions trajectory reflected in a lower climate cumulative impact irrespective of whether we use a GWP_{100} or a GWP* climate metric (Fig. 9B, D, F). A faster introduction of the mitigation measure also implied a greater reduction in additional temperature caused for the analysed period (2020–2050) in all cases. Mitigations based on shorter-lived CH_4, under the same CO_2-e-based mitigation resulted in a larger near-term reduction in temperature caused than when the reduction was based on CO_2 or N_2O (long-lived GHG).

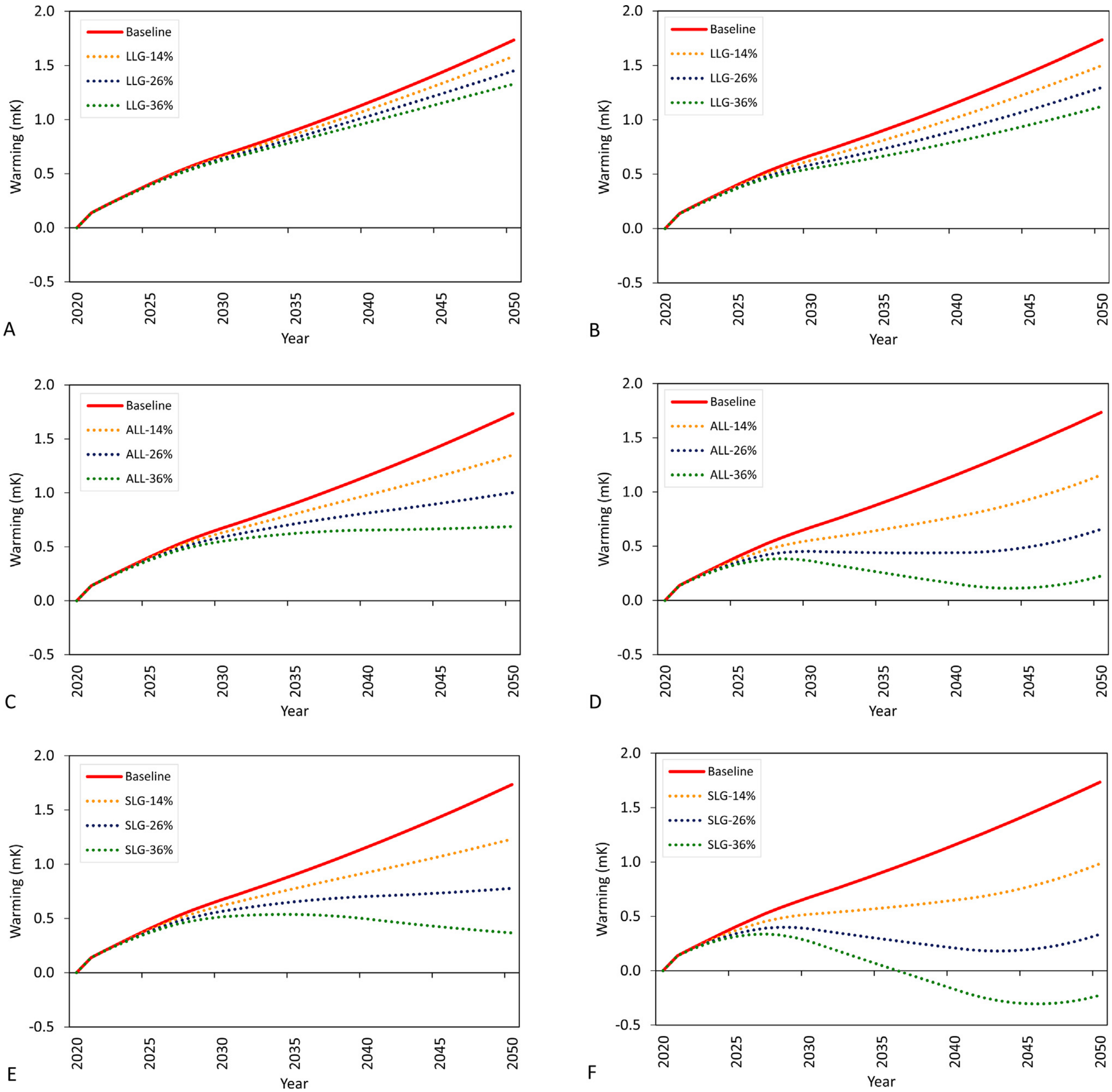

Fig. 9. Temperature change between the 2020–2050 period caused by GHG emissions from grassland-based cattle systems for the Sub-Saharan Africa region as estimated by multiplying meat production and projections by FAOSTAT in the region with GHG emissions intensity (EI) as simulated by Gerber et al. (2013) (solid red line) (baseline scenario). This temperature change from this baseline scenario is compared with mitigation scenarios where, under the same meat production and projections, changes are introduced as three levels of reductions in EI: moderate: 14% (yellow-dotted line), ambitious: 26% (blue-dotted line) and very ambitious: 36% (green-dotted line). The reductions in EI are based on: only long-lived gases (LLG) (A, B), a combination of LLG and short-lived gases (SLG) (C, D) and only SLG (E, F). Additionally, two speeds of mitigation adoption are tested: sustained (A, C, E) and fast introduction followed by unchanged (B, D, F). Abbreviation: GHGs = Greenhouse gases.

Discussion

Warming-equivalent emission metrics (e.g. GWP*) provide an alternative way of assessing and reporting GHG emissions. They are especially relevant to activities like ruminant livestock production where CH_4 makes a major contribution to the total emissions profile. As highlighted in the examples above, the different climate behaviours that result from the distinct dynamics of short- and long-lived gases, and so ultimately what might be missed through metrics such as the GWP_{100} that assume a more 'direct' CO_2-equivalence but captured through a 'warming-equivalent' approach, depend on the emission scenario.

Case study 1 demonstrates that different GHGs show distinct behaviours. Illustrating the principles discussed in the introduction, the different gases, and especially CH_4 and CO_2, have fundamentally different dynamics, and simpler emission metric approaches like GWP_{100} (or aggregated footprints using metrics like this) will lose climatic detail, and cannot provide a reliable way to link different emissions scenarios to temperature outcomes. If CH_4 and CO_2 really were directly equivalent, in all respects but with relative impacts scaled by a single-weighting factor as in the GWP_{100}, we would not see the significant reduction in CH_4-induced warming rate that occurs after the first few decades, reflecting the fact that, by this point, CH_4 emissions start to be balanced by natural removals. Even more strikingly, an understanding of the impacts of the different gases based on the GWP_{100} only would leave us unable to anticipate the markedly different outcomes of reducing emissions of either gas, with CH_4-induced warming rapidly reversed once emissions start to decline but CO_2-induced warming persisting for the very long-term even when emissions have ceased.

Our first case study also shows that GWP*, as a simplifying metric, is also not without limitations as a proxy for warming. Over the longer-term (centuries and longer), our reported CO_2-warming-equivalent emissions start to exaggerate the additional warming resulting from sustained CH_4 and N_2O emissions. For CH_4, this is because the small component intended to capture the long-term, slow-climate response to CH_4 emissions (which effectively acts cumulatively in the GWP* formulation) is eventually fully realised, and so does not contribute additional temperature increases for stable emission rates. For N_2O, CO_2-warming-equivalent emissions are generated by treating it as an entirely cumulative pollutant directly equivalent to CO_2 (hence it is calculated using GWP_{100}), as this captures the relative dynamics for short- to medium-term timescales. With an average atmospheric lifetime of just over 100 years, however, N_2O still does not have the extremely long persistence that a large portion of CO_2 emissions will show, and so on timescales of the order of multiple centuries, N_2O too can be considered as shorter-lived, where fossil CO_2 emissions will still have cumulative effects. Similarly, GWP* implies some long-term CH_4-induced warming is retained indefinitely, but which would be expected to very slowly start to be undone in reality, and also does not reflect that N_2O-induced warming will eventually be reversed over millennial timescales after emissions cease (much faster than for CO_2), as shown in the modelling. Nonetheless, GWP* reveals the key dynamics over commonly investigated timescales of decades to centuries.

These different dynamics have profound implications for understanding how different sectors or activities contribute to global temperature increases, and consequently what must be achieved to meet climate targets.

A goal of climate stabilisation, or indeed any temperature-based goal, would imply different targets for different gases: 'net-zero' emissions are required for no further CO_2-induced warming, but for CH_4, even significant ongoing emissions can be compatible with stable temperatures, as past emissions are continuously removed.

Allen et al. (2022) reviewing the principles behind 'net-zero', suggest a definition of 'climate neutrality' which "denote[s] a situation in which human activities cause no additional increase or decrease of the global average surface temperature over multi-decadal timescales", and that "[i]n the context of multiple GHGs ... climate neutrality corresponds to sustained net-zero CO_2-warming-equivalent emissions." Hence by this definition, a CH_4 emitter might be able to achieve 'climate neutrality': no additional warming (equivalent in relative temperature outcome to a CO_2 emitter reaching net-zero); or even go beyond this, with temperatures dropping below current levels as caused by past emissions (equivalent in relative temperature outcome to a CO_2 emitter reaching net-negative emissions); even with some ongoing CH_4 emissions, and without having to reach GWP_{100}-defined net-zero or net-negative emissions. GWP* can reveal these dynamics in a way that GWP_{100} cannot.

Case study 2 illustrates some of these points. Where CH_4 emissions have been significantly reduced over the period under analysis (e.g. European sheep sector: Del Prado et al., 2021), there is a reversal of warming relative to the start of the assessment period: despite not achieving GWP_{100} CO_2-e 'net-zero', this scenario has net-negative CO_2-we. It is important to note that while this way in which GWP* can achieve 'negative CO_2-we' and highlight a reversal of warming simply by lowering CH_4 emissions is physically consistent with 'CO_2—warming-equivalent' temperature response, it is only possible for having some level of ongoing CH_4 emissions from which to decline.

Case Study 1 reveals how total cumulative emissions (hence temperature increase) are still positive compared to before they started emitting these CH_4 emissions, and reducing CH_4 emissions can only result in 'negative CO_2-we' back down towards this initial level. Similarly, each CH_4 emission results in a warmer climate compared to not having emitted it, even if the relative impact of a long-term emitter may decline by emitting less CH_4 now than they did at an earlier date. Metrics like the GWP_{100}, in fact, provide this type of information (how much climate change could be avoided or vice versa, averaged over the next 100 years, by a given emission compared to that emission not occurring).

GWP* could also be deployed to compare different scenarios of emitting or not emitting GHGs, which would essentially explore impacts relative to a 'reference condition' of no emissions, which would look like the results shown in Case Study 1, where the avoidable impact of these emission pathways from a certain point would be the same as imagining them being introduced at this time. This type of application reflects the type of information provided by the GWP_{100}, but retains a dynamic component in the case of GWP*. For this paper, we have more examples exploring the use of GWP* to estimate relative temperature changes compared to current or recent warming contributions, as in the Case Study 2 onward, which may be interesting in considering 'climate neutrality' in the light of the definition noted above. It is important to note these two approaches (avoidable climate impacts of emitting vs not emitting, and temperature change relative to a pre-existing level) provide fundamentally different information. A challenge in using GWP* is then in a user identifying and/or justifying the appropriate application of CO_2-we to address the question of interest, and how to relate the information to CO_2 emissions or emitters, where, because all emissions act additively, these different decisions relating to reference point will lead to the same result.

The scenario dependence and broader context within which to consider GWP* CO_2-we is particularly notable in the light of Case Study 3, highlighting that where there have been recent increases in CH_4 emissions rates (e.g. Brazilian cattle at 2.4% CH_4 increase/yr in this example) CO_2 emissions estimated using the equivalency of GWP_{100} for CH_4 emissions from Brazilian cattle, would result in much lower warming than the associated additional warming contribution from Brazilian cattle CH_4. The manner in which GWP_{100} undervalues the relative temperature increase from sustained CH_4 emissions for the first century of their emission has been observed elsewhere (Huntingford et al., 2015; Brazzola et al., 2021), and Lynch et al. (2020) note that GWP* provides a greater CH_4 valuation than GWP_{100} over any periods where CH_4 emissions increase by more than around 1% per year. Any periods of increasing emissions are omitted in Case Study 2, however, as they occurred before the period studied. Including the initial increase in CH_4 emissions is not required to infer the European sheep sector's temperature change over this period or into the future, but recognising that these CH_4 emissions do still contribute to elevated global temperatures, and this impact could be lowered by reducing them, is still relevant for questions related to, for example, the overall warming impact of different activities or global distribution of CH_4 emissions. Applying GWP* to investigate contemporary temperature changes should therefore not be used to directly inform targets in a way that unduly penalises new emitters or allows emitters to continue emitting CH_4-based solely on historic precedence (Rogelj and Schleussner, 2019).

Therefore, while every emitter reaching net-zero CO_2-we and climate neutrality would result in stable temperatures, they would be stabilising their own potentially very different contributions to global temperature rise. This is also the case for setting net-zero

CO_2 alone; but Reisinger et al. (2021) argue that different practical and ethical considerations may apply, as while for CO_2, overall contribution to global warming depends on total past emissions, for CH_4, the absolute level of warming primarily reflects current emission rates. Using GWP* to explore how different emitters' contributions to temperature increase relative to current levels could be useful for example, allowing us to sum up the temperature increase from future emission pathways and determining whether they are compatible with any given global temperature target (essentially being able to express how short-lived gases affect the remaining C budget). But it does not necessarily mean that reaching net-zero CO_2-we is itself an appropriate or sufficient target for CH_4 emitters: what an appropriate target might be cannot be resolved by metrics alone.

One consideration for what must be achieved across different GHGs is plausible multi-gas emission reductions that are compatible with global targets. Integrated climate-economic modelling indicates that in pathways to limit global mean surface temperature to 1.5 °C above pre-industrial times, biogenic CH_4 reduces by 24–47% (from unspecified sectors) relative to 2010 (Rogelj et al., 2018). This level of CH_4 reductions would imply that CH_4 would be responsible for less warming in future than in 2010, while CO_2-induced warming will only start to reverse if we achieve net-negative emissions (see Cain et al., 2022 for further details on gas-specific temperature increase in meeting climate targets).

Hence, in order to achieve ambitious global climate targets, significant reductions in CH_4 emissions from livestock are expected. Our case study 4, dairy cattle in California, shows the types of interventions that may help contribute to these emission reductions, and shows what they would mean for relative temperature change from regional emitters. For intensive livestock production systems like this, where animals are kept fully housed all year round, manure CH_4 emissions represent a large share of total CH_4 emitted (e.g. about 40% in dairy cattle in the US: EPA, 2021). One option to mitigate CH_4 intensive livestock systems with manure storages is through implementing anaerobic digestion. By doing so, manure CH_4 is enhanced, but instead of being emitted, the CH_4 is captured and used as a fuel that can replace fossil gasoline or diesel. GWP* can reflect the impacts of these decreased emission sources on additional warming over time; in contrast, using GWP_{100} would not reflect the immediate impacts on temperature caused from decreasing SLCP emissions.

Returning to potential climate stabilisation, our example for intensive beef production in Australian feedlots, Case Study 5, the link between GHG mitigation at the level of the animal enteric fermentation (e.g. *Asparagopsis* seaweed as feed supplement) and its contribution to relative temperature changes over specified periods can also be found. The CO_2-we emissions reported for the individual years provided indicate that, in 2018, the level of temperature increase caused by Australian beef production rose further, but in 2030, the supplement could cause a sufficient reduction in the CH_4-induced temperature increases to offset the further warming from CO_2 and N_2O emissions, resulting in little net temperature change. This would have a climatically equivalent outcome to a CO_2 emitter achieving net-zero emissions through C capture in 2030. As noted above, the sector will still have a substantial, positive CO_2-e emission footprint using GWP_{100} as GWP_{100} is based exclusively on the marginal future impacts of the emissions being reported, so could also be thought of as telling us the abatement potential of not making these emissions or the avoidable contribution to global warming from those unabated emissions (in terms of average radiative forcing over 100 years). GWP* as applied in the example provides a dynamic context for how the relative impact of an emitter changes over the period assessed. Again, the challenge is in choosing which standard to apply in assessing impacts or setting targets for different emitters, because the additive, long-term, impact of each CO_2 emission results in these two perspectives being essentially the same.

This example also highlights that, even if reporting a single result (as in the annual 'footprints' here), GWP* still implies a dynamic perspective, and requires CH_4 emissions in the form of a scenario (even if a simple hypothetical one) covering at least 20 years, rather than an individual emission. This approach is necessary to indicate 'warming-equivalence' between long- and short-lived gases, but users may only want to consider an emission quantity in isolation, or there may be challenges in obtaining or anticipating multi-annual data. In this case, single-weighting emission metrics may still be preferred (see below).

GWP* can be used at the global level to better represent the impact of CH_4 on global temperature (Clark et al., 2020; Costa et al., 2022) and for the design of mitigation strategies (e.g. Pérez-Domínguez et al., 2021), but not in all cases at the product and national levels (Hörtenhuber et al., 2022), which it would depend on what period is covered and how it is used (Lesschen, 2021). The requirement to take a dynamic perspective can also impose challenges in applying GWP* at smaller scales. Global or national assessments may provide relatively stable or moderately shifting herd sizes and/or emissions over time, but individual farms or firms can abruptly grow, shrink, merge, split, or cease operation, such that emissions can change abruptly. Such scenarios may result in large but temporary swings in GWP* reported emissions. It is important to remember here that it is cumulative CO_2-we emissions that provide a direct link to temperature, with Allen et al. (2018) highlighting that average Global emission rates across multiple years could be used to correspond to a single CO_2-we quantity, and so noisy scenarios or dramatic results for individual years should be viewed in this perspective.

Finally, building on the previous examples, Case Study 6 highlights how GWP* can be a useful tool to analyse the climate impact of different prospective emission scenarios depending on reductions of emissions intensities (expressed as kg CO_2-e/kg meat) that vary in the speed of adoption and target GHG (SLCPs vs LLCPs). In some scenarios from case study 6 for Sub-Saharan African beef grassland-based systems, animal dietary interventions (e.g. improving quality and digestibility of swards), for example, that can be highly successful in reducing CH_4 emissions (realistically it can reach over 30%, as estimated by Goopy, 2019), would result in much greater immediate impact on lowering global temperature changes. On the other hand, mitigation measures that would reduce the emission intensity for the Sub-Saharan African beef grassland-based systems at the same CO_2-e, but based on long-lived GHG reductions (e.g. incorporating compost and biochar: Smith et al., 2014 or agroforestry practices: Corbeels et al., 2019) would be less effective at lowering the global temperature in the near-term. Additionally, the faster the mitigation measures are introduced, the lower temperature levels are caused.

We reiterate that it is still better for the climate for us not emit any GHGs, of any lifetime, where they can be avoided without significant trade-offs, so the animal research community should continue their valuable efforts to understand the emissions associated with livestock production and try to reduce them. As a broad aim, this can be done at a per gas level without the complications of trying to infer 'CO_2-equivalence'. Researchers should be reminded that, regardless of what emission metrics are used, it is crucial of all to provide original, disaggregated data on individual gases, so that information is not lost (Lynch, 2019). Users may still want to report outcomes using a shorthand weighting or aggregation measure, however, and without the need to consider or contextualise scenarios as required for GWP*. In this case, the GWP_{100} can still be used, and it still provides valid climatic information (as outlined in the introduction, a CO_2-relative index of the total energy added to climate system for the 100 years following an emission, compared to not making the emission). Here, however, we highlight guidance from the UNEP-SETAC Life Cycle Initiative recommending that, due to the sensitivity of conventional emission metrics to time-horizon, alongside using GWP_{100} to report shorter-term climate impacts, the 100-year Global Temperature change Potential is included to represent longer-term impacts, and GWP_{20} can be used in sensitivity analysis of very short-term impacts (Jolliet et al., 2018). If one does want to link emissions to higher level outcomes, such as sectoral contributions to global temperature increase, however, these require more than simply a relative weighting of individual emissions, for the reasons discussed above.

The distinctions in gas dynamics have important implications for what strict requirements we might set for different sectors, and how we interpret terms like 'net-zero', 'climate neutrality', or even 'sustainability'. We highlight to the animal research community that reporting emissions using GWP_{100} does not provide transparency in what any overall or sector-specific temperature outcomes of a given emission pathway will be, and net-zero GWP_{100} as an overall or sectoral target will not result in the same temperature outcomes for emitters of different gases.

As shown here, GWP* and CO_2-warming-equivalents can provide a straightforward but quite physically robust tool to investigate questions over warming contribution over time from livestock systems relative to the warming at a reference point caused by prior emissions up to that point. We suggest that the broader implication is that the emergence of warming-equivalent emission metrics calls for a more critical assessment of aggregated GHG emissions information (Duffy et al., 2022). Despite this, GWP* is still a simplifying tool that misses some elements revealed in more complex climate modelling approaches, and we should remember that for some uses, climate modelling remains a superior option (and, indeed, for many applications, particularly in the research sphere, we may not need any simplifying emission metrics at all). Beyond just the use of GWP* itself, it may prove valuable as a reminder to policy-makers, researchers, and individual consumers that there may be more to consider than simply an assessment of relative GWP_{100} emission intensity or pursuit of 'net-zero' GWP_{100} emissions.

Supplementary material

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Ethics approval

Not applicable.

Data and model availability statement

Data or models were not deposited in an official repository. The data/models that support the study findings are available from the authors upon request.

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Declaration of interest

None.

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