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LETTER

Climate metrics and the carbon footprint of livestock products: where's the beef?

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Abstract

The livestock sector is estimated to account for 15% of global greenhouse gas (GHG) emissions, 80% of which originate from ruminant animal systems due to high emissions of methane (CH_4) from enteric fermentation and manure management. However, recent analyses have argued that the carbon footprint (CF) of ruminant meat and dairy products are substantially reduced if one adopts alternative metrics for comparing emissions of GHGs—e.g., the 100 year global temperature change potential (GTP_{100}), instead of the commonly used 100 year global warming potential (GWP_{100})—due to a lower valuation of CH_4 emissions. This raises the question of which metric to use. Ideally, the choice of metric should be related to a climate policy goal. Here, we argue that basing current GHG metrics solely on temperature impact 100 years into the future is inconsistent with the current global climate goal of limiting warming to 2 °C, a limit that is likely to be reached well within 100 years. A reasonable GTP value for CH_4, accounting for current projections for when 2 °C warming will be reached, is about 18, leading to a current CF of 19 kg CO_2-eq. per kilo beef (carcass weight, average European system), 20% lower than if evaluated using GWP_{100}. Further, we show that an application of the GTP metric consistent with a 2 °C climate limit leads to the valuation of CH_4 increasing rapidly over time as the temperature ceiling is approached. This means that the CF for beef would rise by around 2.5% per year in the coming decades, surpassing the GWP based footprint in only ten years. Consequently, the impact on the livestock sector of substituting GTPs for GWPs would be modest in the near term, but could potentially be very large in the future due to a much higher (>50%) and rapidly appreciating CF.

1. Introduction

The global food system is a significant contributor to greenhouse gas (GHG) emissions, a large part of which stems from animal husbandry [1]. However, due to the large share of non-CO_2 GHGs in the emissions from livestock production, the choice of GHG metric used to compare emissions of different GHGs is crucial, both for assessing the aggregate contribution of the livestock sector to climate change and for highlighting hot-spots in the animal food chain where emission reductions are most cost-effective.

The most commonly used metric for comparing GHGs in life cycle assessment (LCA) and carbon footprint (CF) studies is the 100 year global warming potential (GWP_{100}), but other metrics are increasingly discussed in the literature, most importantly the global temperature change potential (GTP). Given that the GWP_{100} value for methane of is 28 and the corresponding GTP on a 100 year time horizon (GTP_{100}) is 4 [2], adopting GTP_{100} substantially lowers the carbon-equivalent emissions associated with livestock production and may in some circumstances also alter mitigation priorities. For instance, comparing emissions of different GHGs using GTP_{100} values reduces the contribution of the livestock sector to global GHG emissions, as estimated in the recent publication by the Food and Agricultural Organization of the United Nations [3], by close to a third, from 14.5% to 10%,. A number of recent publications have also highlighted the importance of the choice of GHG metric when assessing CFs of livestock products, primarily ruminant meat [e.g., 4–6].

Different GHG metrics have different properties and aims, and comparisons of the consequences for CFs of using different metrics have to be made in a context where the purpose the metric is supposed to serve is made explicit. Unfortunately, recent analyses of the impacts of metric choice on livestock systems have not put the choice of metric in this broader climate policy context, which means that important points are missed and that readers (and possibly policy makers) may end up with an impression that the choice of metric is arbitrary.

The purpose of this paper is to (1) discuss the rationale for using different metrics in different policy contexts, (2) demonstrate the difference in short and long term consequences of applying GWP or GTP metrics in CF accounting of animal products, and (3) discuss policy implications of the choice between GWPs and GTPs for the role of the livestock sector in climate mitigation.

The reason for focusing on the difference between using GWPs and GTPs—apart from the fact that the GTP is the principal alternative to the GWP being discussed [2]—is that they are conceptually consistent with two possible, but different, interpretations of the current international climate policy goal of limiting temperature change to 2 °C above pre-industrial levels. GWPs, based on cumulative impacts, reflect the contribution of emissions to climate change damages, in line with a cost-benefit approach to climate policy, whereas GTPs are conceptually consistent with a cost-effectiveness approach to climate policy where aggregate mitigation costs for staying below 2 °C warming is minimized [7]. In line with the latter, we argue that if GTPs are used they should be time-dynamic, reflecting the time left until we reach a given temperature stabilization limit. For GWP on the other hand, the time horizon is static, reflecting value judgments over how to weigh near-and long-term climate impacts, akin to the use of a discount rate. Here we adopt a 100 year time horizon since that is what is used within the current climate policy regime.

Adopting time-dynamic GTPs has two important implications. First, given the range of projections for when we will reach (or breach) the 2 °C limit, the current CF of beef evaluated using dynamic GTPs should be substantially higher than the GTP_{100} used in recent analyses of the CF of livestock products. Second, with time dynamic GTPs, the CF of beef will increase rapidly over time as the temperature limit draws nearer, likely exceeding that calculated using GWP_{100} already within the next 15 years and ultimately becoming 2.7 times larger. Consequently, the choice of metric can have large implications for the future impact of climate policy on the livestock sector.

2. Background—GHG metrics

To have a meaningful discussion about the implications of different choices of GHG metrics, it is useful to clarify the fundamental purpose of metrics. Metrics are needed to compare emissions of different GHGs on a common scale, typically CO_2-equivalent (CO_2-eq.) emissions. Having a common scale is necessary when determining an overall emission reduction target for a set of gases (often referred to as a *single-basket approach*, adopted for instance in the Kyoto Protocol) or when estimating the total climate impact in an LCA or CF study. However, because different GHGs have divergent atmospheric lifetimes the climate impacts resulting from emissions of different gases will exhibit disparate temporal dynamics (see figure 1). Therefore, there is no metric that will ensure equivalence across all relevant climate impacts [8, 9], and different metrics will assign different values to each gas relative to CO_2 depending on metric formulation and parameter choices (this effect is particularly pronounced for gases that exhibit a much shorter lifetime than CO_2, such as CH_4).

In other words, a given GHG metric ensures that the impacts from equal amounts of emissions (expressed in CO_2-eq.) of different gases are identical with respect to a certain indicator (say, temperature increase in a certain year) but typically not to others (say, contribution to sea level rise or overall climate damage). Thus, the choice of metric is based on underlying value judgements about the main priority for climate mitigation and consequently how climate policy goals should be formulated.

As an example, consider once again the two most commonly used metrics: GWPs and GTPs. The GWP of a GHG is defined as the time-integrated radiative forcing of an emission pulse of the gas, divided by the corresponding time-integrated radiative forcing of an emission pulse of CO_2 of equal mass. According to the IPCC's most recent assessment report (AR5), the GWP_{100} for CH_4 is 28 [2]. Equal amounts of CO_2 and CH_4 emissions, as measured in GWP_{100}-equivalents, will ensure equal integrated radiative forcing after 100 years (though not for shorter or longer time horizons). However, the temperature change after 100 years will be nearly seven times higher for the emission pulse of CO_2 than the emission pulse of CH_4. Thus, the GWP may be a good proxy for cumulative, or integrated, temperature change (as radiative forcing measures the energy input to the atmosphere-ocean system [10]) but it says little about an emission's contribution to global average surface temperature change at a future point in time.

Equating future temperature change is instead the rationale of the GTP of a GHG, defined as the temperature impact at a future point in time due to an emission pulse of the gas, divided by the corresponding temperature change from an emission pulse of CO_2 of equal mass. According to the IPCC AR5, the

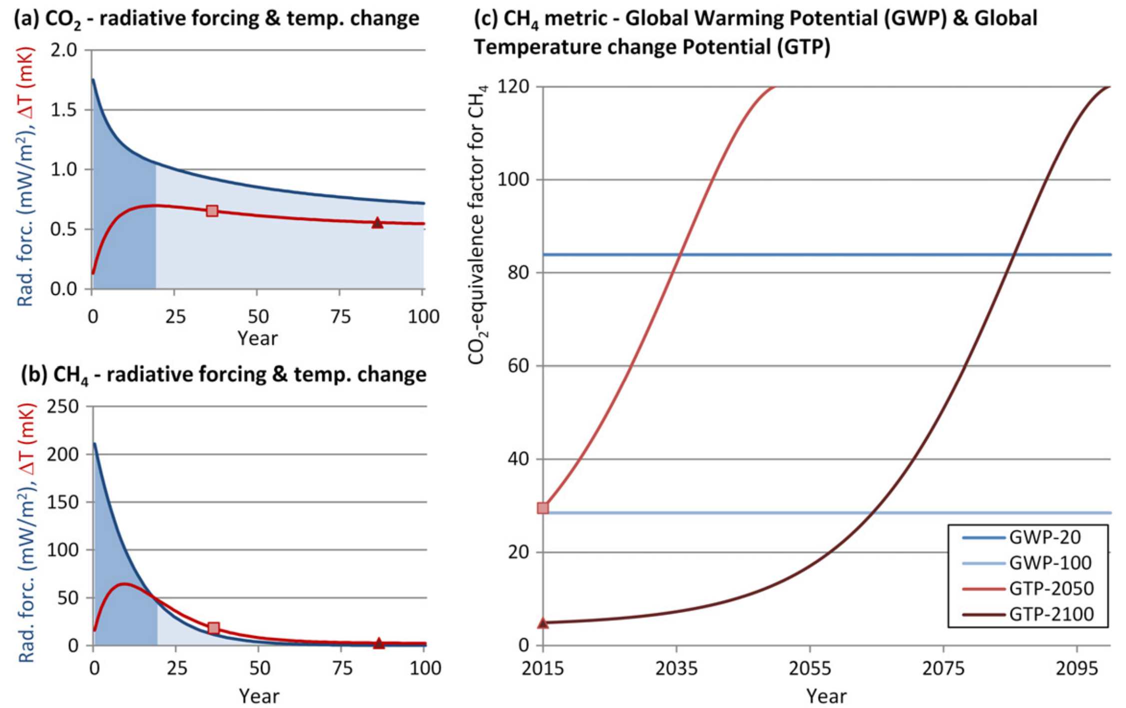

Figure 1. Panels (a) and (b) show the radiative forcing (blue line) and surface temperature change (red line) resulting from pulse emissions of one million tonnes of carbon dioxide (CO_2) and methane (CH_4), respectively. The global warming potential (GWP) for CH_4 compares the integrated radiative forcing over a given time period—e.g., 20 years (dark shading) or 100 years (light shading)—to that of CO_2, while the global temperature change potential (GTP) compares the surface temperature response at a given time. Panel (c) displays the evolution of the GTP value for CH_4 for two different cases, where the temperature limit is met in either in 2050 or in 2100. The GTP value in 2015 consequently reflects absolute the temperature impact (AGTP) for each gas 36 years into the future (square markers in panels (a) and (b)) or 86 years into the future (triangle markers in panels (a) and (b)). Note that there are uncertainties around exact metric values due to uncertainties in input parameters regarding, inter alia, atmospheric lifetimes, radiative efficiencies, indirect effects, and climate sensitivity.

GTP_{100} for CH_4 is 4.2 (Myhre *et al* 2013). Hence, equal amounts of CO_2 and CH_4 emissions, measured in GTP_{100}-equivalents, will ensure equal temperature impact after 100 years (though not before, nor after, that point in time), but the level of integrated forcing (and temperature change) will be almost seven times larger for the emission pulse of CH_4 compared to that of CO_2.

Figure 1 illustrates the GWP and GTP metrics graphically. The calculations of metric values presented here and used in later sections follows the same set of assumptions regarding radiative efficiency, atmospheric lifetimes and indirect effects of CH_4 and N_2O, and the impulse response functions for atmospheric CO_2, as those used for calculating GWP and GTP values in IPCC AR5 [2]. We use a two-box model of temperature response to radiative forcing that is calibrated to the IPCC impulse-response function [10, 11] in order to be able to alter the climate sensitivity when calculating GTPs. Details, as well as the full calculations, are available in the supporting material to this paper, available at stacks.iop.org/ERL/10/034005/mmedia.

Note that there are considerable uncertainties regarding the exact metric values due to uncertainties in input parameters regarding atmospheric lifetimes, radiative efficiencies, indirect effects and temperature responses (climate sensitivity and inertia), as well as due to the treatment of climate carbon cycle feedbacks for non-CO_2 GHGs (not considered in this study) and the assumption of a constant background atmosphere[1]. Uncertainties are larger for short-lived than for long-lived GHGs, with an estimated uncertainty in the GWP_{100} and GTP_{100} for CH_4 of ±30% and ±75%, respectively (excluding uncertainty due to carbon-cycle feedbacks, which can raise the CH_4 GTP_{100} by as much as 160%) [2].

The discussion on the GWP and GTP metrics above serves to illustrate the point that there is no best metric. Rather, choosing a metric requires determining, *inter alia*, (1) which impact to evaluate (i.e., which point along the effect chain from radiative forcing and temperature change to climate change impacts and damages), (2) whether to assess impacts at a given point in time or time-integrated impacts, and (3) which time-horizon to consider (and whether discounting should be used) [2, 14]. Many of these choices are normative and cannot be determined solely by scientific arguments. One way to resolve this has been to argue that the choice of metric should be guided by

[1] Under climate stabilization scenarios GWP and GTP values for CH_4 and N_2O are expected to change only slightly (<10%) in the coming decades due to changes in background concentrations [12, 13].

the policy or goal it is intended to serve [9, 15, 16]. Indeed, one of the strongest criticisms against the GWP metric is its lack of connection to any specific climate goal [9, 12]. Notably, the GWP was introduced in the IPCC first assessment report as a potential metric candidate, serving 'to illustrate the difficulties inherent in the (metrics) concept' [8].

It has been shown that the use of GWPs is inconsistent with a target of cost-effectively staying below a pre-defined temperature limit (e.g., 2 °C) [7]. But if the 2 °C limit is viewed as an imperfect proxy for an overarching climate target of reducing the aggregate damages from climate change—a possible interpretation the United Nations Framework Convention on Climate Change (UNFCCC) objective to 'prevent dangerous anthropogenic interference with the climate system' —then basing the GHG metric on aggregate contributions to radiative forcing can be consistent with that goal [7] (though the arbitrary time horizon employed in GWP calculations is still problematic).

While the GTP is more aligned with a climate goal that sets a limit for future warming, it can be criticized for focusing solely on temperature change at one point in time, completely disregarding climate impacts occurring prior to or after this date. Further, we want to stress here that if the rationale for using GTPs is to reflect how the current international climate goal is formulated, we should not use GTPs with a constant time horizon (e.g., 100 years). Instead, the GTP value chosen should pertain to the point in time at which we expect to hit the temperature ceiling [17], otherwise the metric would not serve the purpose of guiding policy towards that goal. Suppose that the world approaches a 1.9° temperature increase in 2060. If GTP_{100} were used at that time, very little mitigation focus would be put on strong and short-lived gases such as methane (since the GTP_{100} would focus on the temperature impact in 2160), increasing the risk that the world would not keep global temperature change below 2 °C. Consequently, analyses have also shown that using GTPs with a fixed time-horizon can substantially increase the aggregate costs of staying below a climate forcing or temperature limit [4, 18].

Thus, GWPs and GTPs are consistent with two possible, but different, ways of framing the current climate policy goal of limiting warming to 2 °C. Time-dynamic GTPs are consistent with a cost-effectiveness approach [7], leading to a metric for short-lived GHGs (such as CH_4) that increases over time, as the climate limit draws nearer and the short-term temperature response becomes more imperative (see figure 1). The temporal dynamics of the GTP evaluated against a fixed point in time have similarities to that of other proposed metrics such as price ratios (or global cost potentials) that calculate the cost-effective ratio between prices on emissions of different gases under a given temperature stabilization target [e.g., 7, 15, 19], or the similar, but purely physically-based, cost-effective temperature potential metric [20] (under a set of rather restrictive assumptions these three metrics are identical [7, 20]). The GWP, on the other hand, can be seen as a special case of a metric based on the integrated and discounted economic damages due to a GHG emission pulse, representing a cost-benefit approach to climate policy [7]. It is similar to other metrics proposed, such as the integrated GTP or the sustained GTP [21].

3. The choice of GHG metric and the CF of livestock products

What are the implications of the above discussion for the use of metrics in assessing the climate impact and mitigation potential in the livestock sector? Here, we want to highlight three aspects of this question: first, what is a reasonable GTP value to use today (i.e., over which time horizon should we evaluate the GTP) given the current understanding of when we may approach a given climate limit; second, how does the choice of metric affect current and future CFs of livestock products; third, what are the implications of this for the impact climate policy might have on the livestock sector.

3.1. Uncertainty-adjusted GTPs

The recent analyses of the impact of metric choice for the CF of beef and dairy systems [5, 6] have contrasted the GWP_{100} and GTP_{100}. Because GHG emissions from these systems are dominated by CH_4, lowering the metric value for this gas from 25 (the GWP_{100} value used in these studies) to 4 (GTP_{100}) has a large impact on the CF. However, if the reason for adopting GTPs is to cost-effectively guide mitigation towards the current UNFCCC climate target, it is reasonable to evaluate the GTP for the year when that target is likely to be met. Recent analyses show that temperature change is likely to reach the 2 °C limit somewhere between 2050 and 2100 for emission scenarios leading to a temperature stabilization [22, 23].

The main reasons for the wide range in estimates of when warming may hit the 2 °C limit stem from uncertainties concerning the emission pathway, carbon cycle, climate sensitivity, and ocean heat uptake (which affects the transient climate response) [23–25]. A higher climate sensitivity likely implies that 2 °C warming will happen sooner, leading to a higher current GTP value for CH_4 if the choice of metric is to be guided by the climate policy goal of keeping the temperature increase below 2 °C [17]. In addition, the higher climate sensitivity in itself raises the GTP for CH_4 (see figure S1).

Considering the uncertainty in climate sensitivity and the time at which the climate limit may be reached, a reasonable range for the CH_4 GTP value today (2015) is from 2.6 (corresponding to a case where the 2 °C limit is hit in 2100 and where the climate sensitivity is 1.5 K for a CO_2 doubling) to 32.8

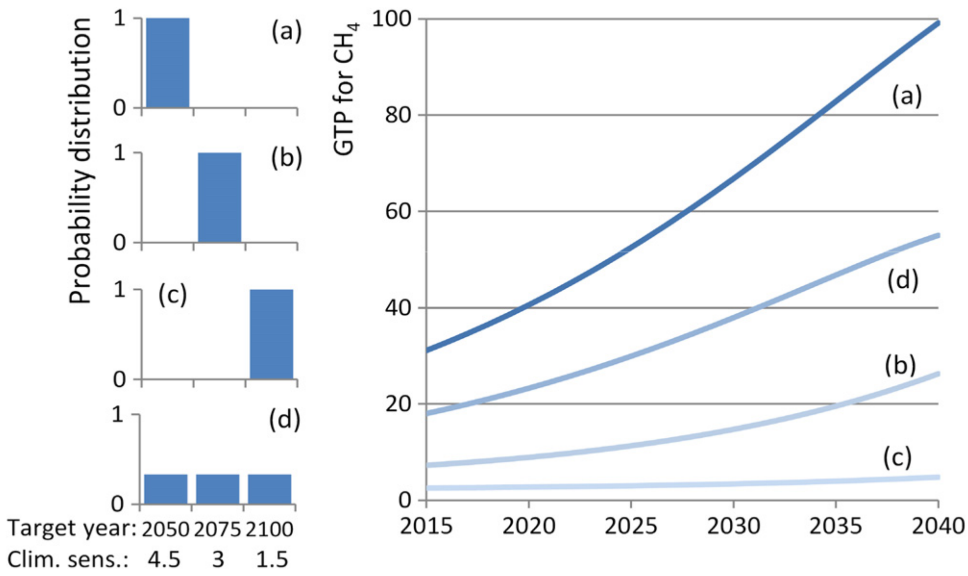

Figure 2. Global temperature change potential (GTP) for methane (CH_4) in the period 2015–2040 under different assumptions regarding the year the future temperature change is evaluated (a)–(d), left panels; representing the range of projections for when a 2 °C climate limit will be reached), as well as corresponding climate sensitivities (4.5, 3, and 1.5 K for a CO_2 doubling, respectively). The main point is that the GTP for a uniform probability distribution ((d); equal probability that the target is reached in in 2050, 2075 and 2100) is higher than the GTP for the expected limit year ((b); 2075).

(corresponding to a case where the 2 °C limit is hit in 2050 and where the climate sensitivity is 4.5 K). The GTP for CH_4 evaluated using the expected target year and climate sensitivity (2075, 3 K) is 7.5.

In order to cost-effectively stay within a temperature limit in a situation when there is uncertainty around the year when the limit becomes binding, the relative valuation of short-lived climate forcers like CH_4 should be higher than if simply determined by the expected year of hitting the limit [18, 26]. The reason for this is that the absolute future temperature change (AGTP) for a CH_4 emission pulse is more sensitive to assumed time horizon than is the AGTP of CO_2 (see figure 1, panels (a) and (b)). How much higher the uncertainty-adjusted GTP will be compared to a GTP based on the expected target year depends on the exact probability distribution for when the limit will be hit. For instance, if we assume that it is equally likely that the 2 °C limit will be reached in 2050, 2075 and 2100 (aligned with assumptions that the climate sensitivity is either 4.5, 3 and 1.5 K for a CO_2 doubling, respectively), the uncertainty-adjusted GTP value for CH_4 in 2015[2] is 18.0, 2.4 times higher than the expected GTP value (figure 2).

3.2. Metric choice and the CF for livestock products

Recently, guidelines for CF accounting have been developed and CFs for meat, milk and eggs from different production systems and regions are now well reported in the scientific literature [e.g., 3, 27, 28]. There is a large difference between, on the one hand, beef and, on the other, pork and poultry, in terms of the life cycle emissions, with reported CF numbers for 1 kg cattle meat typically being five to ten times higher than for 1 kg meat from monogastrics [e.g., 3, 27, 28]. The main reason for the difference is low feed-efficiency in ruminant animal systems [29] and the emissions of methane emanating from ruminants´ enteric fermentation.

Figure 3 shows the estimated CFs for beef and chicken based on average European production systems [28], estimated using the metrics discussed here. Using the GWP_{100}, the CF of beef is 23.5 kg CO_2-eq. per kg carcass weight (kg CW) while that of chicken is much lower, 4.6 kg CO_2-eq./kg CW. The current beef footprint evaluated using the GTP is in the range 11.4–25.1 kg CO_2-eq./kg CW, depending on which year (2050 or 2100) the GTP is evaluated against and the associated climate sensitivity (4.5 and 1.5 K, respectively). The corresponding range for the current chicken footprint is much smaller (4.3–4.8 kg CO_2-eq./kg CW), due to the fact that CH_4 emissions are close to zero in the poultry system (whereas for beef, they constitute over half of the CF). The beef footprint calculated using the uncertainty-adjusted GTPs is 18.9 kg CO_2-eq./kg CW, which is more than four times higher than the corresponding chicken CF, but only about 20% lower compared to the footprint calculated using the GWP_{100}.

As is also seen in figure 3, the proximity to the climate limit has a large impact on the CF for beef, which rises rapidly over time, while the CF for chicken remains rather constant. The reason for the latter is that while the GTP for N_2O changes over time, from a

[2] This value results from taking the average temperature response in 2050, 2075 and 2100 from a pulse emission of CH_4 in 2015 and dividing by the corresponding average for a pulse emission of CO_2.

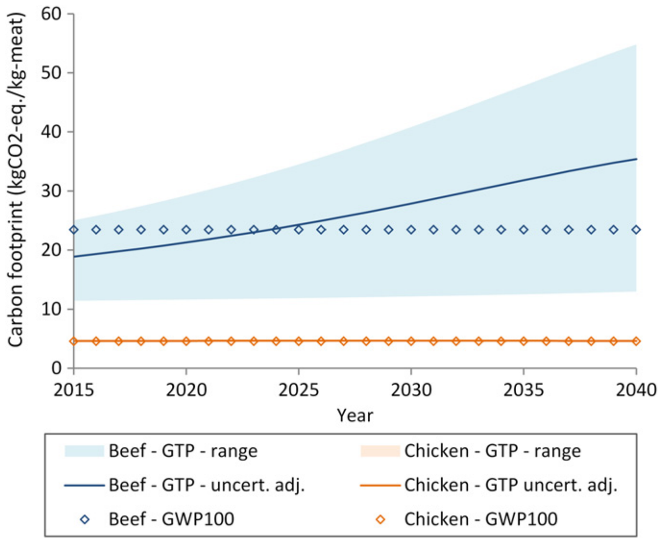

Figure 3. The evolution of the carbon footprint (CF) of beef and chicken (based on current average European production systems) over the period 2015–2040 if evaluated using the global temperature change potential (GTP) or the global warming potential (GWP). The shaded range around the beef GTP–CF reflects the point in time at which the temperature impact is assessed, with the higher values corresponding to year 2050 and the lower to year 2100. The solid line corresponds to a GTP metric that accounts for this uncertainty. Because of the low share of methane emissions (the gas primarily affected by the year temperature impact is assessed) in chicken systems, the range is so small that it is not visible.

low of 245 to a high of 286, N_2O emissions constitute only half of the chicken footprint implying that the corresponding change in the CF is less than 5% (or 0.2 kg CO-eq./kg CW).

For beef, the CF evaluated using the uncertainty-adjusted GTP increases by on average 2.5% per year between 2015 and 2040, more than doubling by mid-century. This rapid increase is due to the nonlinear relationship between the CH_4 GTP and the proximity to the limit year (see figure 1), which in turn is explained by the short atmospheric lifetime for CH_4. By 2040 the uncertainty-adjusted GTP for CH_4 is 46.7. Note, though, that as we move towards 2040 we should gain knowledge about when the temperature limit will be reached, implying that the growth rate in the GTP and its value in 2040 can be both higher (if the limit is reached earlier than expected) and lower (if the limit will be reached later than expected) than the uncertainty-adjusted numbers presented here. If in 2050 we find that 2 °C warming likely lies another 50 years into the future, the GTP for CH_4 would be 13.8 and the corresponding CF for beef 17 kg CO_2-eq./kg CW; if on the other hand the temperature limit is imminent, the CH_4 GTP would be 120 resulting in a CF for beef of 63 kg CO_2-eq./kg CW.

3.3. The choice of GHG metric and implications for mitigation in the livestock sector

Recent studies have shown that by mid-century, under business-as-usual scenarios livestock emissions alone may exceed the total emission space available if we are to stay below 2 °C warming with high certainty [30, 31]. Taking steps to reduce these emissions would have to involve (1) improved feed-efficiency, especially in developing regions [29, 31], (2) introducing novel technical mitigation options, such as feed additives to reduce methane emissions [32] or altered manure management systems [33], measures that currently are at the research stage, and (3) dietary shifts to reduce beef and dairy consumption [30, 31]. Presently, however, there are few climate policies in place to incentivize these changes, implying that irrespective if one continues using GWPs or adopts GTPs there is a need for policy instruments targeting GHG mitigation in the livestock sector.

The choice between GWPs and GTPs that are dynamic and consistent with the 2 °C limit can, however, have large implications for the pressure climate policy would exert on the livestock sector in the mid- to long-term. As shown in figure 3, adopting uncertainty-adjusted GTPs aligned with the 2 °C limit would imply a larger climate footprint for beef than using current GWPs in just ten years' time. If GHG emissions from agriculture in the future are priced at the same level as those from the energy sector—whether directly through emissions taxes or inclusion in cap-and-trade systems, or indirectly through input or output taxes [34] or command and control instruments—the price for beef can be expected to rise sharply over time, especially since the technical mitigation potential for non-CO_2 emissions in beef systems is limited [35, 36].

In addition to the CF increasing over time, under climate stabilization scenarios carbon prices should increase over time, ideally at a rate corresponding to the discount (or interest) rate which typically is around 5% per year (see, e.g., the carbon prices for stabilization scenarios in IPCC AR5 [24, figure 6.21]).

With the CF for beef increasing by 2.5% per year due to the use of dynamic GTPs, the carbon cost of beef could increase by 7–8% per year in the decades leading up to 2040. In 2040 the global carbon prices needed for 2 °C stabilization is in the order of 100 USD/tCO_2 [24], implying a GHG emission cost for beef of 3.5 USD/kg CW (i.e., in the same order of magnitude as present world market beef prices, 4USD/kg [37]). As the CH_4 GTP increases further, more than doubling to reach 120 at the point of stabilization (see figure 1) and carbon prices continue to rise, this cost is set to multiply. This rapid appreciation could have large implications for livestock commodity prices and farmer livelihoods and raises questions about 'the real-world feasibility of implementing time-dependent GTPs in a globally consistent way across all sectors and regions' [4]. That metric choices can have large economic impacts that vary not only across sectors and regions [38], but also across time, needs to be kept in mind when deciding on which metric to use today.

4. Conclusions

The recent literature on GHG metrics has argued for the need to re-examine GHG metrics, a key point being to better align the choice of metric with agreed upon climate policy goals [9, 14, 16]. Such a reconsideration of GHG metrics should be conducted in a multi-disciplinary setting and engage policy makers, given that metric choices ultimately depend on value judgements. The aim of the analysis here has been to elucidate the link between climate policy goals and the application of different GHG metrics in the evaluation of the contribution to climate change from livestock products. Our first key conclusion is that while adopting a GTP approach may seem more consistent with the current international climate goal, expressed as limiting global warming to 2 °C, choosing a time horizon for the GTP of 100 years is incongruent with this limit. A reasonable interpretation of the GTP metric in light of the 2 °C limit gives a current valuation of CH_4 of 18 and a CF of beef that is only 20% lower than if evaluated using GWP_{100}.

However, while substituting GTPs for GWPs has a modest impact on the CF of beef in the near term, the rapid appreciation of the GTP for CH_4 over time implies that the beef CF can be expected to be 50% higher already by 2040 and ultimately, at the point of stabilization, 2.7 times larger. Consequently, and this is our second key conclusion, the choice of metric between GWP and GTP is more important for the future role of the livestock sector in GHG mitigation, than for its current role.

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