# Climate impact of beef: an analysis considering multiple time scales and production methods without use of global warming potentials



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PAPER

# Climate impact of beef: an analysis considering multiple time scales and production methods without use of global warming potentials

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## Abstract

An analysis of the climate impact of various forms of beef production is carried out, with a particular eye to the comparison between systems relying primarily on grasses grown in pasture ('grass-fed' or 'pastured' beef) and systems involving substantial use of manufactured feed requiring significant external inputs in the form of synthetic fertilizer and mechanized agriculture ('feedlot' beef). The climate impact is evaluated without employing metrics such as $CO_2$e or global warming potentials. The analysis evaluates the impact at all time scales out to 1000 years. It is concluded that certain forms of pastured beef production have substantially lower climate impact than feedlot systems. However, pastured systems that require significant synthetic fertilization, inputs from supplemental feed, or deforestation to create pasture, have substantially greater climate impact at all time scales than the feedlot and dairy-associated systems analyzed. Even the best pastured system analyzed has enough climate impact to justify efforts to limit future growth of beef production, which in any event would be necessary if climate and other ecological concerns were met by a transition to primarily pasture-based systems. Alternate mitigation options are discussed, but barring unforseen technological breakthroughs worldwide consumption at current North American per capita rates appears incompatible with a 2 °C warming target.

## 1. Introduction

Environmental impacts of agriculture have become widely appreciated in recent years [1–6], substantiating and augmenting pioneering earlier work (e.g., [7, 8]). Among other things, agriculture is the source of 15%–25% of U.S. and global greenhouse gas (GHG) emissions as measured by 100-year global warming potentials [9, 10], and is a key contributor to biodiversity losses [11, 12]. A substantial body of literature (e.g. [1, 5, 6, 13–18] highlights the disproportionate representation of livestock in general and beef in particular in incurring these large environmental costs [19–22]. Barring major cultural changes, or policy actions designed to discourage meat consumption, it is likely that beef consumption will rise in the future, as a result of growing population and the increase in per capita consumption typically associated with rising affluence [23, 24].

Beef production strategies vary widely. Of the many factors involved, key is the cattle diet employed, in particular the relative roles of grazing and industrially produced feed. Dedicated beef cattle production, in which calves of both genders subsist nearly exclusively on grazing through weaning (for most around 8–10 months) vary primarily by calves' post-weaning (i.e., 'finishing') life history. The key divergence is continued reliance on grazing on the one hand, versus the transition to a fully served diet in large-sale concentrated animal feeding operations (CAFO's) typically handling many thousands of animals at any given time. Importantly, characteristic daily weight gains in CAFO's are 2–3 times those achieved on grass. Dairy associated systems, in which beef production proceeds from culling dairy herds or making use of excess (primarily male) calves, can be carried out on a similar spectrum of dietary options. A key attraction of grass finishing is the conversion of phytomass largely indigestable by humans into human food, and thus the potential to augment human diets relying on marginal land—land unlikely to produce human food more efficiently [22]. (Competition with biofuel production complicates this argument [25, 26].)

From a biological perspective, grass is clearly the diet for which cattle evolved. Grass-fed beef may have superior nutritional qualities [27, 28], and because grass feeding involves less CAFO time and more time on the range, pre-slaughter animal welfare is improved. Well managed pasture can reduce runoff of water and polluting solutes [20], and may also preserve or even promote biodiversity and other ecological benefits [29]. (But see [30] or [31] for results that challange these expectations.) Set against these attractions are a number of disadvantages, including increased land use per beef unit, increased deforestation pressure [32], and possible pasture degradation.

This letter focuses on the climate effects of various beef production systems, choosing characteristic cases that epitomize the above feeding strategies. We do not address the issue of the amount of beef, if any, that is nutritionally necessary or desirable in the human diet.

As for all agricultural production, the climate effect of beef is mediated chiefly by production of the greenhouse gases $CO_2$,$CH_4$ and $N_2O$. $CO_2$ is produced as a result of the various energy inputs in farming, including energy and fossil fuel feedstocks required to produce nitrate and ammonium fertilizers. Ruminant production, including beef, is a potent source of $CH_4$, because of the enteric fermentation involved in digesting cellulose, lignin and related substances. Agricultural soils are a source of $N_2O$ as a byproduct of N transformation processes (nitrification and denitrification), and in fertilizer production $N_2O$ is formed when ammonia is oxidized into nitric acid in the course of producing nitrate. In addition to the $N_2O$ emission involved in producing cattle feed (whether grass or grain), meat production produces additional $N_2O$ from decomposition of manure, which is also a source of additional $CH_4$. Grass-fed systems invariably produce more $CH_4$ per unit of beef produced, because of the greater amount of complex carbohydrates fermented in the rumen, and because the cattle take longer to reach slaughter weight. In principle, this disadvantage can be offset by reduced $CO_2$ and $N_2O$ emission occasioned by reduced on-farm energy usage, reduced use of synthetic fertilizers, and better manure management. However, we will see that this offset is not realized in all grass-fed systems.

Well-managed pasture may act as an enhanced sink of atmospheric $CO_2$ [33]. However, essentially all of the carbon which plants take up from the atmosphere is initially stored in above-ground plant matter and near-surface root systems subject to rapid recycling into atmospheric $CO_2$. Only a small part of soil carbon is transformed into pools that remain sequestered on the millennial time scale, and even these are subject to releasing $CO_2$ if they are disturbed. The rate at which short term plant carbon is converted to the long term pool, and the way this rate may be affected through increasing grassland biological productivity, is unknown, and current models do not even represent the processes needed to properly address this problem [34]. With the present state of knowledge, it would be premature to count on carbon sequestration as a climate benefit of pastured beef production, and therefore we do not factor this potential into our analysis.

A grand-challenge of all assessments of agricultural climate impacts, is the necessity of characterizing the climate impacts of a mix of gases that differ greatly in their atmospheric lifetimes and per-molecule climate forcing. At concentrations near present values, $CO_2$ has a relatively low climate forcing per molecule, while $CH_4$ is larger and $N_2O$ is larger still. However, $CH_4$ has a short atmospheric lifetime, decaying into climatically insignificant amounts of $CO_2$ on a time scale of only 12 years. $N_2O$ has a longer lifetime of 114 years, but even that pales by comparison with the duration of the significant climate effect of $CO_2$ which extends into millennia [35]. Also if future work were to establish that well-managed pasture can sequester significant amounts of carbon in pools with a millennial lifetime, then similar timescale issues are engaged, insofar as the sequestration in pastureland would trade sequestration of a very long-lived greenhouse gas ($CO_2$) against increased production of a very short-lived one ($CH_4$).

The conventional metric used in an attempt to characterize the aggregate effect of a basket of greenhouse gas emissions is equivalent $CO_2$ based on weighting by 100-year global warming potentials (called $CO_2e - 100$ in this paper). However, a growing body of work has demonstrated that $CO_2e - 100$ provides a very incomplete and often misleading picture of the climate impact of a mix of emitted gases [36]. Emissions having identical $CO_2e - 100$ can have quite different consequences for future climate [36], primarily because the climate impact of $CO_2$ is sensitive to cumulative emissions wheras that of short-lived gases is not. This issue is particularly pressing in comparing the climate impacts of various modes of beef production, which often trade higher $CH_4$ emissions against lower emissions of $CO_2$ and $N_2O$, but given that $CO_2e - 100$ from beef production tends to be dominated by $CH_4$ —the shortest-lived gas in the mix—shortcomings of the $CO_2e - 100$ metric distort the comparison of the climate impacts of all modes of beef production with the impacts of fossil-fuel burning, which are dominated by $CO_2$ emissions.

The need to go beyond $CO_2e - 100$ and to consider impacts at multiple time scales has already been recognized in some analyses of beef production [37]. However, the problem cannot adequately be addressed simply through choice of metric, since all metrics that aggregate effects of gases with disparate lifetimes have serious shortcomings of one sort or another [36]. These shortcomings become particularly severe if one wishes to understand the impact of dietary choices on

**Table 1.** Emissions of the three principal greenhouse gases by various beef production strategies. Emissions of $CO_2$ are given as kg of carbon (C) per kg of bone free beef produced, whereas the emissions of $CH_4$ and $N_2O$ are given as kg of gas per kg of bone free beef. The table also gives the kg of $CO_2$-equivalent based on 100 year global warming potentials of 25 for $CH_4$ and 298 for $N_2O$. Data for the 'pastured midwest' and 'feedlot midwest' cases are based on the analysis of midwest US production in [20], broken down into contributions from the three gases based on supplementary information provided by the author of the study (N Pelletier, pers. comm.). Terminology follows that of [20], but significant portions of the production lifecycle are carried out outside the midwest, and the 'pastured' strategy involves considerable use of cattle feed. The 'pastured Brazil' case is based on data for Brazilian beef production in [39] and includes emissions from transport to European markets. It does not include emissions due to any deforestation that may have occurred in the process of creating pasture. Data for 'ranch system, Sweden' is from the analysis of a pastured production system given in [40], and data for 'Sweden average beef' is from the analysis of predominantly dairy-associated Swedish production given in [41].

| | $CO_2 - C$ | $CH_4$ | $N_2O$ | $CO_2e - 100$ |
|---|---|---|---|---|
| Feedlot midwest | 1.4 | 0.6 | 0.05 | 35 |
| Pastured midwest | 1.8 | 0.8 | 0.06 | 45 |
| Pastured Brazil | 0.3 | 1.2 | 0.03 | 40 |
| Ranch system Sweden | 0.3 | 0.8 | 0.02 | 27 |
| Sweden average beef | 1.0 | 0.7 | 0.02 | 28 |

millennial time scales. Given the growing interest in the way societal choices will affect the character of the Anthropocene [38], and given that if our species is going to be around for the next several millennia we will be eating something, there is a necessity to consider the way dietary choices will affect the long term evolution of climate.

In this letter we adopt the approach of [36], and eschew all forms of greenhouse gas metrics in favor of actual calculations of the warming caused by emissions of the mix of greenhouse gases, using a simple energy balance and carbon cycle model. In this approach, the relative contributions of the various gases can be identified for any given time, which can help point the way toward mitigation strategies. The framework introduced here also simplifies the task of characterizing the climate impact from $CO_2$ released when pasture is produced by deforestation; the cumulative-carbon accounting we employ eliminates the need for arbitrary choice of amortization periods for such emissions.

## 2. Description of the calculation

### 2.1. Emission intensity estimates

The principal greenhouse gases emitted as a result of beef production are $CO_2$, $CH_4$ and $N_2O$. Different modes of production differ in the amounts and proportions of emission of these gases. Emissions for a few representative cases are summarized in table 1, based on comprehensive life-cycle analyses which account for emissions associated with all inputs to the production system. The *feedlot midwest* case represents an end-member example of a crop-intensive production method with high inputs from synthetic fertilizers and mechanized agriculture, while the *pastured Brazil* case is probably the closest realized example to a purely grass-fed operation with little input of synthetic fertilizers or use of mechanization. Comparison of these two cases confirms the expectation that grass-fed systems produce lower $CO_2$ and $N_2O$ emissions at the expense of higher $CH_4$ emissions. The complexity of the subject is revealed, however, by comparison with the *pastured midwest* case, which surprisingly has higher emissions than the *feedlot midwest* case for all three of the greenhouse gases. Although this system produces beef that would generally be characterized to the consumer as 'grass fed' or 'pasture raised,' it in fact still involves a considerable amount of feed production, and of synthetic fertilizers applied to pasture.

The *ranch system Sweden* case shows, however, that other forms of pasture-finished beef production can achieve better results, comparable to the Brazilian system with regard to $CO_2$, and superior to it with regard to $CH_4$ and $N_2O$. Data for this case come from a detailed study of an individual organically certified ranch in Southern Sweden. Land use is very extensive relative to the number of animals grazed. No pesticides or synthetic fertilizers are applied, but some externally sourced pig manure is applied for growing winter silage. Very efficient animal management allows the cows to give birth to approximately one calf per year and permits a relatively low slaughter age; this accounts for much of the reduction in $CH_4$ emissions relative to the *pastured Brazil* case.

The *Sweden average beef* case, which is based on a top-down lifecycle analysis of the entire Swedish beef industry, exemplifies yet another general approach to beef production. Like most Western European beef production, the average Swedish production is closely associated with dairy production; 60% of Swedish beef comes from culling of dairy herds and their surplus calves. This is the chief distinction from the two midwest systems discussed above, which are aimed at producing beef alone. The *Sweden average beef* case achieves much lower $CO_2$ and $N_2O$ emissions than either midwest case, with $CH_4$ emissions only slightly in excess of the *feedlot midwest* case. The $CO_2$ emissions are nonetheless considerably in excess of those for the highly optimized *ranch system Sweden* case.

The 'Brazil pastured' case represents an estimate of the emission profile of a truly pastured operation under the hypothetical circumstance that the pasture is managed so as to allow sustained production without degradation of pastureland, and that none of the pasture was created by deforestation. Neither of these hypotheticals apply to actual Brazilian beef production. Increased beef production in Brazil has in fact led to considerable deforestation, and the resulting carbon release has been substantial [32]. Deforestation in Brazil results in 161 tonnes C released per hectare cleared [32], and given that one hectare of pasture produces 40–60 kg carcass weight of beef annually [32], production of beef at a rate of 1 kg of bone-free-beef per year incurs a net carbon release of 3.8–5.7 tonnes C. The usual way to fold this release into life-cycle studies is to turn it into an annual emissions rate by positing an amortization period, but in section 4 we will show how it can be more naturally accounted for using the cumulative carbon framework.

### 2.2. Consumption trajectories

We consider two families of consumption trajectories. The first is designed to illustrate some basic points about the way the relative warming from the three greenhouse gases evolves over time. It consists of constant beef consumption by a population of 10 billion people at a per capita rate of 25 kg annually (roughly the current rate of US beef consumption), followed by an exponential decay of consumption with a time constant of 50 years, beginning either at year 100, year 200, or never.

The second family represents a business as usual (BAU) storyline which starts at the present consumption rate $C_0$, and then grows over a certain period of time to a peak $C_m$ corresponding to a population of 10 billion consuming at a per capita rate of 25 kg per year, in such a way that the growth rate falls smoothly to zero at the time of the peak. The assumptions yield $C_m/C_0 = 6.17$. Two alternatives are considered after the peak. In the first, the consumption rate is held fixed at $C_m$ indefinitely—the *BAU+stabilized* scenario. In the second alternative, beef consumption is gradually ramped down to a global rate $C_\infty$ corresponding to 75% of current consumption, and thereafter held constant. We call this the *BAU+sustainable* scenario, insofar as it represents an optimistic future in which there is by one means or another eventually a transition to a more sustainable level of beef consumption. $C_\infty$ in this case is taken from an estimate of how much beef could be produced worldwide using only pasture-based methods [22]. The equations for the BAU family are given in the supplementary data.

The peak consumption rates assumed in the BAU family are not necessarily realizable, as it is far from certain that so much beef could be produced annually by any means, and it is virtually certain that such production rates could not be attained by pastured methods. Rather, it gives a picture of what would happen if current North American dietary preferences (which are by no means the highest with regard to per capita beef consumption) were emulated worldwide and constraints on resources did not come into play. The projection is also not far from what would happen if current trends continued for a century. The projected rate of growth of bovine meat consumption out to 2050 is 1.2% per year [42], which would yield $C_m/C_0 = 3.3$ if extended out to 100 years.A modest increase to 1.83% per year, which could arise from a high-end population growth scenario or greater than expected growth in wealth, would bring the value up to that assumed in the BAU family. We do not claim this is a particularly realistic future. Something will very likely intervene to prevent that future from occurring, and the question is only what limitation (or onset of wisdom) will be encountered first.

### 2.3. Modeling of climate impact

The first step in calculating the climate impact of greenhouse gas emissions is to turn the emission trajectory $E(t)$ of each gas into a radiative forcing trajectory $\Delta F(t)$. $E(t)$ is the rate of emission of the gas, in units such as gigatonnes (Gt) of gas per year; in the case of $CO_2$ it is common to use gigatonnes of carbon in the gas (GtC) per year. The radiative forcing $\Delta F(t)$ is a measure of the amount by which the inventory of gas remaining in the atmosphere affects the Earth's radiation budget, and is conventionally measured in Watts per square meter of the Earth's surface (W $m^{-2}$). The radiative forcing at time $t$ depends on the emission rate $E(t)$ over past times up to $t$.

For $CO_2$ emissions, $\Delta F$ is computed using the radiative forcing impulse response function introduced in [36], which simultaneously takes into account ocean uptake and the logarithmic dependence of $CO_2$ radiative forcing on $CO_2$ concentration. For the cases of $CH_4$ and $N_2O$, concentration trajectories were computed using atmospheric lifetimes of 12 years and 114 years respectively, and the resulting concentrations were obtained by multiplying the concentration by the appropriate linearized radiative efficiency coefficient [43]. In the case of $CH_4$, the direct radiative efficiency is multiplied by 1.45 to account for amplification by stratospheric water vapor and ozone feedbacks, and for radiative efficacy. With regard to climate response, the key difference among the gases is that the radiative forcing due to a pulse of $CH_4$ largely disappears after 12 years and that due to a pulse of $N_2O$ largely disappears after 114 years, whereas a substantial portion of the radiative forcing due to a pulse of $CO_2$ stays around essentially forever.

The warming resulting from $\Delta F(t)$ was computed using the transient energy balance climate model employed in [36]. This model incorporates a two-box ocean which allows for the delay in warming associated with the time it takes for the deep ocean to warm up to equilibrium. Parameters were set corresponding to an equilibrium climate sensitivity of 3 °C per doubling of $CO_2$ and a short-term transient climate sensitivity that is $\frac{2}{3}$ of the equilibrium value.

## 3. Results

Figure 1 compares the warming caused by midwest feedlot versus Brazil pastured beef for the idealized family of consumption trajectories, without taking into account deforestation effects. The perpetual consumption cases illustrate the basic property that

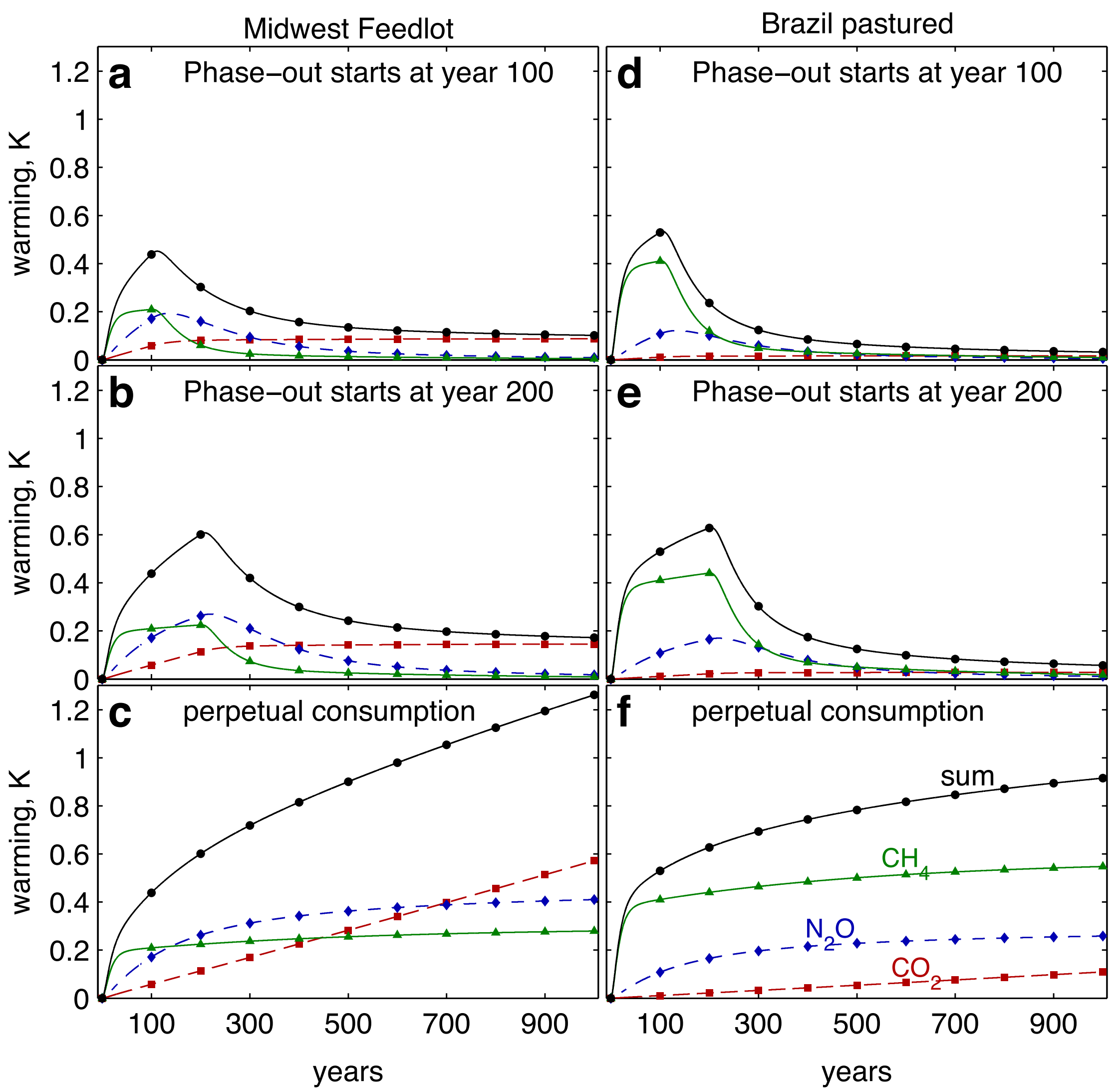


**Figure 1.** Warming versus time due to emissions of the three principal greenhouse gases for the 'midwest feedlot' strategy (left column) and 'Brazil pastured' strategy (right column). Line legends are indicated in the lower right panel. The top row assumes constant consumption of beef at 250 Mt $yr^{-1}$ followed by a phase out of consumption over 50 years beginning in year 100. The middle row is similar, but the phase-out begins in year 200. The bottom row assumes that the constant consumption rate is maintained over the full 1000 years of the analysis.

the warming due to $CH_4$ essentially stops growing after two decades and that warming due to $N_2O$ stops growing after two centuries, whereas the warming due to $CO_2$ emissions continues to grow indefinitely. There is a slight long term growth beyond the gas lifetime in the warming due to the two shorter lived gases, because of the delaying effect of deep ocean heat uptake.

The two phase-out cases illustrate that the warming due to $CH_4$ and $N_2O$ is reversible, whereas the warming due to $CO_2$ is not (at least not on any time scale of relevance to human societies). The higher $CO_2$ emissions in the midwest feedlot case lead to a persistent warming of .1 °C if beef consumption is phased out starting at 100 years, and .2 °C if the phase-out begins at 200 years. For the Brazil pastured case there is very little persistent warming. With a phase-out at 100 years the peak warming in the Brazil pastured case is worse than the peak warming in the midwest feedlot case, because $CH_4$ exerts a dominant role on these time scales; in the midwest feedlot case the peak warming is due in equal measure to $CH_4$ and $N_2O$, whereas in the Brazil pastured case, most of the warming comes from $CH_4$ If phase-out is delayed to 200 years, however, the effect of $N_2O$ and $CO_2$ become more important, and the peak warming in the two cases becomes nearly equal.

It is in the perpetual consumption cases that the differences between the methods become most pronounced. There is very little long-term growth in the Brazil pastured case, because $CO_2$ emission is so low. Even after 1000 years, $CO_2$ makes only a minor contribution to the warming. In the midwest feedlot case, however, the contribution of $CO_2$ becomes increasingly dominant as time goes on. The warming due to $CO_2$ has grown to nearly .6 °C at the end of 1000 years,

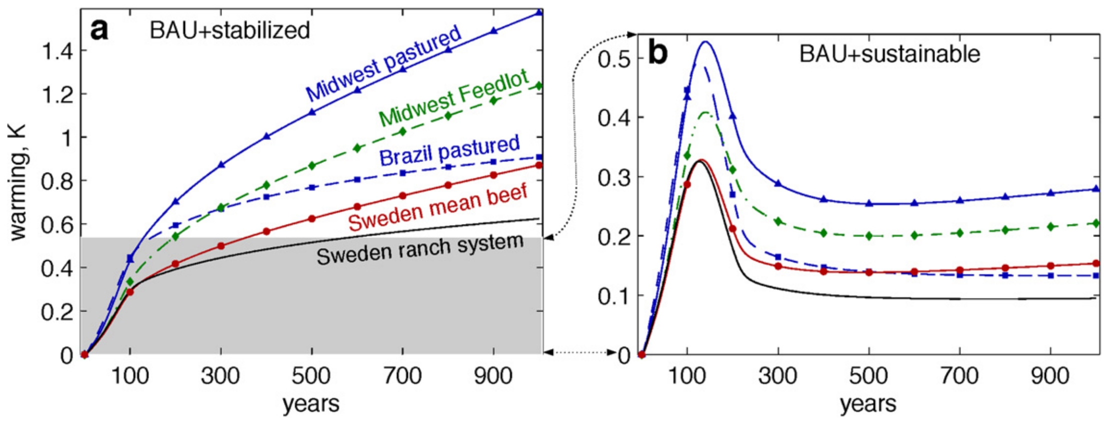


**Figure 2.** Net warming versus time due to all greenhouse gases emitted in the two 'business as usual' storylines.

and will continue to grow so long as beef production continues. Even in this case however, $CO_2$ accounts for only half of the warming at 1000 years, so that $CH_4$ and $N_2O$ are substantial factors in the long term climate impact. Except in the early years, the midwest feedlot case is warmer than the Brazil pastured case. Because the warming due to $CH_4$ emissions essentially stops growing after two decades, the adverse effect of higher $N_2O$ and $CO_2$ emissions in the midwest feedlot case quickly overwhelms the adverse effect of the higher $CH_4$ emissions in the Brazil pastured case. At the end of 1000 years, the warming in the midwest feedlot case is 1.25 °C, whereas in the Brazil pastured case it is .9 °C.

Given that the midwest pastured method yields higher emissions of all three greenhouse gases than the midwest feedlot case, it is no surprise that the climate impact at all time scales and from each of the gases (supplementary material, figure S 1) is correspondingly more severe than the midwest feedlot results in figure 1.

Figure 2 compares the warming for all five beef production methods, under the two BAU storylines. The *BAU + stabilized* cases, which ramp up gradually to a steady maximum consumption level, look very much like the perpetual consumption cases in figure 1(c) and (f), except for a somewhat slower rate of warming in the early years. The midwest feedlot system produces more long-term warming than the Brazil pastured case, because of its greater emission of $CO_2$, but exhibits a slower initial rate of warming because of reduced $CH_4$ emissions. The Sweden ranch system emerges as a clear winner, because it achieves $CO_2$ emissions as low as the Brazil pastured system, with much lower $CH_4$ emissions.Because of relatively low $N_2O$ emissions, the Sweden ranch system limits the warming at 1000 years to .6 °C—half the value of the midwest feedlot case—while still being slightly better than the midwest feedlot case in the first century. Swedish Mean Beef has similar short term impacts to the Swedish ranch system, but yields larger long-term warming because of its greater $CO_2$ emissions. However, the long term warming is similar to the Brazil pastured case, and considerably better than the midwest feedlot case. As expected, the midwest pastured system is the clear loser (neglecting deforestation effects in the Brazil system). It has the greatest long term warming while showing short term warming as bad as the Brazil system.

The results for the *BAU + sustainable* storyline in figure 2 show that for all methods a substantial portion of the warming due to beef production is reversible if production is phased down to more sustainable values beginning at 100 years. The methods producing more $CO_2$ leave more long-term residual warming, and the methods with more $CH_4$ and $N_2O$ yield higher peak warming, but the Swedish ranch system performs well in both regards. The Brazil pastured method (without deforestation) has nearly as high a peak warming as the worst case (midwest pastured), but the warming decays much more quickly and to a lower value, owing to its lesser $N_2O$ and $CH_4$ emissions.

## 4. Discussion and conclusions

The greatly disparate time scales for removal of $CH_4$, $N_2O$ and $CO_2$ from the atmosphere have important consequences for the way various scenarios for beef production method and consumption rate affect future climate. The aggregation of emissions into a single metric such as $CO_2e - 100$, as is common practice, destroys information needed to make a proper assessment of climate damage. Therefore, our most fundamental conclusion is that life cycle studies of beef production, and indeed of any agricultural production system, should always report the emissions of the individual greenhouse gases involved in the impact, rather than aggregating gases into a metric. The same applies to any activity producing greenhouse gases, but it is of particular importance in the analysis of agricultural production, as $CH_4$ and $N_2O$ account for a large proportion of the climate impact of such

**Table 2.** Equivalent cumulative carbon, $CC_{eq}$ for $CH_4$ and $N_2O$ emitted by various modes of beef production. The numbers represent kg of $CC_{eq}$ corresponding to a steady production rate of 1 kg yr$^{-1}$ of bone-free beef. The table also gives the actual cumulative carbon emitted by deforestation (in cases where the required pasture was produced by tropical deforestation) and the cumulative carbon in the form of direct $CO_2$ emissions over 1000 years. The final column gives the net of all cumulative carbon and $CC_{eq}$ associated with beef production at a rate of 1 kg yr$^{-1}$. Deforestation effects associated with extratropical pastured production have not been evaluated.

| | $CC_{eq}$ $CH_4$ | $CC_{eq}$ $N_2O$ | $CC_{eq}$ $N_2O + CH_4$ | $CC$-deforest $CO_2$ | 1000 yr $CC$-dir $CO_2$ | $CC_{eq}$ Total |
|---|---|---|---|---|---|---|
| Feedlot midwest | 587 | 873 | 1460 | - | 1429 | 2889 |
| Pastured midwest | 756 | 1150 | 1906 | ? | 1753 | 3659 |
| Pastured Brazil | 1150 | 550 | 1700 | - | 273 | 1973 |
| Brazil w/deforestation | 1150 | 550 | 1700 | 4750 | 273 | 6723 |
| Ranch system Sweden | 756 | 346 | 1102 | ? | 270 | 1372 |
| Sweden average beef | 654 | 419 | 1073 | - | 950 | 2023 |

activities, and most agricultural strategies are distinguished from each other by the relative proportions of the three major greenhouse gases emitted.

All methods of beef production have severe climate impacts when extrapolated to peak production rates corresponding roughly to the current US per capita rate being consumed by a population of 10 billion. If the peak consumption is maintained indefinitely, the resulting warming at the end of 1000 years is .6 °C–1.6 °C, and in situations where the consumption rate after the peak is phased down to a more sustainable level the transient peak warming is .3 °C–.6 °C, depending on the method of beef production. In all cases, including those with high annual $CO_2$ emissions, the contributions of $CH_4$ and $N_2O$ remain important throughout the millennium, and is strongly dominant in the first century.

Production systems such as CAFO's (exemplified by the midwest feedlot case) require high external inputs from fossil fuels for energy and fertilizer feedstocks, and the resulting high $CO_2$ emissions lead to a comparitively high degree of irreversible warming in cases where initially high consumption rates are phased out, and comparitively high secular warming growth on the millennial time scale in any scenario with continued beef production. The midwest pastured example shows that 'grass-fed' systems do not necessarily produce low $CO_2$ emissions, but suitably designed pastured systems, as in the Sweden ranch or Brazil pastured systems can have very low $CO_2$ emissions if no deforestation is involved in producing the pasture land; as a result they produce less irreversible warming and less millennial-scale secular growth in warming. The high $CH_4$ emissions of the Brazil pastured case lead to larger and more rapid short-term warming than the midwest feedlot case, but this effect is overwhelmed in the long term by the lower $CO_2$ emissions in the pastured case. Dairy associated systems (e.g. Sweden average beef) can, however, have climate impact similar to or lower than the purely pastured Brazil system at all time scales, highlighting the potential benefits of hybrid systems. The highly optimized Sweden ranch system shows that careful management practices can significantly reduce the high $CH_4$ emissions that tend to plague pastured systems, and this system merits careful study to see if some of the techiques can be applied at larger scale.

In [36] it was pointed out that for a relatively short-lived gas like $CH_4$ or $N_2O$, the warming at time scales longer than the gas lifetime is proportional to the emission *rate*, so that a steady emission *rate* of a short-lived greenhouse gas is equivalent to a fixed *amount* of cumulative carbon in the form of $CO_2$. For situations with a steady emission rate $E$ (e.g. in kg yr$^{-1}$) of a short-lived gas, we can then determine an equivalent mass of cumulative $CO_2$ carbon which we'll call $CC_{eq}$ (measured e.g. in kg). Let $a'$ be the radiative efficiency of the gas defined as radiative forcing per unit mass of gas in the atmosphere (e.g. in W m$^{-2}$ kg$^{-1}$). Let $\tau$ be the atmospheric lifetime of the gas (e.g. in yr). The asymptotic radiative forcing due to the sustained emission is then $a'\tau E$, which has units of W m$^{-2}$. To translate this into a temperature, we introduce a climate sensitivity parameter $\lambda$, measured in units of W m$^{-2}$ K$^{-1}$, whence the warming $\Delta T = a'\tau E/\lambda$ has units of temperature (K). Finally, we introduce the cumulative carbon sensitivity parameter $\Gamma$, which gives the proportionality between the mass of cumulative carbon emitted (as $CO_2$) and the resulting warming, and can be measured in units of K/kg (counting kilograms of carbon, not of $CO_2$) . For example, using the values in [44], $\Gamma \approx 2 \times 10^{-15}$ K kg$^{-1}$, which is equivalent to 2 K per trillion tonnes carbon. Thus, the equivalent cumulative carbon for sustained emission at rate $E$ is

$$CC_{eq} = \frac{a'\tau E}{\lambda \Gamma}. \tag{1}$$

If mass is measured in kg wherever it appears in quantities on the right hand side, then $CC_{eq}$ will also come out as a mass in kg. The notion that the closest thing to an equivalence between emission of a short-lived gas and emission of $CO_2$ involves a comparison of a *rate* to an *amount* is somewhat difficult to grasp. It is really just another way of saying that there is no completely correct way to aggregate the two kinds of emissions, and that the choice of a means of aggregation depends very much on the sort of situation being analyzed, and the kind of climate target to which the aggregation is applied.

The $CC_{eq}$ statistic is given in table 2 for the modes of beef production discussed in this letter. The units are kg of $CC_{eq}$ corresponding to sustained beef production at a rate of 1 kg bone-free-beef per year. The table also shows the cumulative carbon (due to $CO_2$ emissions alone) that would be emitted if the pasture used to produce beef at that rate resulted from Brazilian deforestation. In cases where the pasture was not recently deforested, but would revert to forest if left alone, this statistic also represents an opportunity cost in foregoing the carbon sink in order to allow continued beef production on that land. The climate effect of the direct $CO_2$ emissions incurred by an annual production rate of 1 kg $yr^{-1}$ of beef are different, as the cumulative carbon produced grows annually so long as the beef production continues; as a point of reference for the magnitude of direct $CO_2$ emissions, table 2 gives the carbon from direct emissions which accumulates over 1000 years.

In the case of midwest feedlot beef, for example, the $CH_4$ and $N_2O$ emissions associated with a sustained production of 1 kg $yr^{-1}$ of beef would need to be offset by a reduction of 1460 kg in cumulative carbon from fossil fuel burning, in order to keep within an agreed climate objective. More broadly, we can put these numbers in perspective by relating them to per capita consumption. It has been estimated that the remaining cumulative carbon that can be emitted without breaching a 2 °C warming threshold, if divided equally amongs the world's population, amounts to about 70 tonnes per person[45]. Taking into account the total equivalent emissions given in the last column of table 2, a sustained consumption of 10 kg $yr^{-1}$ would use up the equivalent of 28.89 of these tonnes, or nearly half of the total allocation. If the beef were produced by the Swedish ranch system, only 13.72 tonnes would be used up, but that is still a significant amount in view of the fact that the carbon allocation must cover all the other energy and food requirements of society, as well as beef.

Table 2 shows that the effects of tropical deforestation used to produce pasture overwhelm all other emissions associated with beef production. For that portion of Brazilian beef which is produced from deforested land (or land that could revert to forest) the deforestation effects turn the beef from one of the more climate-benign forms to by far the most climate-threatening form—almost twice as bad as the midwest pastured case.

What kind of beef consumption and production scenarios are compatible with a 2 °C warming target? If consumption were to grow by a factor of three from its present 58 Mt $yr^{-1}$ value, and the beef were produced by the midwest feedlot system, the equivalent cumulative carbon would be 504 Gt, which all by itself is enough to use up the remaining allocation of cumulative carbon corresponding to a probable warming below 2 °C. Given the high land-use of pastured systems, production of so much beef is likely to require feedlot or dairy-associated systems (such as Sweden average beef). Such systems require high inputs in the form of fossil-fuel energy and fertilizer feedstocks [46]. Given the challenges of altering the basic biochemistry of enteric fermentation that leads to $CH_4$ production, the chief opportunity for mitigation in such a high-consumption scenario is through replacing these inputs with carbon-neutral alternatives. If the $CO_2$ component of the midwest feedlot system could be eliminated after 100 years, then the equivalent cumulative carbon for the high consumption future would go down to 279 Gt; if the same could be done for a dairy-associated system, the emission would be 203 Gt. These figures still represent such a large fraction of the remaining cumulative carbon allocation that staying within 2 °C warming limit would be practically impossible. There may be possibilities for modest reductions in $CH_4$ and $N_2O$ emissions through capture of $CH_4$ from manure or animals in enclosed spaces and from more efficient fertilizer production, but on the other hand the assumption of complete decarbonization of the production system is an extreme one unlikely to be achieved. Note that consumption growth by a factor of 3, spread over a world population of 10 billion, amounts to a per capita consumption rate of 17 kg $yr^{-1}$, which is only 70% of the current US rate. It thus appears that substantial growth in worldwide beef consumption is incompatible with a 2 °C warming target. [47] came to a similar conclusion. This points towards policies that promote replacement of beef consumption with alternatives (such as pork and poultry) that have lower unit greenhouse gas emissions [6].

Suppose that beef consumption were limited to 75% of the current world output. If this amount of beef could be produced by pastured schemes with emissions similar to the Swedish ranch system, it would add the equivalent of 60Gt to the world's cumulative carbon emission inventory, which is far from insignificant but leaves much more leeway to accomodate other demands on the remaining cumulative carbon budget. Given the high land usage and specialized nature of this system, however, it is far from clear that the assumed production could be achieved on the world's available pasture. In considering the amount of pasture available for beef production, it should also be noted that there are substantial biodiversity and carbon storage benefits in allowing existing tropical pasture to revert to forest, in places where the climate would allow such a succession [48]. An alterative pathway to purely pastured production would be to make use of a decarbonized form of a dairy-associated system like Sweden average beef, which could achieve the same production with an equivalent cumulative carbon emission of 50 Gt. A full analysis of the consequences of this pathway would require consideration of the emissions attributable to the associated dairy sector.

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