DR. ANDY REISINGER (Orcid ID : 0000-0002-6631-7188)

Article type   : Primary Research Articles

Title:

How much do direct livestock emissions actually contribute to global warming?

Running head:

Contribution of livestock to actual warming

Authors:

Andy Reisinger and Harry Clark

New Zealand Agricultural Greenhouse Gas Research Centre, Private Bag 11008, Palmerston North 4442, New Zealand

Corresponding author:

Andy Reisinger; ph: +64 21 613 125; andy.reisinger@nzagrc.org.nz

Keywords

Livestock, non-CO$_2$ mitigation, climate change metrics, attribution, Global Warming Potential, Paris Agreement, 1.5°C warming

Abstract

Agriculture directly contributes about 10-12% of current global anthropogenic greenhouse gas (GHG) emissions, mostly from livestock. However, such percentage estimates are based on Global Warming Potentials (GWPs), which do not measure the actual warming caused by emissions and ignore the fact that methane does not accumulate in the atmosphere in the same way as CO_2. Here we employ a simple carbon cycle-climate model, historical estimates and future projections of livestock emissions to infer the fraction of actual warming that is attributable to direct livestock non-CO_2 emissions now and in future, and to CO_2 from pasture conversions, without relying on GWPs. We find that direct livestock non-CO_2 emissions caused about 19% of the total modelled warming of 0.81°C from all anthropogenic sources in 2010. CO_2 from pasture conversions contributed at least another 0.03°C, bringing the warming directly attributable to livestock to 23% of the total warming in 2010. The significance of direct livestock emissions to future warming depends strongly on global actions to reduce emissions from other sectors. Direct non-CO_2 livestock emissions would contribute only about 5% of the warming in 2100 if emissions from other sectors increase unabated, but could constitute as much as 18% (0.27°C) of the warming in 2100 if global CO_2 emissions from other sectors are reduced to near or below zero by 2100, consistent with the goal of limiting warming to well below 2°C. These estimates constitute a lower bound since indirect emissions linked to livestock feed production and supply chains were not included. Our estimates demonstrate that expanding the mitigation potential and realizing substantial reductions of direct livestock non-CO_2 emissions through demand and supply side measures can make an important contribution to achieve the stringent mitigation goals set out in the Paris Agreement, including by increasing the carbon budget consistent with the 1.5°C goal.

Introduction

Governments have agreed to limit global warming to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C (UNFCCC 2015). Achieving this goal will require significant and sustained global efforts in all sectors to reduce GHG emissions. Direct emissions from agriculture are estimated to constitute about 10-12% of total global GHG emissions in 2010 (Smith et al. 2014), with additional indirect emissions from deforestation, energy use and the production of animal feed (Gerber et al. 2013b). The majority of direct agricultural emissions come from livestock, mostly ruminants (Opio et al. 2013; Smith et al. 2014). Reducing livestock emissions therefore appears necessary to support stringent global mitigation goals (Hedenus et al. 2014; Wollenberg et al. 2016).

The Paris Agreement sets out a goal of achieving a net balance of sources and sinks for greenhouse gases in the second half of the 21st century to remain within stipulated temperature limit. Most importantly, net emissions of carbon dioxide (CO_2), the most important GHG from human activities, would need to be reduced to net or below zero well before the end of the 21st century (IPCC 2014b) through decarbonisation of energy supply, reductions in energy demand in a range of sectors, and CO_2 removal technologies (see e.g. Bauer et al. 2017; Clarke et al. 2014; Riahi et al. 2017). Emissions of non-CO_2 gases are expected to decline much less in than CO_2 in deep mitigations scenarios due to the current higher cost or, in the livestock sector, complete absence of zero-emissions technologies. As a result, the fraction of non-CO_2 gases in total GHG emissions is expected to increase in stringent mitigation scenarios from about 26-29% in 2005 to more than 100% of total emissions by 2100 (Gernaat et al. 2015). Reducing non-CO_2 emissions can therefore be expected to become increasingly important to remain within the warming limits envisaged in the Paris Agreement especially if net negative CO_2 emissions technologies remain limited due to cost, social or environmental concerns (Fuss et al. 2016; IPCC 2014b; Smith 2016).

The question of *how much* livestock emissions have to be reduced to support stringent global mitigation efforts is contentious, however. One reason is of course that in some regions, livestock play a critical role for food security and provide other vital services such as draught power, nutrient cycling, social capital and insurance (Herrero and Thornton 2013; Rivera-Ferre et al. 2016). Another reason is that direct livestock emissions occur in the form of GHGs other than CO_2, namely methane (CH_4) from enteric fermentation and manure management, and nitrous oxide (N_2O) from manure management and nitrogen deposition or application on pastures and croplands. Methane has a much shorter lifetime (about 12.4 years) in the atmosphere than CO_2 (centuries to millennia) but a much higher warming efficacy per molecule and per kg.

The Global Warming Potential (GWP), the metric most commonly employed to convert emissions of different GHGs into "CO_2-equivalent" emissions, only partially reflects these fundamentally different properties of CH_4 and CO_2 (Myhre et al. 2013). The GWP considers the warming effect of an emissions pulse from a non-CO_2 gas relative to that of CO_2, averaged over a fixed time horizon in a hypothetical atmosphere with constant (present-day) GHG concentrations. While this approach captures differences in warming efficacy and atmospheric lifetime of CO_2 and non-CO_2 gases, the weighting given to the emission of short-lived gases such as CH_4 depends strongly on the time horizon chosen (IPCC 2014b). Furthermore, if CH_4 is treated simply as another kind of CO_2-like gas, its emissions would have to be reduced to zero (or be compensated for by additional CO_2 sequestration) to be consistent with efforts to stabilise the climate at any level. Yet given its short lifetime, CH_4 does not accumulate in the atmosphere and CH_4 emissions do not have to be reduced to zero to limit global warming even to well below 2°C, in sharp contrast to CO_2 and other long-lived GHGs (IPCC 2014c; Myhre et al. 2013). Comparing emissions of different gases based on simplifying CO_2-equivalence metrics can therefore result in contradictory assessments about the importance and long-term targets for mitigation in different sectors.

Given these shortcomings of the GWP (Allen et al. 2016; Daniel et al. 2012; IPCC 2014b; Myhre et al. 2013; Shine 2009), scientific and political opinions remain divided on the importance of reducing emissions of short-lived climate pollutants such as CH_4. Positions range from strong support for prioritizing such reductions (CCAC 2014; Shindell et al. 2012; Victor et al. 2015) to concern that such efforts could dilute the non-substitutable priority of reducing global CO_2 emissions to zero over the 21st century (Allen et al. 2016; Bowerman et al. 2013; Pierrehumbert 2014).

A variety of metrics other than the 100-year GWP have been proposed and discussed extensively in the scientific literature (Kolstad et al. 2014; Myhre et al. 2013). For example, the Global Temperature change Potential (GTP) is based on the warming caused by today's emissions in a given target year in the future (Shine et al. 2005). However, the GTP does not consider warming and associated climate impacts accumulating up to the target year, and the time horizon would need to be adjusted continuously for future emissions as the target year is approached (Shine et al. 2007), making its application in a policy context more challenging. Yet other metrics actively include consideration of the economic cost of abatement (e.g. Boucher 2012; Johansson 2011).

There is broad consensus that no single metric is optimal in all policy contexts, and the choice of metric and time horizon depends (or should depend) on the type of application and policy context (IPCC 2014b, Box 3.2; Levasseur et al. 2016). Given the value judgements inherent in all GHG metrics and time horizons, relying solely on the 100-year GWP (or any other single GHG metric such as GTP) to determine the importance of mitigating non-CO_2 emissions could thus result in inadvertent biases. Evaluating the effects of direct livestock emissions on actual warming without relying on any simplifying GHG equivalence metric is therefore highly desirable to inform robust mitigation choices.

Direct emissions from livestock production are reasonably robustly documented (Smith *et al*. 2014, and databases evaluated therein), but it is surprisingly difficult to find estimates of the actual warming that those emissions have caused or will cause in future, and how this warming compares to that from other sectors whose emissions are dominated by CO_2. A recent study demonstrated (without recourse to GWP) that current North American patterns of beef consumption, if adopted globally, would be incompatible with the 2°C limit (Pierrehumbert and Eshel 2015), but the warming from more realistic global livestock production and mitigation scenarios has not been quantified. Absence of such information can allow misunderstandings about the warming effect of non-CO_2 gases, particularly the contribution from the short-lived gas CH_4, to permeate into public discussions (e.g. Grieve 2017; Henderson 2015), which in turn can limit the ambition of farmers, policymakers and the public to support actions to reduce GHG emissions from livestock (Sharman and Perkins 2017).

This study seeks to fill this gap by using historical estimates and future emissions scenarios and a reduced-complexity climate model to determine, without reliance on any GHG equivalence metric, the actual amount and fraction of total warming attributable to direct non-CO_2 livestock emissions to date and in future under alternative scenarios. We also quantify the warming due to historical emissions of CO_2 arising directly from the conversion of other land into pastures. We do not consider indirect emissions associated with livestock feed production, fertiliser use and transport due to limited data and divergent future scenarios (see Section 2.3 for details). Our results therefore represent a lower bound of the actual contribution of livestock systems to global warming as we rely solely on emissions that can be directly and unambiguously attributed to livestock.

Materials and Methods

Historical direct non-CO_2 livestock emissions

This study used the EDGAR emissions database (JRC and PBL 2012) to estimate historical emissions from livestock from 1970-2010, which was also used in the most recent IPCC assessment (IPCC 2014c). EDGAR directly provides data for CH_4 from enteric fermentation and CH_4 and N_2O from manure management, but only aggregate direct and indirect N_2O emissions from agricultural soils. To estimate soil N_2O emissions attributable to livestock, we used FAOSTAT (Tubiello et al. 2013) to infer the percentage contributions to total soil N_2O emissions from livestock manure (either left on pasture or deposited back onto land), fertilizer, and crop residue burning. Crop residue burning contributes approximately 10% of total soil N_2O emissions in FAOSTAT and this percentage was subtracted from the EDGAR total soil N_2O emissions. Fertilizer contributed 24% of soil N_2O emissions in 1970 and 43% in 2010 according to FAOSTAT, and these percentages were also subtracted from the EDGAR total soil N_2O emissions with linear interpolation between 1970 and 2010. The remaining EDGAR soil N_2O emissions were assumed to be due to animal manure applied to land or left on pastures.

The direct non-CO_2 (CH_4 and N_2O) livestock emissions derived using this method are broadly consistent with the range of estimates from other studies (see overview in Herrero et al. 2016) and constitute two thirds of the total direct non-CO_2 emissions from agriculture (Smith et al. 2014), or approximately 7% of total global GHG emissions of 49 Gt CO_2-eq in 2010 (IPCC 2014b, using the 100-year GWP).

For emissions prior to 1970, estimates from van Aardenne et al. (2001) were used for enteric CH_4 back to 1890, and it was assumed that emissions from manure management and manure deposition on soils during this period scale accordingly. Estimates from Stern and Kaufmann (1996) were used to scale emissions for the period 1860 to 1890 to connect smoothly with the estimates of van

Aardenne et al. (2001) in 1890. Prior to 1860, we assume no livestock emissions given the scarcity of data. The error introduced by this assumption for temperatures in 2010 or 2100 is likely very small, given the short lifetime of CH_4 and relatively small domestic livestock numbers prior to 1860.

Prior to about 1900, human-induced reductions in populations of wild ruminants (such as bison and caribou) may have reduced net livestock emissions, and some estimates indicate such reductions may have been appreciable for some North American countries (Hristov 2012; Kelliher and Clark 2010). However, atmospheric concentrations of CH_4 and N_2O have been remarkably stable for many centuries prior to the 19th century (Masson-Delmotte et al. 2013). This indicates that global net emissions of CH_4 and N_2O cannot have changed appreciably globally before the emissions increases seen in the 20th and 21st century when domestic livestock numbers increased substantially. We therefore did not consider anthropogenic changes in wild ruminant populations for this study.

Projected future livestock emissions and global emissions scenarios

Future direct livestock emissions will depend strongly on changes in global human population, dietary trends and other socio-economic trends, as well as productivity of livestock systems (Popp et al. 2017). Projections are therefore inherently uncertain, and the goal of our study is not to develop detailed new scenarios but to allow global order-of-magnitude estimates consistent with published and detailed process-based projections. To this end, we developed two livestock emissions scenarios to 2100, one business-as-usual and one stringent mitigation scenario, each embedded in a global emissions scenario across all sectors. We also explore the sensitivity of our results around assumptions for the stringent mitigation scenario.

The business-as-usual, high emissions scenario uses aggregate emissions across all sectors as set out in the RCP8.5 scenario, which assumes continued growth in most GHG emissions throughout the 21st century and no dedicated climate policy to reduce emissions (see Riahi et al. 2012, including details on emissions from other sectors). Within this scenario, we use FAOSTAT projections that indicate an increase of direct non-CO_2 livestock emissions by about 15% by 2030 and by 30% by 2050, relative to 2010 (Tubiello et al. 2013). As food demand is projected to increase by about 70% by 2050 (Alexandratos and Bruinsma 2012), this much more restrained increase in GHG emissions of 30% implies on-going improvements in the efficiency and productivity of livestock systems, consistent with historical and projected future trends (Bennetzen et al. 2016). Modelling detailed changes in food demand, animal numbers and productivity per animal was well beyond the scope of our study, however, and we therefore simply applied the scaling factors from FAOSTAT for emissions in 2030 and 2050 relative to 2010 to the direct non-CO_2 livestock emissions in 2010 inferred from the EDGAR database as described above.

The 30% increase by 2050 in our scenario lies well within the range of 8-48% increase of global livestock CH_4 emissions in a detailed scenario analysis under alternative socio-economic futures (Havlík et al. 2015), but lies below the range indicated by a number of global Integrated Assessment Models, which suggest increases from 50% to more than 100% in 2050 relative to 2010 (Gernaat et al. 2015). It is beyond the scope of this study to explore the reasons for this wide range in projections, which are likely related to model assumptions about on-going improvements in efficiency, productivity and intensity of livestock systems (Bennetzen et al. 2016) as well as population growth and dietary trends. More recent studies indicate that alternative assumptions about socio-economic development can significantly influence the future demand for livestock products, production efficiencies and associated emissions (Popp et al. 2017). Given the wide range of emissions projections across existing scenarios, the particular scenario choice in our study should not be seen as a prediction of future emissions but rather as a reference point; if alternative scenarios indicate livestock emissions above or below those assumed in our study, the contribution of direct non-CO_2 livestock emissions to actual global temperature increase would scale approximately proportionally to the change in livestock emissions relative to our scenario.

Beyond 2050, livestock emissions trends become even more uncertain due to unknown developments in global human population, wealth and dietary preferences. We assumed a further 10% increase in emissions in 2075 relative to 2050, and constant emissions from 2075 to 2100. Such a trend is consistent with baseline scenarios of enteric CH_4 emissions from a range of current global Integrated Assessment Models (Gernaat et al. 2015). Since CO_2 emissions roughly triple between 2010 and 2100 in the RCP8.5 scenario (Riahi et al. 2017), the *relative* contribution of direct livestock emissions to overall GHG emissions declines substantially. Alternative trajectories for livestock emissions (Popp et al. 2017) do not change this picture fundamentally, given the increasingly dominant influence of CO_2 on warming in a high-emissions world. Hence we did not explore alternative livestock emissions scenarios within the context of an RCP8.5 emissions scenario.

The second scenario used in our study follows the RCP2.6 pathway for aggregate emissions across all sectors (van Vuuren et al. 2011), which would give a reasonable (about 66%) chance for the global average temperature increase to remain below 2°C. This scenario assumes that emissions across all sectors follow stringent mitigation pathways that result in zero or below zero net global CO_2 emissions before 2100, and significant reductions in emissions of other GHGs depending on their respective abatement potential (for details see e.g. Clarke et al. 2014; Riahi et al. 2017). An intercomparison of Integrated Assessment Models and underlying process-based models shows a wide range of potential reductions of direct livestock emissions in deep mitigation scenarios, ranging from 9% to 43% below respective business-as-usual levels in 2100 (Gernaat et al. 2015). Consistent with this analysis, we assumed livestock emissions in our stringent mitigation scenario to be 40% below our estimated business-as-usual emissions by 2100, with a linear increase in this mitigation rate between 2010 and 2100.

We note that such mitigation levels may be highly optimistic, given numerous practical constraints to the implementation of mitigation options assumed in Integrated Assessment Models (Wollenberg et al. 2016), unless significant reductions occur simultaneously in livestock product demand (see overviews in Aleksandrowicz et al. 2016; Herrero et al. 2016). Note that in the default RCP2.6 scenario, global CH_4 emissions from all sectors are lower than our business-as-usual CH_4 emissions from livestock alone, so a substantial reduction in livestock CH_4 emissions below business-as-usual is necessary for those emissions to be internally consistent with the RCP2.6 pathway.

With these assumptions, enteric CH_4 emissions constitute an increasing share of total global anthropogenic CH_4 emissions in RCP2.6, rising from approximately 30% in 2010 (Ciais et al. 2013) to about two thirds in 2100. This increasing share reflects the assumption in the RCP2.6 scenario that CH_4 emissions from fossil fuel extraction and use, which were of comparable magnitude to enteric CH_4 emissions in 2010, are eliminated almost entirely by 2100 along with most of the CH_4 from landfills (van Vuuren et al. 2011). As a result, livestock CH_4 emissions constitute by far the biggest global source of CH_4 by 2100 in a deep mitigation scenario (Gernaat et al. 2015).

While reducing livestock emissions by 40% below business-as-usual is ambitious, it may yet underestimate feasible future mitigation given the potential for socio-economic and technological change in the sector. Further reductions could arise from additional demand-side management (e.g. Aleksandrowicz et al. 2016; Alexander et al. 2015; Stehfest et al. 2009) or novel supply-side mitigation technologies, such as inhibitors that suppress enteric CH_4 (Hristov et al. 2015) or N_2O from pastoral soils (Di and Cameron 2002; Misselbrook et al. 2014). For the purpose of this study, the detail of how further emissions reductions might be achieved is secondary (see Gerber et al. 2013a for an overview), and we simply test the sensitivity of our results if direct non-CO_2 livestock emissions could be reduced by another 50% between 2050 and 2075 below the trajectory described above for livestock non-CO_2 emissions within the RCP2.6 mitigation scenario.

Figure 1 shows the resulting direct CH_4 and N_2O emissions from livestock for 1900-2100 in the baseline and mitigation scenarios, and Table 1 summarizes baseline emissions for key dates. Havlik *et al.* (2015) indicate that climate change itself would have only a minor impact on global GHG emissions from livestock, as these are dominated by changes in human population, demand for livestock products and productivity changes. Hence climate change impacts on global livestock GHG emissions were not considered further.

Treatment of indirect GHG emissions

Livestock systems directly emit only non-CO_2 gases, but are also responsible for a range of indirect emissions. These arise from livestock-induced land-use change, fertiliser use (on pastures and croplands to produce livestock feed), and energy and transport emissions related to livestock operations and supply chains.

Methodologies for lifecycle assessment of livestock supply chains at project scale have been developed (e.g. the Livestock Environmental Assessment and Performance Partnership LEAP), but quantification of indirect livestock emissions remains challenging at global scales where data sets are limited and sector interactions change over time. For example, land conversions may occur for a mix of purposes including timber, crop production for human uses, livestock feed and grazing, with land-use shifting over time. In some regions, by-products from human food crops constitute a significant feed resource for animals but livestock are not the primary driver for emissions from food crop production. Furthermore, livestock systems use nitrogen fertiliser in some world regions but livestock manure is also an important fertiliser resource in itself for food crop production in other regions.

Global lifecycle assessments suggest that in 2005, direct non-CO_2 emissions from livestock accounted for more than two thirds of total lifecycle livestock emissions, and indirect emissions associated with land-use change, animal feed and energy use for up to one third (Gerber et al. 2013b; Herrero et al. 2016). However, such assessments are very data intensive, which makes it nearly impossible to construct complete and robust time series such as needed for this study from before 1900 through to 2100. In addition, future changes in feed sources and associated emissions from feed production and land-use change could change indirect emissions substantially (Popp et al. 2017), making projections of future lifecycle emissions from livestock highly contentious. Gerber et al. (2013b) estimate that in 2005, land-use change related to dedicated livestock feed production (mainly soybeans) was about half of that related to pasture expansion, but consistent data for land-use change for livestock feed production are lacking for historical or future time periods.

Given these challenges, our study included only those indirect emissions that can be attributed unambiguously and directly to livestock at a global scale, namely emissions arising from the expansion of pasture land. Houghton and Nassikas (2017) provide recent estimates for CO_2 emissions from land use change from 1850 to 2015, including estimated emissions arising from conversion of land into pastures. These estimates are conservative because their study did not account for shifting cultivation and they assumed that pastures were converted from non-forest ecosystems unless data suggested otherwise. Using this approach, Houghton and Nassikas (2017) arrive at net emission of 144 Mt CO_2 from pasture conversions in 2005, which is markedly lower than the 426 Mt CO_2 estimated by Gerber et al. (2013b) using detailed geo-referenced data for the same year. It is beyond the scope of our study to attempt to reconcile those global-scale differences, and we confine our analysis to exploring the sensitivity of our results to the differences between those two studies.

The expansion of grasslands has halted on a global scale during the past decade although significant trends exist in some regions (Houghton and Nassikas 2017). Future scenarios suggest that the area of grasslands may increase or decrease globally depending on socio-economic development, and contract more significantly under stringent mitigation scenarios (Alexander et al. 2015; Popp et al. 2017). This contraction could offer a substantial mitigation potential (Golub et al. 2012; Havlík et al. 2014) depending on the land-use that replaces pastures. For the purpose of our study, which seeks to understand the warming *directly attributable* to livestock rather than indirect effects including foregone alternative land uses, we set land-use emissions directly attributable to livestock from pasture conversions to zero from 2015 onwards.

We emphasise that this approach does not constitute a full lifecycle assessment and thus the warming attributed to livestock in this study is likely to underestimate the warming attributable to the full livestock supply chain. However, our approach constitutes a robust lower bound in that it relies only on emissions that can be attributed unambiguously to livestock regardless of definitions of system and sectoral boundaries.

Modelling approach

This study employed the climate model MAGICC (Meinshausen et al. 2011a; Meinshausen et al. 2011c; Wigley and Raper 1992) to simulate the concentration changes, radiative forcing and global temperature change resulting from global GHG emissions. MAGICC is a reduced-complexity climate model with an upwelling-diffusive ocean and is coupled to a simple carbon cycle model including CO_2 fertilization and temperature feedback parameterisations of the terrestrial biosphere and oceanic uptake. MAGICC version 6 as used in our study was calibrated to the mean climate response from 19 Atmosphere-Ocean General Circulation Models (AOGCMs) as assessed in the IPCC's Fourth Assessment Report (Meehl et al. 2007) and to the Bern carbon cycle model (Joos et al. 2013), as described in Meinshausen et al. (2011a).

MAGICC has been shown to reproduce results from much more complex climate models and thus allows the efficient study of different emissions and mitigation scenarios (Joos et al. 2013; Meinshausen et al. 2011a). As the overall projected climate change in response to a given amount of forcing has changed little over the past 10 years (Rogelj et al. 2012), we considered it adequate to use MAGICC calibrated to the average of the models assessed in the IPCC's Fourth rather than Fifth Assessment Report. With these settings, MAGICC simulates warming of 1.0°C under the RCP2.6 scenario and 3.8°C under the RCP8.5 scenario in 2081-2100 relative to 1986-2005, which corresponds very well to the warming of 1.0 (0.3-1.7) °C and 3.7 (2.6-4.8) °C simulated by a range of more recent complex climate models under these same scenarios (IPCC 2013).

To infer the contribution from direct livestock emissions to observed and projected future warming, MAGICC was first run for the full set of global emissions corresponding to the RCP2.6 and RCP8.5 scenarios (Meinshausen et al. 2011b), and then with those same emissions minus the direct CH_4 and N_2O emissions attributed to livestock (separately for CH_4 only, and for CH_4 and N_2O combined). The differences in simulated temperature are considered to be the contribution to actual warming from direct livestock non-CO_2 emissions (i.e. warming that would not have occurred in the absence of those emissions). The same approach was taken to model the warming from CO_2 emissions directly attributed to pasture conversions, where those CO_2 emissions were subtracted from CO_2 emissions prescribed in the RCP2.6 and RCP8.5 pathways. As the purpose of our study is to understand the relative contribution from livestock to total warming, we did not run the model with alternative climate sensitivities since this would have little impact on the relative contribution from individual gases and sectors.

Results

Contribution of direct livestock emissions to present-day warming in 2010

We first analyse the contribution from direct livestock emissions to warming in the year 2010. Figure 2 shows the modelled warming from GHG and aerosol emissions from all sectors of 0.81°C relative to pre-industrial temperatures. This modelled warming agrees fairly well with the observed warming of 0.78 (0.72 to 0.85) °C in the 2003-2012 period, relative to 1850-1900 (IPCC 2013).

If global total CH_4 emissions are reduced by the direct CH_4 emissions attributed to livestock, the model simulates a lesser warming of 0.70°C, meaning that 0.11°C or about 14% of the modelled warming in 2010 was due to direct livestock CH_4 emissions.

This modelled amount of warming can be cross-checked against a simple estimate. The radiative forcing from all anthropogenic emissions in 2011 was about 2.29W/m^2, while radiative forcing from all CH_4 emissions including indirect effects was about 0.97W/m^2 (Myhre et al. 2013). Livestock contribute about 30% of total anthropogenic CH_4 emissions in 2010 (Ciais et al. 2013). This implies that roughly 13% of the total radiative forcing in 2011 is due to direct livestock CH_4 emissions. Given the strong association between radiative forcing and total temperature increase, this simple calculation is consistent with and supports the more detailed model-based result.

Estimated direct N_2O emissions from livestock, also shown in Figure 2, made a smaller but growing contribution to global temperatures to reach just over 0.04°C by 2010. Thus total direct non-CO_2 emissions from livestock have contributed about 0.16°C or 19% of the total modelled warming of 0.81°C in 2010. The net emissions of CO_2 arising from the conversion of land into pastures contributed 0.03°C by 2010, slightly less than direct N_2O emissions, bringing the total direct warming from livestock to 23% of the modelled temperature change in 2010.

As noted earlier, a geo-spatially explicit analysis by Gerber et al. (2013b) arrives at an almost three times higher emissions estimate than Houghton and Nassikas (2017) for the year 2005. If this underestimate were to hold throughout the period 1860-2010, the warming due to CO_2 from pasture conversions would be three times greater at 0.09°C. Notably, even if this were the case, direct emissions of CH_4 remain the largest contributor to warming in 2010 directly attributable to livestock.

Contribution of direct livestock emissions to future warming to 2100

In the RCP8.5 scenario, the warming due to livestock CH_4 emissions increases from 0.11°C in 2010 to 0.14°C in 2100 owing to the increasing rate of emissions (see Figure 3). The contribution from N_2O more than doubles, from 0.04°C in 2010 to 0.09°C in 2100, bringing the total warming from direct non-CO_2 emissions to 0.23°C.

The contribution from N_2O grows much more than that from CH_4 because N_2O is a much longer-lived GHG whose emissions and hence warming effect accumulate in the atmosphere throughout the century. Overall though, direct non-CO_2 emissions from livestock would make a declining relative contribution to the overall warming in the RCP8.5 scenario, responsible for only 5% of the total modelled warming of 4.63°C in 2100 (relative to 1850-1900), as emissions of fossil CO_2 roughly triple and hence dominate the warming in the absence of any mitigation measures.

Even though we assume emissions of CO_2 from pasture conversions to have stopped after 2015 and remain zero through the rest of the 21st century in our simulation, they still contribute 0.02°C to warming in 2100. The declining absolute warming is mostly because ambient CO_2 concentrations rise strongly, which reduce the radiative efficacy of historical CO_2 emissions to contribute to warming later in the 21st century.

The contribution of direct livestock non-CO_2 emissions to overall warming is markedly different in a world that seeks to limit total warming to less than 2°C above pre-industrial temperatures, as in the RCP2.6 scenario. In our default mitigation scenario, even though total direct livestock emissions are assumed to be 40% lower than in the RCP8.5 scenario, the absolute warming due to livestock CH_4 in 2100 is higher, at about 0.18°C. This is because the radiative efficacy of CH_4 declines with rising CH_4 and N_2O concentrations (Ramaswamy et al. 2001). In the RCP2.6 scenario, emissions of CH_4 from fossil fuel use and waste management are assumed to decline rapidly given the wide range of cost-effective abatement options, with global total CH_4 emissions falling by more than 50% between 2010 and 2010. As a result, global CH_4 concentrations decline substantially between 2010 and 2100 in this scenario (from about 1800 to 1100 ppm) and the radiative efficacy of CH_4 increases. The trend goes in the opposite direction in the RCP8.5 scenario, where CH_4 concentrations rise from 1800 to more than 3500 ppm by 2100; increasing warming in the RCP8.5 scenario further reduces the atmospheric lifetime of CH_4. Thus a given amount of CH_4 emitted in the late 21st century produces markedly more warming in the RCP2.6 than in the RCP8.5 scenario, resulting in a greater total warming due to direct livestock CH_4 emissions in the RCP2.6 scenario in 2100 despite the quantity of those emissions being significantly lower.

The modelled warming from livestock N_2O emissions in 2100 is 0.09°C, slightly lower than the warming in the RCP8.5 scenario. This is not only because livestock N_2O emissions in the RCP2.6 scenario are reduced compared to RCP8.5, but in contrast to CH_4, total N_2O concentrations continue to rise even in the RCP2.6 scenario, given the much longer lifetime of N_2O in the atmosphere. The total warming contribution from direct livestock non-CO_2 emissions in 2100 in the RCP2.6 scenario is thus estimated at 0.27°C, or 19% of the total warming modelled in 2100 relative to pre-industrial levels.

Past emissions of CO_2 from pasture conversions contribute 0.03°C to warming in 2100, almost as much as in 2010. This demonstrates the long-term legacy of historical CO_2 emissions on the Earth's climate. Even though the emissions are the same as in the RCP8.5 scenario (emissions from pasture conversions are set to zero in both scenarios from 2015), the warming from those emissions in the RCP2.6 scenario is higher because CO_2 concentrations rise much less and hence the radiative efficacy of historical CO_2 emissions remains higher than in the RCP8.5 scenario.

We also tested how the contribution of direct non-CO_2 livestock emissions to actual warming would change under the enhanced livestock mitigation scenario (see Section 2.2). To model this, we reduced total CH_4 and N_2O emissions in the RCP2.6 scenario consistent with the reduced CH_4 and N_2O emissions from livestock in the enhanced mitigation scenario. We then ran MAGICC first with the lower RCP2.6 baseline emissions and then with the direct livestock CH_4 and N_2O emissions subtracted. Figure 4 shows the results of this sensitivity test, comparing absolute warming and the contribution from direct livestock non-CO_2 emissions in the default and enhanced mitigation scenario.

Enhanced mitigation of direct livestock non-CO_2 emissions would reduce total modelled warming in 2100 by 0.08°C relative to warming under the default RCP2.6 scenario. Most of this reduction comes from reduced warming from livestock CH_4 (0.07°C), with a much smaller contribution from N_2O (0.01°C), even though the enhanced mitigation scenario assumes that CH_4 and N_2O from livestock are both reduced by another 50% between 2050 and 2075. The reason for this substantial difference is that CH_4 has a much shorter atmospheric lifetime and hence reducing CH_4 emissions results in a rapid drop in CH_4 concentrations and reduced actual warming. By contrast, the atmospheric concentration of N_2O is dominated by cumulative emissions over the past two centuries, and hence the benefits of mitigation in terms of reduced warming take much longer to materialise.

The relative contributions of livestock CH_4 and N_2O to total modelled warming in the enhanced mitigation scenario changes accordingly, with direct livestock CH_4 contributing 0.11°C (8%) and N_2O contributing 0.08°C (6%) in 2100. Direct non-CO_2 emissions together contribute 0.19°C (14%) to total modelled warming in the enhanced mitigation scenario, compared to 0.27°C (19%) in the default mitigation scenario. Table 2 provides a summary of the modelled warming and contributions from direct livestock non-CO_2 emissions and from CO_2 emissions from historical pasture conversions under the different scenarios.

Discussion

One striking conclusion from our analysis is that the contribution of direct livestock non-CO_2 emissions to current warming (in 2010) is significantly larger (19%) than the estimated current percentage of those emissions of total global GHG emissions (roughly 7% based on the 100-year GWP for the year 2010).

This disproportionate contribution from livestock occurs mostly because the 100-year GWP underestimates the fraction of warming caused by historical GHG emissions over the 20th century. This is because the GWP is commonly applied only to GHGs but not aerosols (which are associated mostly with fossil-fuel based power generation and biomass burning and had a net cooling effect to date), and hence the contribution from each individual GHG to total actual warming is greater than its share of GHG emissions. A secondary reason for the relatively greater contribution of livestock non-CO_2 emissions to today's warming is that direct livestock emissions constituted a higher share of total global GHG emissions during the 20th century than in 2010. In addition, the radiative efficacy of CH_4 was higher during the 20th century than today, owing to the almost doubling of CH_4 concentrations between 1900 and 2010.

An earlier study (Tanaka et al. 2009) found that the changes in 20th century temperature are best simulated if a 44-year rather than a 100-year GWP is used to weigh CH_4 emissions relative to CO_2 emissions, implying a greater contribution of CH_4 emissions to historical temperature change than indicated by today's 100-year GWP. Our study complements this conclusion by demonstrating that the fraction of today's warming attributable to livestock non-CO_2 emissions is significantly greater than the fraction of livestock emissions in total global GHG emissions expressed using the 100-year GWP.

A recent study (Gernaat et al. 2015) concluded that in ambitious mitigation scenarios that give a reasonable (>50%) chance of temperatures remaining below 2°C, non-CO_2 emissions could constitute the great majority of remaining GHG emissions (using 100-year GWP); and that while strong emissions reductions of non-CO_2 gases from the energy supply and waste sectors can be achieved, options for land-based sectors were more limited but potentially very important to help achieve stringent mitigation goals. Our study takes these conclusions further and demonstrates (without relying on any simplifying climate metric such as GWP) that in ambitious mitigation scenarios, direct livestock non-CO_2 emissions alone could constitute about 0.19-0.27°C or 14-19% of the total warming in 2100, depending on the level of additional abatement that can be achieved for direct non-CO_2 emissions from livestock.

It is noteworthy that the fraction of total warming attributable to direct livestock non-CO_2 emissions remains virtually the same in 2010 and 2100 (19%) under the default RCP2.6 scenario, even though livestock emissions remain at roughly the same level while emissions from many other sources, particularly those related to fossil fuel production and use, decline to zero. This reflects the contrast between CO_2 emissions, which accumulate in the atmosphere and hence historical emissions contribute to future warming long after emissions have ceased, and the much shorter lifetime of CH_4 emissions whose contribution to warming is related mainly to the rate of emissions. However, even if livestock non-CO_2 emissions could be reduced by another 50% below those assumed in an already ambitious mitigation scenario, their contribution to total warming in 2100 would still remain significant at about 14%.

Even though CH_4 emissions do not have to decline to zero for the climate to stabilise, the rate of CH_4 emissions nonetheless can have an important influence on the level of peak warming and the costs and feasibility of remaining within a given temperature limit. Recent studies indicated that increasing the mitigation potential of agriculture would substantially increase the allowable cumulative CO_2 emissions and reduce global carbon prices consistent with a specific temperature goal (Rogelj et al. 2015a; Rogelj et al. 2015b) even without considering the climate benefits of reduced livestock land-use (Golub et al. 2012; Smith et al. 2010; Stehfest et al. 2009). Our study offers a ready physical explanation for this: because livestock emissions constitute such a substantial fraction of the actual warming in a deep mitigation scenario, reducing livestock emissions beyond what is currently considered feasible in the RCP2.6 scenario would increase the atmospheric 'space' for CO_2 emissions consistent with a given temperature goal. This conclusion holds independent of the use of any simplifying CO_2-equivalence metric.

The change in the carbon budget consistent with a given temperature goal can be readily quantified using the results from our study. The last IPCC assessment found a near-linear relationship between cumulative CO_2 emissions and resulting warming, with about 1°C warming for an additional 2,200 $GtCO_2$ (Collins et al. 2013). The carbon budget consistent with a goal of limiting warming to 2°C with a probability of at least 66% has been estimated at 1,000 $GtCO_2$, whereas the carbon budget to limit warming to 1.5°C with just 50% probability was put as low as about 500 $GtCO_2$ (IPCC 2014b). Reducing the warming from direct non-CO_2 livestock emissions from 0.27°C in the default RCP2.6 mitigation scenario to 0.19°C in an enhanced livestock mitigation scenario would thus increase the carbon budget consistent with any given temperature goal by 176 $GtCO_2$. This would increase the estimated allowable carbon budget for the 1.5°C goal by more than a third, and for the 2°C goal by almost one fifth. While carbon budgets have significant uncertainties depending on their exact definition and methodological approaches (see e.g. Millar et al. 2017; Rogelj et al. 2016), our estimates demonstrate that enhanced mitigation of non-CO_2 gases has quantifiable and significant benefits for the allowable CO_2 budget. Expanding the mitigation potential for livestock can thus make an important contribution to enable the world to achieve more ambitious mitigation targets, achieve a given target at lower costs across all sectors, or increase the probability that a given target will in fact be achieved.

In conclusion, our study demonstrates that the relative contribution from direct livestock emissions to future warming and hence the benefits from reducing those emissions are strongly dependent on global actions and goals to limit overall climate change. If the world does not make any effort to reduce GHG emissions from any other sector, direct livestock emissions would contribute only about 5% to total warming well in excess of 4°C by 2100, hence reducing livestock emissions would do little to avert widespread damages from unmitigated climate change (IPCC 2014a). By contrast, in a stringent mitigation scenario that seeks to limit warming to well below 2°C, direct livestock non-CO_2 emissions could be responsible for as much as one fifth of the total warming in 2100 even if livestock emissions are reduced well below business-as-usual trajectories. Indirect emissions associated with livestock supply chains, which were not quantified in our study, would increase the contribution from livestock further. Expanding the mitigation potential for direct livestock non-CO_2 emissions and implementing measures to reduce those emissions could thus make an important contribution to enable the world to meet ambitious mitigation goals (Wollenberg et al. 2016), especially to limit warming to 1.5°C as in the Paris Agreement.

Acknowledgements

We are grateful to Richard Houghton and Alexander Nassikas, Woods Hole Research Center, for providing us with data on CO_2 emissions from pasture conversions. The manuscript also benefited considerably from constructive comments from two reviewers.

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Table 1. Global direct non-CO_2 emissions from livestock based on the EDGAR database, and business-as-usual projections to 2050 and 2100 (for details, see text).

Source category	**1970**	**2010**	**2050**	**2100**
CH_4 from enteric fermentation and manure management (Mt CH_4 / yr)	80	113	143	157
N_2O from manure management (kt N_2O-N / yr)	149	218	314	346
N_2O from manure on soils (kt N_2O-N / yr)	1,332	1,873	2,510	2,761

Table 2. Contribution of direct livestock CH_4 and N_2O emissions and of CO_2 emissions from historical pasture conversions (CO_2 LUC) to modelled warming from all human activities, in 2010 and 2100. Percentage contributions are rounded. For details, see text.

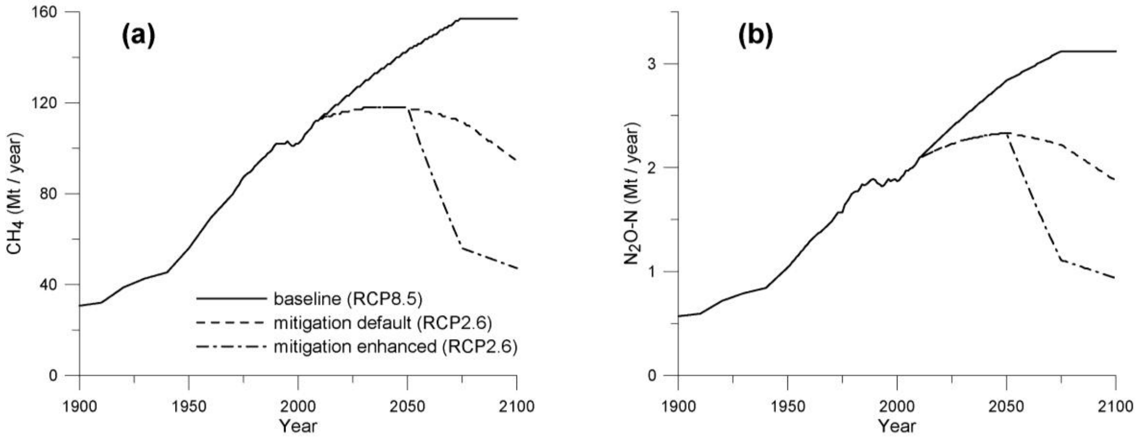
Year / scenario	**Modelled warming (MAGICC)**	**Contribution to modelled warming from direct (or directly attributable) livestock emissions**				
		CH_4	N_2O	non-CO_2	CO_2 LUC	**total**
2010	0.81°C	14%	5%	19%	3%	**23%**
2100 – RCP8.5	4.63°C	3%	2%	5%	0%	**5%**
2100 – RCP2.6	1.47°C	13%	6%	19%	2%	**20%**
2100 – RCP2.6 (enhanced mitigation)	1.38°C	8%	6%	14%	2%	**16%**

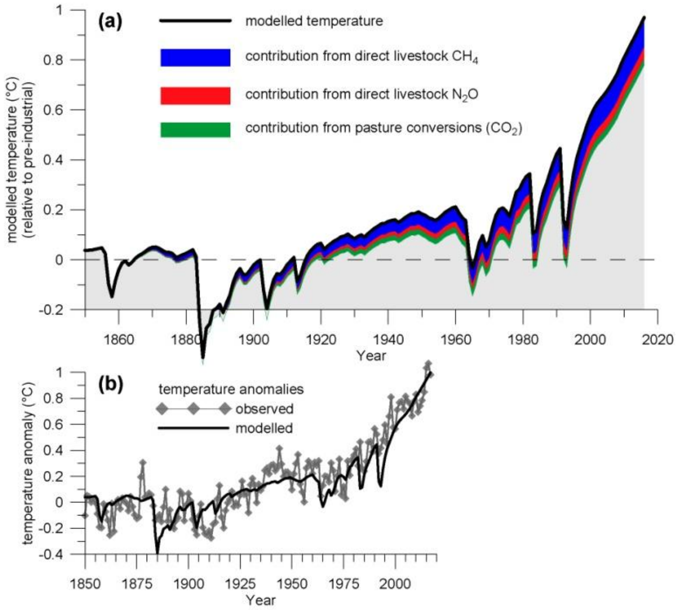
Figure 1. Estimated CH_4 (left: Fig. 1a) and N_2O (right: Fig 1b) emissions from 1900 to 2100, for a business-as-usual scenario associated with RCP8.5 (solid lines) and two stringent mitigation scenarios associated with RCP2.6 (dotted and dash-dotted lines).

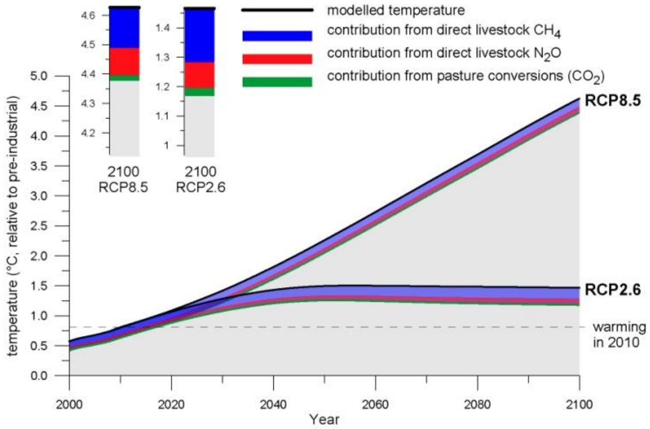
Figure 2. Modelled atmospheric temperature anomalies from 1850 to 2015 (top panel: Fig. 2a) for all anthropogenic emissions (bold black line), and with direct livestock emissions of CH_4 (blue), N_2O (red), and CO_2 from pasture conversions (green) subtracted from total global emissions. The lower panel (Fig. 2b) shows modelled and observed warming (HadCRUT4 with indicative data for 2017, relative to 1850-1900; Morice et al. 2012).

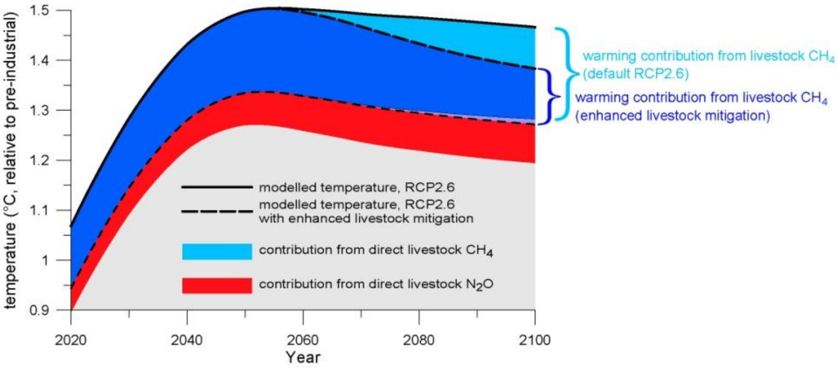
Figure 3. Modelled atmospheric temperature anomalies from 2000 to 2100 for all anthropogenic emissions (bold black line), and with livestock-related emissions of CH_4 (blue), N_2O (red), and CO_2 from pasture conversions (green) subtracted from total global emissions, for the RCP8.5 and RCP2.6 scenarios. Inset bar graphs show the absolute contributions of those emissions to modelled temperatures in 2100 for both scenarios. Note y-axes have the same spread in both insets, illustrating that the absolute warming from livestock-related emissions is greater in the RCP2.6 than in the RCP8.5 scenario despite lower non-CO_2 emissions.

Figure 4. Modelled atmospheric temperature anomalies from 2020 to 2100 for all anthropogenic emissions for the standard RCP2.6 pathway (solid lines) and with enhanced mitigation of direct livestock non-CO_2 emissions (dashed lines).


(a)
CH$_4$ (Mt / year)
160
120
80
40
0
1900
1950
2000
2050
2100
Year
baseline (RCP8.5)
mitigation default (RCP2.6)
mitigation enhanced (RCP2.6)
(b)
N$_2$O-N (Mt / year)
3
2
1
0
1900
1950
2000
2050
2100
Year


(a)
modelled temperature
contribution from direct livestock CH$_4$
contribution from direct livestock N$_2$O
contribution from pasture conversions (CO$_2$)
modelled temperature (°C) (relative to pre-industrial)
1
0.8
0.6
0.4
0.2
0
-0.2
1860
1880
1900
1920
1940
1960
1980
2000
2020
Year
(b)
temperature anomalies
observed
modelled
temperature anomaly (°C)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1850
1875
1900
1925
1950
1975
2000
Year


modelled temperature
contribution from direct livestock CH_4
contribution from direct livestock N_2O
contribution from pasture conversions (CO_2)
RCP8.5
RCP2.6
warming in 2010
temperature (°C, relative to pre-industrial)
Year
2000
2020
2040
2060
2080
2100
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
2100 RCP8.5
2100 RCP2.6
4.2
4.3
4.4
4.5
4.6
1
1.1
1.2
1.3
1.4


warming contribution from livestock CH_4 (default RCP2.6)
warming contribution from livestock CH_4 (enhanced livestock mitigation)
modelled temperature, RCP2.6
modelled temperature, RCP2.6 with enhanced livestock mitigation
contribution from direct livestock CH_4
contribution from direct livestock N_2O
temperature (°C, relative to pre-industrial)
Year
2020
2040
2060
2080
2100
0.9
1
1.1
1.2
1.3
1.4
1.5