

The tragedy of the cows: exploring the short and long-term warming effect of methane emissions in agricultural mitigation

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Abstract

This paper investigates how the short-lived character of methane could have important implications for the design of global climate change mitigation policies in agriculture, sector which is often seen to have a limited contribution to a net-zero carbon economy. Motivated by the renewed attention for the short-term versus long-term warming effects of methane, we explore how various appreciations of global warming affect cost-efficient mitigation policies and dietary transitions, and the implied warming. Results show that the choice of a particular metric is decisive if used to determine optimal mitigation options. For instance, focusing on the long-term warming effect of agricultural methane emissions could lead to a higher relevance of low meat diets relative to stringent mitigation policies. Moreover, a combination of stringent mitigation and dietary changes could help reverse the contribution of agriculture to global warming.

Introduction

Governments around the world have committed to reduce their greenhouse gas (GHG) emissions to limit the global temperature increase to well below 2 °C, while pursuing efforts to limit the increase to 1.5 degrees [1]. The Paris Agreement [2] establishes the framework to define countries' commitments through the elaboration of Nationally Determined Contributions (NDCs). The targets of the Paris agreement require careful consideration of the mitigation role of the agriculture sector. In their recent survey of targets and policies for mitigating GHG emissions in the Agriculture, Forestry and Land Use Change (AFOLU) sectors, the OECD shows that many countries already include specific targets for AFOLU emissions, with mitigation targets more frequent for agriculture for developed countries and the contrary for less developed ones [3]. However, agricultural emission reduction policies remain a long way from achieving the significant reductions that are suggested by modelled scenarios compatible with limiting warming to 1.5 - 2°C [4]. In addition, there are ongoing discussions around the role of short-lived greenhouse gases like methane, and associated metrics, with particularly significant implications on how agriculture contributes to climate mitigation and how this contribution is perceived.

GHG emission metrics pursue the goal of comparing the global warming contributions of different climate gases in a transparent and understandable way, without compromising climate scientific knowledge. As accounting tools, these metrics are commonly used to inform national frameworks for climate policies that are not derived from global climate modelling (i.e., based on explicit temperature targets), but instead from national decarbonisation trajectories. The latter are tracked through yearly national GHG inventories under the United Nations Framework Convention on Climate Change (UNFCCC) to check compliance with NDCs.

Non-CO₂ emissions are commonly reported as 'CO₂-equivalents' (CO₂€) and calculated using the 100-year Global Warming Potential (GWP₁₀₀) [5] [6] [7]. NDCs in which nations set out their emission reduction targets and economic costing tools valuing different emissions (or mitigations thereof), are largely built on this approach. The GWP₁₀₀ metric assumes that any emission of any climate gas, methane included, contributes to global warming in the same linear fashion. However, due to the short-lived character of methane, constant or decreasing methane emission rates would not induce additional global warming as the total stock of methane in the atmosphere would decrease [8] [9] [10].

Proposals to account for this effect include adding supplementary information in NDCs about the emissions levels of individual GHGs (e.g., as New Zealand having a separate target to reduce biogenic methane emissions), and/or reporting aggregated emissions using different metrics, such as shifting among conventional GWPs with different time horizons [11] or using alternative metric approaches, like GWP* [12] [13]. While this debate on the usefulness of alternative metrics is still ongoing in the scientific literature, the short-term and long-term warming effect of methane is well-established, but its implications for agricultural sector mitigation options needs to be explored. The effect of methane emissions on global warming is very different from CO₂. Constant emission rates for methane (and other short-lived gases) will result in only a relatively small contribution to additional warming beyond currently experienced temperatures, while increasing (decreasing) emission rates will result in a substantial contribution to global temperature change, causing warming (cooling) with respect to current temperatures. Therefore, accounting for this behaviour could have substantial implications for the way policy options in agro-economic policy analysis are evaluated and designed, and for the policy recommendations based on such studies. In this paper, we explore the impacts of acknowledging the distinct differences between short-lived and long-lived climate gasses in mitigation frameworks.

Contribution of the agricultural sector to ambitious mitigation efforts: a multi-model assessment

An ensemble of large-scale economic land use models is used to quantify the cost-effective contribution of agriculture to mitigating climate change under different valuations of methane based on a similar set of counterfactual scenarios as in [14]. The three economic models (CAPRI, GLOBIOM and MAGNET) have detailed representation of the agricultural sector, cross-sectoral linkages through factor markets and substitution effects, as well as their impact on emissions. Our focus is on the reduction of agricultural emissions over time and their effective contribution to climate change, differentiating between sources (e.g. ruminant, dairy and rice production) and world producing regions [15].

We analyse how mitigation policies (focussing either on the short or long-term effects) affect emission reductions and the consequences for the agricultural sector by way of two mitigation options. First, a global carbon price path on the supply side, inducing both the implementation of

mitigation options to reduce emission intensity and reducing production. Second, a change towards less animal protein based diets on the demand side. ‘Carbon pricing’ is widely acknowledged as an efficient means to achieve the ambitions set out in the Paris-agreement [16] [17] [18] [19]. Since emissions from agriculture are not easily monitored due to their biological nature, diverse land-use techniques and widely different farm management practices [20] [21] [22], carbon prices have been applied in agricultural economic models as a means to identify the cost-effective potential, or as an approximation of other mitigation policies [23] [14].

In this study, we explore alternative methane valuations based on the discussions that have arisen over implications of the short-lived character of methane by means of scenarios combining two different carbon prices (150\$/t and 500\$/t) on non-CO₂ agricultural emissions and a less animal protein based diet (see Table 1). Conventionally, the warming effect of methane is made comparable to CO₂ via the GWP₁₀₀, describing the integral of the induced warming over time (100 years) compared to that of CO₂. The GWP* method [12]^[13] stresses that the short term effect of methane is 4 times higher than in the conventional GWP₁₀₀ method, but is only 0.25 of the conventional GWP₁₀₀ (3.75 of the initial 4 is reversed) in the long term (equation 1). To reflect short term, conventional, or long-term perspective, we apply all three in the pricing schemes. With the GWP₁₀₀ of methane being 25, this results in methane equivalence factors (MEF) of 100, 25 and 6.25 respectively. The short and long-term factors, 100 and 6.25 are actually close to the 20-year Global Warming Potential (GWP₂₀), 84, and the 100-year Global Temperature change Potential (GTP₁₀₀), 4 (IPCC 5th Assessment Report).

$$E_{CO_2-w.e.(CH_4)} = GWP_{100} \times (4 \times E_{CH_4(t)} - 3.75 \times E_{CH_4(t-20)}) \quad (1)$$

Table 1 shows the mitigation and dietary shift scenarios analysed by the three economic models.

Table 1: scenario matrix. MEF-short term: 4x25 = 100, MEF-long term: 0.25x25 = 6.25

<i>Carbon pricing regime for methane</i>	<i>No carbon price</i>		<i>Carbon price 150\$</i>		<i>Carbon price 500\$</i>	
	<i>No dietary change</i>	<i>Low animal protein diet</i>	<i>No dietary change</i>	<i>Low animal protein diet</i>	<i>No dietary change</i>	<i>Low animal protein diet</i>
<i>No carbon pricing</i>	BASE	BASE_D				
<i>MEF-LT (=6.25)</i>			CP150_LT	CP150_LT_D	CP500_LT	CP500_LT_D
<i>GWP₁₀₀ (=25)</i>			CP150	CP150_D	CP500	CP500_D
<i>MEF-ST (=100)</i>			CP150_ST	CP150_ST_D	CP500_ST	CP500_ST_D

Long-term development of methane emissions in a business as usual situation

Our business-as-usual scenario (BASE) with no GHG mitigation policy corresponds to the Shared Socioeconomic Pathway 2 (SSP2), a “middle of the road” scenario which depicts a future of global development where developing countries achieve significant economic growth [27] [28]. With these assumptions, global agricultural methane emissions are expected to increase by over 50% between 2010 and 2070, reaching 170–240 Mt yr-1 in 2070, depending on the model. This increase comes at a decreasing rate (see Figure 1), reflecting a certain convergence of red meat and dairy consumption worldwide: while developed economies show a stable trend, developing countries continue increasing the intake of animal protein from very low levels. Most of the increase in methane emissions is to be attributed to higher productivity per animal in ruminant production, with cattle numbers slightly increasing (beef herds) or even decreasing (dairy herds).

Methane emission projections are very different from a regional perspective, what needs to be considered when mapping global mitigation initiatives into national policies. By 2010, about 57% of total agricultural methane emissions were coming from India, China, Brazil, Sub-Saharan Africa and the South-East Asia regions. By 2050 and 2070, these regions increase their share to about 62%. Sub Saharan Africa and India are expected to remain as the largest methane emitters, with about 40 to 50% of total methane emissions in all models. China in turn is characterized by stable or slightly decreasing emissions, depending on the model projection.

In order to show CH4 and N2O combined for the agricultural sector (and as emissions should not be cumulated when expressed in GWP₁₀₀, due to the short-lived character of methane), we present induced warming from both gases (see methods section on how we derive induced warming). Under the baseline, increasing CH4 emissions alone induce a warming of about 0.1 degree, and about 0.175 degrees together with N2O (see figure 2c and 2d).

Emission mitigation due to carbon pricing

The implementation of a \$150 carbon price (CP) to the agricultural sector based on GWP₁₀₀ yields an average reduction of 12%, 27% and 40% in methane emissions in 2030, 2050, and 2070, respectively (see Figure 2a). Similarly, the average impact of the \$500 carbon price constitutes a reduction of 23%, 40% and 52% in methane emissions for the three projections respectively (see Figure S2a). The impact of these methane

emissions for additional global warming is positive for CP150 (see Figure 2c), but turns negative for CP500 in 2070. High carbon pricing thus leads to substantial reduction in methane emissions, partially reversing some of the warming CH₄ emissions previously caused, as methane concentrations (and subsequently their contribution to warming) will fall if emission rates sufficiently decline. Despite that contribution, the warming effect of total non-CO₂ emissions from agriculture remains positive (plus 0.05 degree, figure 2d).

We further investigate the effects of a carbon price scheme that either focusses on the short-term or long-term temperature impact of methane emissions as explained above. For this, we model carbon pricing based on the short term effects (CP150_ST and CP500_ST) and on the long-term effects (CP150_LT and CP500_LT) derived from the original carbon price scenarios. A carbon price scheme focusing on the short-term temperature effect of methane considerably reduces methane emissions and turns the implied warming effect of this declining emission path negative (Figure 2c). CP500_ST yields the largest reduction in methane emissions since the carbon price level is 4 times higher than the one in CP500. However, emission reductions are considerably less than proportional to the carbon price increase. In fact, at this price level, technological options for mitigation are exhausted and agricultural systems become very constrained, facing severe income losses (Table 2). The opposite applies for CP500_LT, with a 27% reduction in methane emissions in 2070, and a four times lower carbon price compared to the 40% reduction with the original carbon price. The results for CP150_ST and CP150_LT can be found in the supplementary material.

Emission mitigation due to carbon pricing and low animal protein diet

While the simulated dietary shifts lead to further emission reduction on top of carbon pricing, dietary shifts alone have a lower impact on emission reduction compared to carbon pricing – at least for the given assumptions (see Figure 3c). When dietary shifts are combined with carbon pricing, induced warming from methane compared to 2010 turns negative for both carbon prices.

Adding dietary shifts to carbon pricing that focuses on either the short-term or the long-term effect of methane emissions, does not change the main results compared to a situation without dietary shifts. However, the magnitude of the impact is different. The additional impact of dietary shifts on reducing induced warming becomes larger (smaller) if the carbon price is based on the long-term (short-term) effect of methane emissions. Moreover, that effect decreases with the carbon price level consistently across all scenarios: the larger the reduction in warming due to carbon pricing, the less effect dietary shifts will have. When mitigation efforts incorporate the long-term effect of methane, carbon pricing becomes a less powerful mitigation tool relative to dietary shifts, which do not depend on carbon pricing. However, in absolute terms carbon pricing remains more important for mitigation than a dietary shift. The opposite holds when carbon pricing focuses on the short-term effect of methane. In this case, methane is priced heavier and the additional effect of dietary shifts decreases (Table 2).

Emission mitigation impact on global agriculture

Carbon pricing and dietary changes lead to a contraction of agricultural production (see Table 2). Dietary changes have a larger impact on production than carbon pricing. In the absence of carbon pricing, a dietary shift leads to a 13 per cent reduction in 2070 compared to the baseline. Adding a carbon price has minor additional impact. When dietary changes are considered, production drops between 15 and 19 per cent depending on the carbon pricing regime and the carbon price level. However, if no dietary changes are considered, production only decreases with between 2 and 8 per cent depending on the carbon price regime and level. The reason for this result is twofold. Firstly, carbon pricing allows, and incentivises, farmers to implement mitigation options without necessarily reducing production. Secondly, farmers can pass some of the costs over to consumers so to better maintain profitability in production. Table 2 indicates that the prices farmers receive at the farm gate increase in the presence of carbon pricing. In the case of a dietary shift, demand simply decreases. Moreover, producer prices fall, because the remaining production can be produced with lower costs. In the absence of carbon pricing, producer prices fall by 20 per cent. They still decrease up to 14 per cent if dietary shifts are combined with carbon pricing. In one case, CP500_ST_D, the price increase from carbon pricing and the price decrease from dietary shift outweigh each other.

The carbon pricing regime seems to have a limited effect on overall agricultural production, but a stronger effect on producer prices. Carbon pricing regimes that focus either on the short-term or the long-term warming impact of methane emissions, result in a 1 percentage point deviation of production compared to carbon pricing using conventional GWP100. Overall production decreases with 8 per cent under a carbon pricing regime based on the short-term warming impact of methane, while the reduction is 7 per cent under a GWP100 pricing regime and for a carbon price of \$150. A decomposition of the production effects reveals that carbon pricing leads to a decline in both crop, non-ruminant and ruminant production under all carbon pricing regimes and for all carbon price levels. As a major source of methane emissions, ruminant production experiences the largest decrease of the three types of production. At the same time, it is heavily affected by the choice of the carbon pricing scheme. About two-thirds of the decrease in ruminant production are reversed if the carbon pricing regime changes from conventional GWP100 to a regime based on the long-term warming impact of methane. The carbon pricing regime plays a much smaller role if a dietary shift causes the reduction in ruminant production. In this case, only one-tenth of the drop in ruminant production is reversed.

Producer prices show larger impacts, in particular when the carbon pricing regime focuses on the short-term warming impact of methane. For a carbon price of \$500, prices increase by 22 per cent under conventional CP500, but 37 per cent under CP500-ST (see Table 2). Also the uncertainty around those price changes is larger for higher carbon prices and short-term focus (see Figure 4).

Table 2: Result indicators for global agriculture by carbon pricing regime and carbon price level; average of models; percentage change relative to baseline in 2070

Result indicator	Carbon pricing regime	No carbon price	Carbon price level 150\$		Carbon price level 500\$	
		Low animal protein diet	No dietary change	Low animal protein diet	No dietary change	Low animal protein diet
<i>Added warming from CH4 emissions comp. to 2010</i>	No carbon pricing	-36				
	MEF-LT (=6.25)		-51	-80	-88	-109
	GWP ₁₀₀ (=25)		-85	-107	-117	-131
	MEF-ST (=100)		-115	-130	-132	-141
<i>Added warming from non-CO₂ emissions comp. to 2010</i>	No carbon pricing	-23				
	MEF-LT (=6.25)		-34	-53	-58	-72
	GWP ₁₀₀ (=25)		-53	-68	-74	-84
	MEF-ST (=100)		-70	-81	-84	-91
<i>Total production index</i>	No carbon pricing	-13				
	MEF-LT (=6.25)		-2	-15	-6	-17
	GWP ₁₀₀ (=25)		-3	-15	-7	-18
	MEF-ST (=100)		-4	-16	-8	-19
<i>Crop production index</i>	No carbon pricing	-8				
	MEF-LT (=6.25)		-2	-10	-5	-12
	GWP ₁₀₀ (=25)		-2	-10	-5	-12
	MEF-ST (=100)		-3	-10	-6	-12
<i>Non-ruminant production index</i>	No carbon pricing	-30				
	MEF-LT (=6.25)		-2	-30	-4	-31
	GWP ₁₀₀ (=25)		-2	-30	-4	-30
	MEF-ST (=100)		-1	-29	-3	-27
<i>Ruminant production index</i>	No carbon pricing	-27				
	MEF-LT (=6.25)		-8	-35	-17	-42
	GWP ₁₀₀ (=25)		-13	-39	-24	-46
	MEF-ST (=100)		-23	-45	-34	-51
<i>Producer price</i>	No carbon pricing	-20				
	MEF-LT (=6.25)		5	-14	16	-9
	GWP ₁₀₀ (=25)		8	-16	22	-6
	MEF-ST (=100)		15	-13	37	0

Discussion

Our analysis is, to the best of our knowledge, the first attempt of a rigorous modelling exercise to assess the impact of climate mitigation policy acknowledging the transiency of methane emissions on mitigation options in the agricultural sector. We present an analysis of how the choice of mitigation policies based on different valuation of methane relative to CO₂ are influencing methane emission trends simulated by the economic models contribute to further global warming. Conventionally, the impact of a certain sector on climate is evaluated though its greenhouse gas

emissions, typically reported in GWP100. However, due to the short-lived character of methane, (cumulative) CH₄ emissions do not necessarily correctly reflect implied warming, especially not under stringent mitigation scenarios. We therefore present here explicitly the warming induced by agricultural CH₄ and N₂O emissions.

Decreasing methane emissions from agriculture can have a negative warming effect. In this respect, decreasing methane emission rates have, in principle, the same effect as CO₂ uptake or carbon capture and storage technologies. This may allow for some leeway in the design of climate policy packages. However, this effect is not sustained when all climate pollutants are concerned. Our analysis shows that total agricultural emissions will contribute to further global warming irrespective of the carbon pricing regime and carbon price level. Compared to [14], the global warming impact remains unchanged until 2050 and starts decreasing while getting close to 2070, mainly due to a regional convergence of world animal protein consumption and technology adoption induced by carbon pricing. These results are linked to agricultural emission pathways based on medium and long-term projections of agricultural markets.

Consistent with earlier studies on the contribution of agriculture to stringent climate mitigation [29] [14], we find that comparable carbon pricing would reduce agricultural CH₄ and N₂O emissions by up to 58% and 53% respectively compared to the baseline in 2070, respectively, and reduce aggregate warming above 2010 levels to zero in 2070 (from 0.17°C in the baseline). Focussing specifically on the short-term effect of methane, will lead to even larger reductions in methane emissions, but will come with more severe impacts in the agricultural system in term of prices and production indices. The impact of diets as a mitigation option strongly depends on the context in which it is occurring. Reductions in meat consumption and production will significantly contribute to climate stabilisation and become a powerful mitigation technology if carbon pricing is moderate.

The *tragedy of the cows* lies in the increase of the significance of low animal protein diets relative to mitigation technologies. On the one hand, carbon pricing based on the long-term warming impact of methane relieves pressure to reduce cattle herds. On the other hand, that pricing regime also highlights the large immediate benefits of reducing methane as part of a transition towards a low carbon economy in particular given the relative short time horizon in which emission reductions have to be achieved. Moreover, while carbon pricing leaves farmers with the option to implement less emitting technologies that do not reduce herd sizes, a dietary shift simply means less cows.

Our results highlight – beyond the sheer emission and warming effects – the differential impact of various carbon pricing levels and dietary change on the agricultural sector. Carbon pricing has in general the largest effect on emissions, but with increasing carbon price levels, the impacts on the agricultural sector continue to increase, while further emission reductions are relatively small. This reflects a situation where the technical abatement options are fully applied and further reduction comes from price-induced reduction in consumption [29]. Consequently, incentives for agricultural mitigation might better be designed in a way that exploits the full technical abatements, but carefully, and regionally specific, addresses consumption effects.

Our results come with some limitations. Firstly, we apply a comparative-static modelling framework to a dynamic decision problem. Secondly, our model exercise disregards the costs to monitor emissions and to induce dietary shifts. Refraining from these transaction costs, our analysis potentially overestimates the efficiency, and hence the welfare benefits, of the investigated mitigation options. More research is needed to develop and analyse how a switch to metrics that better reflect the warming potential of different climate pollutants can be implemented in practice and whether transaction costs can render the efficiency of these mitigation options.

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Figures

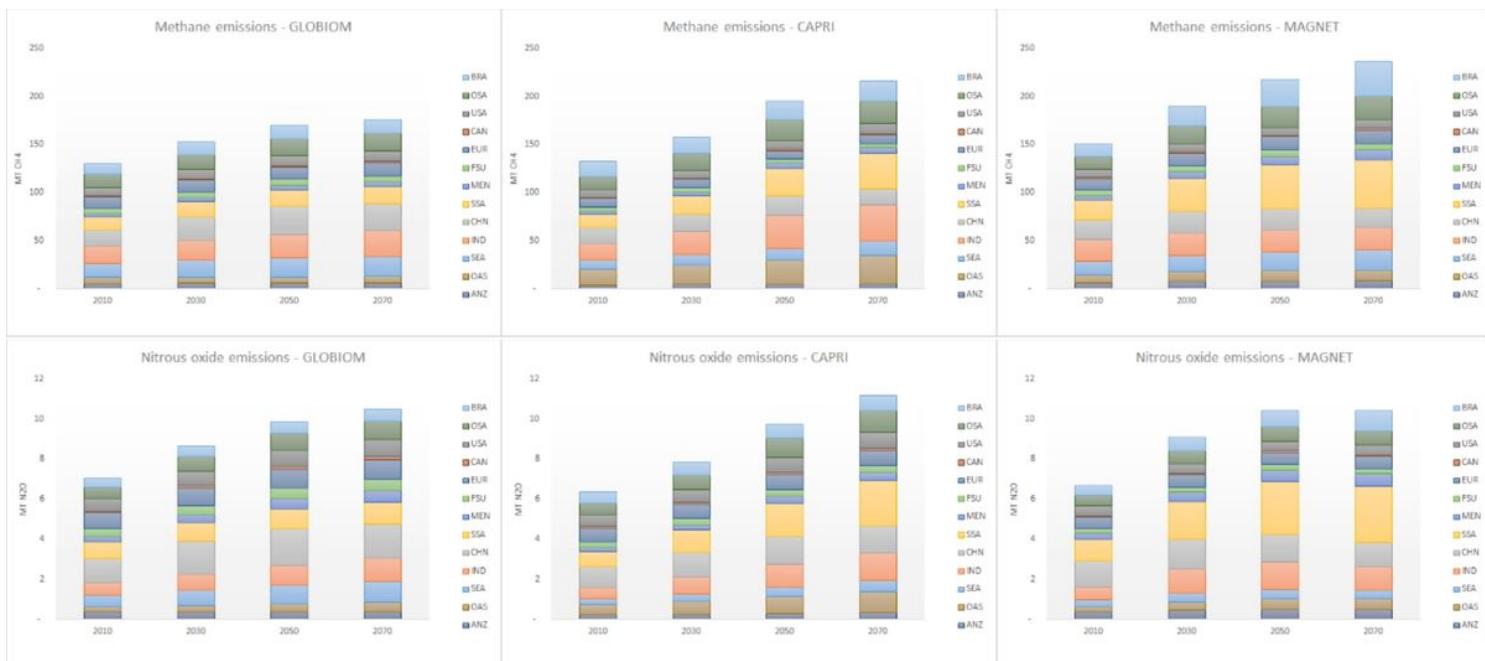


Figure 1

baseline methane emissions, regional totals for scenarios by baseline year and model (Mt CH₄). ANZ, Australia and New Zealand; OAS, other Asia; SEA, Southeast Asia; IND, India; CHN, China; SSA, sub-Saharan Africa; MEN, Middle East, North Africa and Turkey; FSU, former Soviet Union; EUR, Europe; CAN, Canada; USA, United States of America; OSA, other South, Central America and Caribbean (including Mexico); BRA, Brazil.

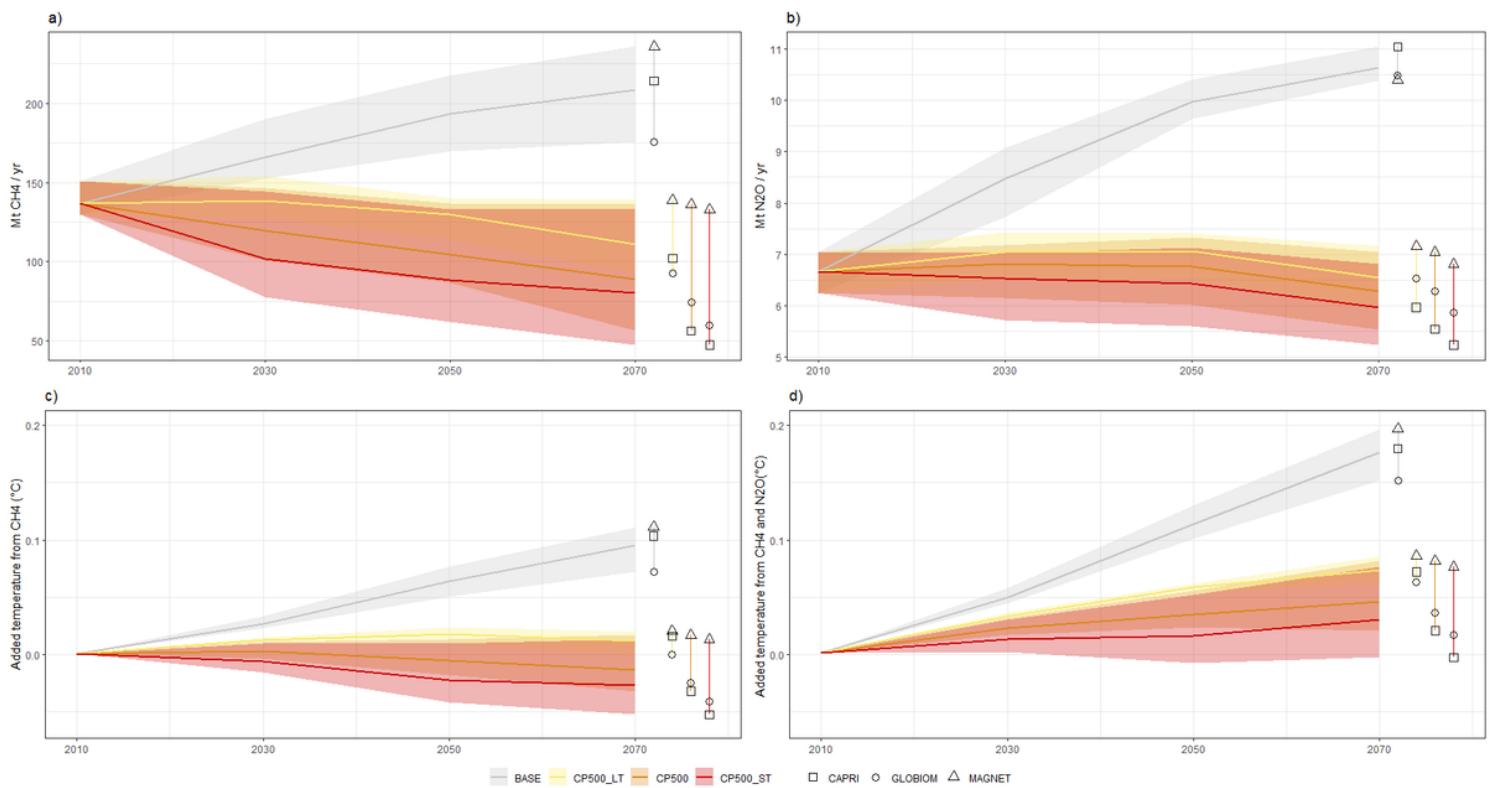


Figure 2

Methane and nitrous oxide emissions for the baseline and 500 \$/t carbon price scenarios; world totals by year and model; (a) annual Mt CH₄; (b) annual Mt N₂O; (c) added warming for CH₄ emissions (°C); and (d) added warming for total non-CO₂ emissions (in °C).

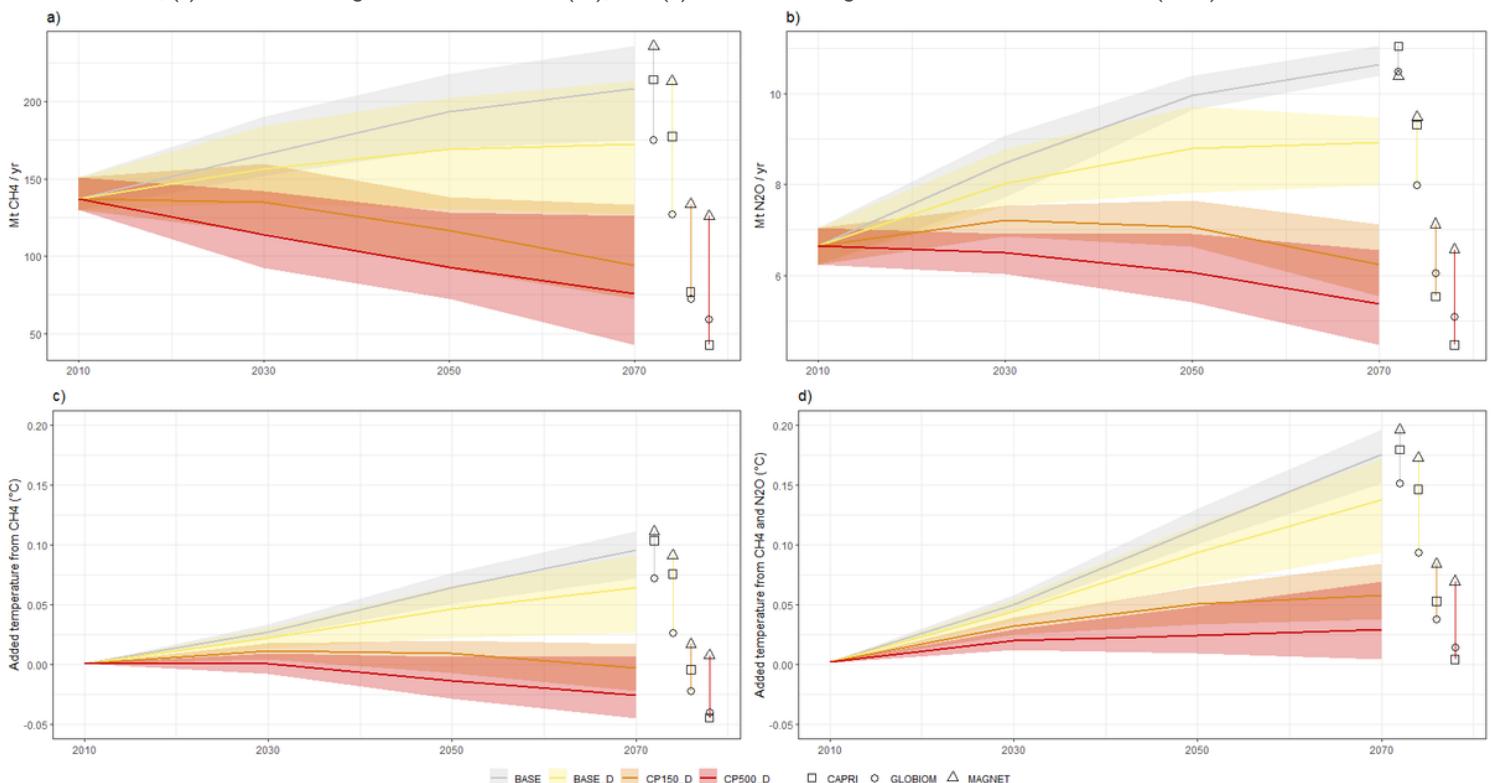


Figure 3

Methane and nitrous oxide emissions for the baseline and scenarios including diet shifts with and without carbon pricing; world totals by year and model; (a) annual Mt CH₄; (b) annual Mt N₂O; (c) added warming for CH₄ emissions (°C); and (d) added warming for total non CO₂

emissions ($^{\circ}\text{C}$).

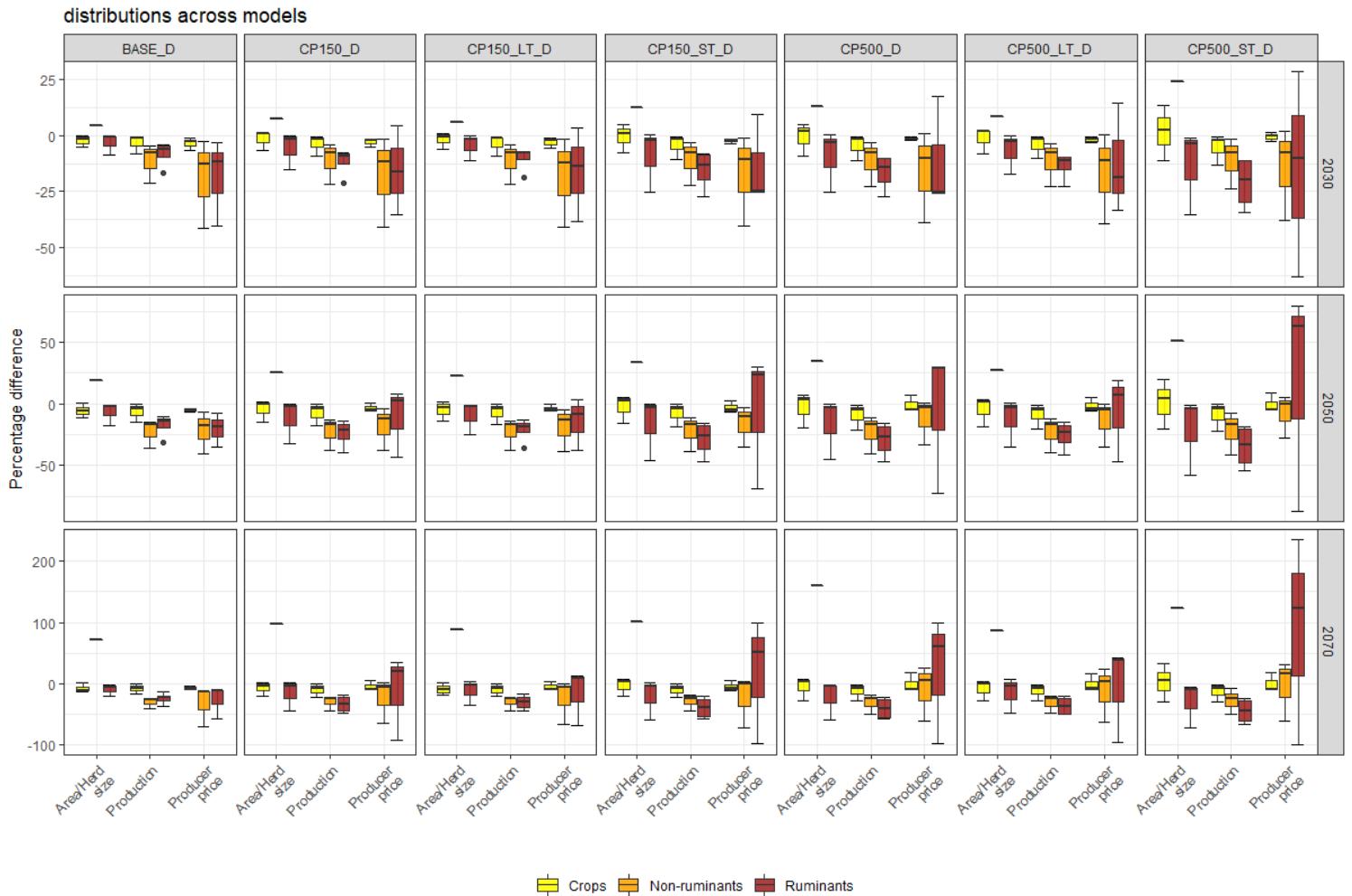


Figure 4

Area / herd sizes, production and producer prices for crops, non-ruminants and ruminants aggregate products; world totals for all scenarios by baseline year; average model estimates; percentage change relative to the baseline in 2070.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- HighlightsThe tragedy of the cow exploring the short and long term warming effect of methane emissions in agricultural mitigation.pdf
- SupplementaryMaterialThe tragedy of the cow exploring the short and long term warming effect of methane emissions in agricultural mitigation.docx