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ORIGINAL ARTICLE

The power and pain of market-based carbon policies: a global application to greenhouse gases from ruminant livestock production

B. Henderson[1,2,5] · **A. Golub**[3] · **D. Pambudi**[4] · **T. Hertel**[3] ·
C. Godde[1] · **M. Herrero**[1] · **O. Cacho**[5] · **P. Gerber**[6,7,2]

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Abstract The objectives of this research are to assess the greenhouse gas mitigation potential of carbon policies applied to the ruminant livestock sector [inclusive of the major ruminant species—cattle (*Bos Taurus and Bos indicus*), sheep (*Ovis aries*), and goats (*Capra hircus*)]—with particular emphasis on understanding the adjustment challenges posed by such policies.

✉ B. Henderson
ben.henderson@csiro.au

A. Golub
golub@purdue.edu

D. Pambudi
daniel.pambudi@nzier.org.nz

T. Hertel
hertel@purdue.edu

C. Godde
cecile.godde@csiro.au

M. Herrero
mario.herrero@csiro.au

O. Cacho
ocacho@une.edu.au

P. Gerber
pgerber@worldbank.org

[1] Commonwealth Scientific and Industrial Research Organization, Queensland Bioscience Precinct, 306 Carmody Road, St Lucia, Qld 4067, Australia

[2] UN Food and Agriculture Organization, Viale delle Terme di Caracalla, 00153 Rome, Italy

[3] Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, West Lafayette, IN 47907-2056, USA

We show that market-based mitigation policies can greatly amplify the mitigation potential identified in marginal abatement cost studies by harnessing powerful market forces such as product substitution and trade. We estimate that a carbon tax of US$20 per metric ton of carbon dioxide (CO_2) equivalent emissions could mitigate 626 metric megatons of CO_2 equivalent ruminant emissions per year ($MtCO_2$-eq year^{-1}). This policy would also incentivize a restructuring of cattle production, increasing the share of cattle meat coming from the multiproduct dairy sector compared to more emission intensive, single purpose beef sector. The mitigation potential from this simple policy represents an upper bound because it causes ruminant-based food production to fall and is therefore likely to be politically unpopular. In the spirit of the Paris Agreement (UNFCCC 2015), which expresses the ambition of reducing agricultural emissions while protecting food production, we assess a carbon policy that applies both a carbon tax and a subsidy to producers to manage the tradeoff between food production and mitigation. The policy maintains ruminant production and consumption levels in all regions, but for a much lower global emission reduction of 185 $MtCO_2$-eq year^{-1}. This research provides policymakers with a quantitative basis for designing policies that attempt to trade off mitigation effectiveness with producer and consumer welfare.

Keywords Mitigation · Greenhouse gases · Ruminants · Carbon policy

1 Introduction

Global measures to tackle climate change are urgently needed to avoid extreme and irreversible impacts on the world's ecosystems and economy (IPCC 2014). Early action will also help to limit large future costs associated with stabilizing atmospheric concentrations of greenhouse gas (GHG) emissions (Stern 2007). Amid strong public support for action on climate change in most jurisdictions, policies for global action are being reformulated as expiry of the Kyoto Protocol in 2020 looms large. The Paris Agreement (UNFCCC 2015) at the 21st session of the Conference of the Parties (COP 21) to the United Nations Framework Conventions on Climate Change (UNFCCC) has led to several sources of renewed optimism. Chief among these is greater involvement from low- and middle-income countries, particularly China. Financial support by high-income countries of US$100 billion per year by 2020 was further fortified with an extension until 2025, and a revised higher goal is to be set after this period (European Commission 2016). Perhaps most significant is the pursuit of a more ambitious target of a 1.5 °C increase above pre-industrial levels—well below the previously agreed 2 °C target (UNFCCC 2015; Mitchell et al. 2016). The need to reduce agricultural emissions while protecting food production also receives explicit mention in the Paris Agreement, an ambition which is explored in this study.

Ever since the livestock sector's substantial contribution to climate change was well publicized in the *Livestock's Long Shadow* report by the Food and Agricultural Organization of the United Nations (Steinfeld et al. 2006), a number of research efforts have been mobilized

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[4] New Zealand Institute of Economic Research, 215 Lambton Quay, Wellington 6011, New Zealand

[5] University of New England, Armidale, NSW 2351, Australia

[6] World Bank, 1818 H Street, NW Washington, DC 20433, USA

[7] Animal Production Systems group, Wageningen University, Wageningen 6708 PB, The Netherlands

to assess the potential for mitigating livestock GHG emissions (Popp et al. 2010; Havlík et al. 2014; Gerber et al. 2013; Smith et al. 2007, 2014). Herrero et al. (2016) recently reviewed the main contributions to this body of work, summarizing the global GHG mitigation potentials and policy options for the livestock sector and identifying important knowledge gaps. The authors found that while the technical potential for the sector to mitigate emissions through supply side practices such as improving animal diets, animal productivity, and carbon sequestration is relatively large (around 2.3 metric gigatons of carbon dioxide (CO_2) equivalent emissions per year ($GtCO_2$-eq year^{-1})), the quantity of emissions that is economically viable to mitigate through these measures is much smaller (around 0.4 $GtCO_2$-eq year^{-1} at US$20 per metric ton of CO_2 emissions ($20 tCO_2-eq^{-1})), owing to high abatement costs and barriers to adoption. The authors find far larger mitigation potentials of 4.3–6.4 $GtCO_2$-eq year^{-1} are possible from substantial reductions in the share of animal products human diets, particularly red meat. However, the economic viability and policy feasibility of such measures is highly uncertain.

In what is essentially a sequel to the *Livestock's Long Shadow* report, Gerber et al. (2013) conduct a comprehensive life cycle assessment of global livestock emissions and estimate the potential for mitigating these emissions. The authors estimate that 1.1 $GtCO_2$-eq year^{-1} of all supply chain emission could be abated if all livestock producers raised their production efficiency to same level as the top 25% of producers in each production system and region. Gerber et al. (2013) explain that economic barriers such as costs of mitigation practice adoption, technology transfer, and perceived risks of practice change all raise the minimum rate of return that producers would be willing to accept to adopt these practices. This provides justification for the use of mitigation incentives such as carbon taxes or abatement subsidies, as long as they are set at levels that do not exceed the marginal damage costs associated with climate change. However, to gain traction among policymakers, mitigation policies need to be commensurate with development and food security goals, particularly in low-income countries.

Global support for carbon pricing as the mitigation instrument of choice has been mounting in recent years. Following a groundswell of support from 74 countries and more than 1000 companies at the 2014 United Nations (UN) Climate Summit, the Carbon Pricing Leadership Coalition was officially launched at COP 21. This unprecedented alliance of government, civil society, and business leaders has emerged to promote the widespread adoption of carbon pricing (Carbon Pricing Leadership 2016). Initiatives specific to the livestock sector have also begun organizing global mitigation efforts around UN Sustainable Development Goals (SDGs), including those based on taking urgent action to combat climate change (SDG 13) and to reverse land degradation (SDG 15), which is an important option for sequestering soil carbon. For example, the Global Dairy Agenda for Action (2016) has expressed its commitment to reducing its GHGs and climate-related impacts through measures including feed and pasture management. The Livestock Global Alliance (2016) and the Global Agenda for Sustainable Livestock (2016) are other important multi-stakeholder coalitions that have expressed their commitment to these SDGs.

With growing enthusiasm for action on climate change as new agreements for the post-Kyoto period continue to be negotiated, now is the opportune time to revisit the potential contribution that globally coordinated mitigation policies in agriculture could make. Accordingly, in this study we assess the *ex-ante* potential of global carbon price policies, focussing on the ruminant livestock sector [inclusive of the major ruminant species—cattle (*Bos Taurus and Bos indicus*), sheep (*Ovis aries*), and goats (*Capra hircus*)]. The agriculture sector as a whole contributed 5.2–5.8 $GtCO_2$-eq $year^{-1}$ in 2010, representing 10–12% of total annual anthropogenic emissions (Smith et al. 2014). Ruminants comprise the dominant share of these emissions: ruminant digestion (enteric fermentation) and manure deposited on pasture by ruminants account for 32–40 and 15% of agricultural GHG emissions, respectively, based on Intergovernmental Panel on Climate Change (IPCC) accounting methods (Smith et al. 2014).

This study contributes to a small but growing body of economic modeling work that has assessed the mitigation potential of carbon price policies in the global livestock sector. It builds on work by Golub et al. (2013) by developing a new disaggregation scheme for the livestock sector, which allows us to explore in more detail the potential impacts of carbon policies on the structure of global ruminant sector. In the "Discussion" section, we compare findings from other global economic mitigation assessments including Golub et al. (2013), Avetisyan et al. (2011), and Wollenberg et al. (2016). These studies all rely on marginal abatement cost (MAC) data from the US Environmental Protection Agency (US EPA 2006; US EPA 2013), which exclude soil carbon and uses an average cost accounting approach for calculating abatement costs. Our study advances on this literature by taking advantage of recently published MAC curves developed by Henderson et al. (2015a), which include soil carbon and accounts for heterogeneity in producer costs within regions and production systems to provide more robust MAC estimates. More details about this MAC study and its integration with the present analysis are provided in "Methods and data."

The main objectives of this research are to assess the GHG mitigation potential of carbon policies targeting ruminant sector producers, with particular emphasis on the additional mitigation potential, as well as the adjustment challenges posed by market-based policy instruments. We test alternative policy designs, which differ with respect to their emphasis on either maximizing mitigation potential or minimizing negative impacts on ruminant producers and consumers. Finally, we draw on a key model revision, namely the specification of dairy as a multiproduct (meat and milk) industry, to provide additional insights about the structural impact that carbon policies would have on the ruminant sector.

2 Methods and data

2.1 Modeling framework

The analysis in this study is based on a version of the general equilibrium model known as the Global Trade Analysis Project–Agro-Ecological Zone–Greenhouse Gas (GTAP-AEZ-GHG) model (Golub et al. 2013; Hertel et al. 2009). The GTAP-AEZ-GHG model is based on GTAP-E model (Burniaux and Truong (2002), McDougall and Golub (2007)), which was initially designed for analyzing energy–economy and environment–trade linkages. The GTAP-E model is in turn based on the standard GTAP model (Hertel 1997). In GTAP-AEZ-GHG, as well as in the standard GTAP model, the regional household collects all factor earnings and taxes. The regional household spends its income according to a Cobb-Douglas expenditure function and derives its utility from three sources: private expenditure, government expenditure, and saving. Private household expenditures on goods and services are determined by a constant difference of elasticity expenditure function. Intermediate inputs (demanded by producers) and final consumption goods (demanded by private households and government in each region) are traded across regions. The Armington approach to trade is employed so that domestic and imported goods and imports coming from different countries/regions are imperfect substitutes. The model assumes perfect competition, constant returns to scale, and profit and utility maximizing behavior of firms and regional households, respectively. Production sectors are modeled using nested constant elasticity of substitution functions. The model also assumes that all markets are in equilibrium. Factor market clearing requires that supply equals demand for skilled and unskilled labor and capital, natural resources and land, and adjustments in each of these markets in response to the climate policy determine the resulting factor price impacts.

The GTAP-AEZ-GHG model extends the GTAP-E and standard GTAP models by incorporating land use and GHG emissions modules. Within each region of the model, the land endowment is split into agro-ecological zones (AEZs) (Lee et al. 2009) to capture heterogeneous environmental and economic characteristics of land use activities. The model incorporates detailed non-CO_2 GHG and CO_2 emissions mapped directly to regions and economic sectors. For the analysis presented here, the GTAP-AEZ-GHG model database was extensively modified to permit a more accurate representation of production, consumption, emissions, and abatement in the global livestock sectors. The GTAP-AEZ-GHG model described by Golub et al. (2013) was based on GTAP version 6 database, representing global economy in 2001. Using GTAP version 7 database (Narayanan and Walmsley 2008), Irfanoglu (2013) updated the model to a base year of 2004. The latter serves as a starting point in the analysis presented in the current paper. Next, the standard GTAP ruminant sector was split into large ruminant and small ruminant meat sectors. The large ruminant sector is almost exclusively comprised of cattle, whereas the small ruminant sector comprises sheep and goats. Following this, we took steps to create a multiproduct dairy sector, producing both meat and milk, based on all animals in the herd that are required to support the production of milk, including milk cows, breeding animals, and animals fattened for meat production as a by-product of the dairy herds. This involved separating the cattle meat associated with our broadly defined dairy sector from the large ruminant sector and then linking this dairy meat commodity to the GTAP dairy sector. In this new dairy sector, meat and milk are produced as joint products. The production and consumption structures of GTAP-AEZ-GHG model were also modified to introduce substitution between ruminant meat produced by the multiproduct dairy sector and meat produced by the specialized beef sector, to reflect that these two meat products are close substitutes.

The standard GTAP database follows the format of one produced commodity per sector. The introduction of a multiproduct dairy sector in our analysis was motivated by the need to account for the vastly different emission intensities of meat produced by the dairy and specialized beef cattle herds. Gerber et al. (2013) estimate that meat from the latter is nearly four times as emission intensive as meat from the dairy herd (Gerber et al. 2013). This large difference in emission intensities relates to the size of the breeding herd overhead and the volume of outputs produced by each production system. As explained by Gerber et al. (2013), the breeding herd overhead refers to the animals in the herd that are dedicated to reproduction rather than production. The breeding herd is the main source of emissions in cattle systems due to their relatively large size and the low quality of feed they receive compared to either milk cows or cattle being fattened. Globally, reproductive animals comprise 69% of the specialized beef herd and only 52% of the dairy herd (Gerber et al. 2013). Moreover, because the dairy herd produces both milk and meat, its GHG emissions are spread over a greater volume of products, both in terms of protein content and economic value, than for specialized beef. Given these differences in emission intensities, we expect that carbon policies will lead to a contraction of meat supplied from the specialized beef sector relative to the dairy sector. To modify the database and create a multiproduct dairy sector, we relied on data from Global

Livestock Environmental Assessment Model (GLEAM) (Gerber et al. 2013), which specifies the proportion of cattle meat from dairy herds and beef herds. GLEAM is a spatial model of livestock production, which models the biophysical relationships between livestock populations, production, and feed inputs for each livestock production system and country in the world (Gerber et al. 2013; Opio et al. 2013). The model has been cross-validated across a range of ruminant production systems, and regions, and publications based on GLEAM have been through rigorous peer review (Gerber et al. 2013; Opio et al. 2013). In addition, the GHG emissions corresponding to the newly created ruminant sectors in the GTAP database were also updated using GLEAM. The abatement responses for each ruminant sector and region were then calibrated to the recently published MAC curves by Henderson et al. (2015a). This was done by linking animal GHG emissions [methane (CH_4) and nitrous oxide (N_20)] to the products of each ruminant sector and then, while constraining output quantities and input prices to match the assumptions of the MAC curves, we adjusted an elasticity parameter governing the tradeoff between production resources and emissions to match the mitigation response of Henderson et al. (2015a) MAC curves at the selected carbon price of \$20 tCO_2-eq^{-1}.

2.2 Emissions and marginal abatement costs

For the purposes of brevity and ease of exposition, the data and results are aggregated into nine global regions, namely South Asia (S Asia), Latin America (L America), Sub Saharan Africa (SSA), East and South East Asia (E and SE Asia), Middle East and North Africa (MENA), Russia and Central Asia (Russia and CA), Europe, Oceania and North America (N America), and two ruminant sectors (multiproduct dairy sector and a combined beef and small ruminant (BSR) sector). This ruminant sector aggregation was also motivated by the management similarities between beef and small ruminants, compared to the relatively more intensively managed dairy sector. Total global ruminant GHG emissions from enteric fermentation and manure sources amount to about 3.36 $GtCO_2$-eq $year^{-1}$, with 45% from the dairy sector and 55% from the BSR sector (Fig. 1). Key regions for emissions are L America, S Asia, SSA, E and SE Asia, followed by N America, Europe, and MENA. This order of emission contributions closely corresponds to size of the ruminant populations in each region.

As articulated by Avetisyan et al. (2011) and Hertel et al. (2009), the cost and therefore the mitigation incentive of a carbon price-based policy depends on the economic emission intensity of a sector's output. That is, the amount of GHG emissions from a sector divided by the economic value of its output. For any carbon price, this will determine the relative cost of the carbon tax to producers. Since ruminant products are one of the most emission-intensive products in the agricultural sector (Golub et al. 2009), we expect carbon prices to generate relatively large mitigation incentives in these sectors. An additional factor influencing the cost of the policy is the flexibility with which producers can reduce emissions without compromising production. This depends on the availability of affordable options for lowering their emission intensity. As shown by Beach et al. (2008), Moran et al. (2011), and Henderson et al. (2015a), there are a number of low-cost mitigation options that can raise productivity and lower the emission intensity of ruminant outputs at the same time (e.g., improved feed quality). In these studies, the MAC curves were estimated under assumptions that typify MAC assessments, such as constant output quantities as well as constant input and output prices. These curves describe incremental increases in the costs of reducing GHG emissions using a range of practices. These marginal costs increase as the cheapest abatement options are

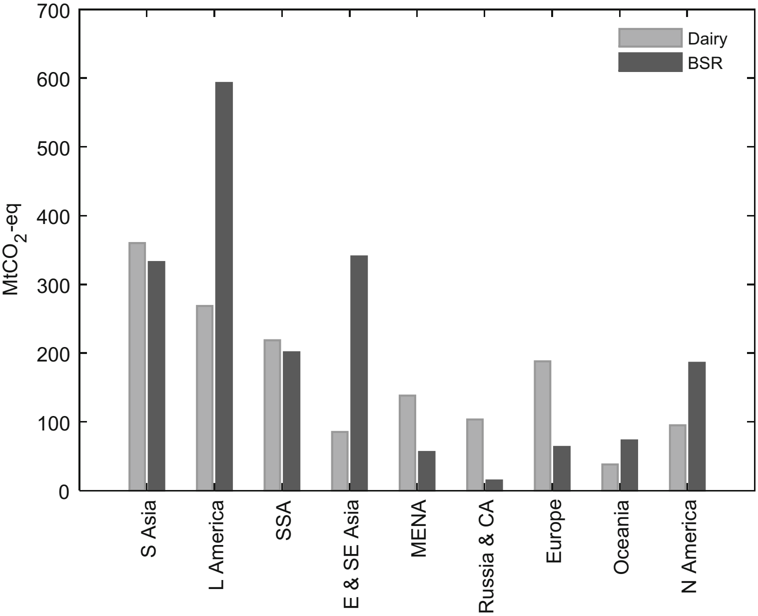

Fig. 1 Ruminant GHG emissions (CH_4 and N_2O from enteric fermentation and manure) by region and sector

exhausted initially, followed by increasingly more expensive options. Given the importance of the MAC curves from Henderson et al. (2015a) in influencing the mitigation outcomes of this study, we provide a brief summary of the options and approach used in that study, but refer readers to the paper for further details.

Henderson et al. (2015a) advanced on previous assessments by incorporating spatial heterogeneity in the costs and benefits of abatement practices to calculate marginal costs rather than more commonly reported average costs of abatement. Five of the most promising available abatement options were selected by Henderson et al. (2015a), based on agreement in the literature about their effectiveness and suitability under a wide range of ruminant production systems. These options included improved grazing management and the sowing of legumes to sequester soil carbon in grazing lands, as well as the feeding of dietary oils and the urea treatment of crop straws to target enteric CH_4. Henderson et al. (2015a) estimate that 249 metric megatons of CO_2 equivalent emissions ($MtCO_2$-eq) could be abated by all ruminant sectors collectively each year at a carbon price of \$20 $tCO_2\text{-eq}^{-1}$. Nearly three quarters of this mitigation potential was from grazing land measures that sequester soil carbon (improved grazing management and legume sowing), with the remaining contribution from the dietary measures that targeted reductions in enteric (CH_4) emissions.

We use these results from Henderson et al. (2015a) as a benchmark in this study to represent the quantity of emission reductions possible at \$20 $tCO_2\text{-eq}^{-1}$ under the usual MAC curve assumptions of constant output and prices. As with other MAC studies, this benchmark does not consider market interactions, which can alter input and output prices and lead to a substitution towards less emission-intensive products by producers and consumers, and change the costs of mitigation, especially when applied at a large scale. We test two scenarios to account for these effects which have the potential to significantly alter mitigation outcomes, as outlined below.

2.3 Policy scenarios

As policy arrangements for the post-2020 period, following expiry of the Kyoto Protocol, are still taking shape, we kept our policy scenarios as general as possible. Two global policy scenarios inclusive of both abatement practices and market interactions were tested and compared to the MAC benchmark which is a purely practice-based mitigation scenario:

MAC benchmark: Practice-based mitigation of ruminant GHG emissions at \$20 tCO_2-eq^{-1}.

Scenario 1: Market and practice-based mitigation with a \$20 tCO_2-eq^{-1} tax levied on ruminant producers' GHG emissions.

Scenario 2: Market and practice-based mitigation with a \$20 tCO_2-eq^{-1} tax levied on ruminant producers' GHG emissions, combined with an output subsidy to offset the cost of the tax.

The MAC benchmark represents the quantity of mitigation that would be possible from implementing abatement practices in the absence of market interactions. It serves as a useful benchmark to compare the subsequent scenarios against, to demonstrate the important role that these interactions play. Scenario 1 is purely motivated by the objective of enhancing economic efficiency, since taxing producers' entire volume of emissions is the most efficient approach to deal with externalities such as GHGs. This approach is economically efficient because, according to economic theory on managing externalities, it creates the correct incentives for producers with high emission intensities to adjust production practices or exit the industry and prevents new emission intensive entrants (Baumol and Oates 1988). This approach however ignores the obvious political resistance that such a policy will generate and the important competing objectives of economic development and food security. Scenario 2 takes these concerns into account and returns the carbon tax revenue collected to producers in the form of an output price subsidy. In doing so this policy seeks to maintain marginal incentives to abate emissions, while compensating producers for the cost of the policy associated with GHG emissions that are too expensive to reduce at the given carbon price. With both policy instruments (Scenario 1 and Scenario 2), the tax on emissions provides an incentive for producers to expend resources to offset or abate emissions. The increase in resource use incurs additional costs and therefore only occurs to the point where the cost of an additional unit of resources (i.e., the marginal cost) is equal to the carbon price of \$20 tCO_2-eq^{-1}. This results in an increase in the price of supplying ruminant products because the additional resources expended to reduce emissions and, in Scenario 1, the unabated taxed emissions increase production costs. We expect the latter costs to dominate in Scenario 1 and result in a significant increase in the price of ruminant products, and cause a corresponding reduction in demand and output. Since the tax costs imposed on unabated emissions are negated by a subsidy in Scenario 2, producers should be able to sell their products at a more competitive price than in Scenario 1, and they should therefore be able to maintain their output at close to baseline levels.

2.4 Sensitivity analysis

To address possible model and data uncertainty, we conducted a sensitivity analysis on a selection of key model parameters and emissions data. We implemented the Gaussian Quadrature approach to systematic sensitivity analysis developed by DeVuyst and Preckel (1997).

For economy-wide equilibrium models such as the one used in this study, this approach is preferred to Monte Carlo methods because it requires much fewer number of solutions. The procedure follows Pearson and Arndt (1998) and generates a mean and standard deviation for each endogenous variable based on the uncertainty underpinning key economic parameters in the model. As mentioned, the GTAP-AEZ-GHG model employs an Armington assumption for the trade of goods, whereby domestic and imported goods are imperfect substitutes, and the same holds true for imports coming from different regions. How easily a region can change the composition of its imports and split between domestic and imported varieties in response to a policy is determined through the value of the Armington trade elasticity. If the trade elasticity is small, then the scope for sourcing from countries with low emission intensities of production and/or from countries with many cheap abatement options is limited. On the other hand, with very high trade elasticities, the global distribution of production will be much more sensitive to any cost differentials that emerge due to the carbon policy, and we will see much larger output and emission reductions in emission-intensive ruminant sectors. Due to the critical role that Armington parameters play in determining these trade patterns, we consider sensitivity of the results with respect to the trade elasticities, both among imports and between composite of imports and domestic goods and services. We also included two other important parameters in the sensitivity analysis, namely the calibrated MAC elasticities that determine responsiveness of mitigation to the carbon price policies in each ruminant sector and region, and the region- and sector-specific emission intensities of ruminant production. For each of these parameters, we specified symmetric triangular distributions, assumed the parameters range from 0.5 to 1.5 times the central value, and varied all of the parameters together. That is, if one parameter is over-estimated, then all of them are. The latter assumption will give us the maximum standard deviation of the results and hence the most conservative confidence interval.

3 Results

3.1 Scenario 1

The results in this study reflect average annual changes over the medium term (i.e,. an approximate 20-year period). The global mitigation results presented in Fig. 2 clearly reveal the power of market incentives. By harnessing important market interactions such as product substitution and trade in Scenario 1, it was possible to generate a massive additional increase in the overall quantity of emission reductions from 249 to 626 MtCO$_2$-eq year^{-1}. This is because the taxed ruminant products in emission-intensive regions and sectors become more expensive and are substituted by other meat products and ruminant products from less emission-intensive regions and sectors.

Three quarters of the total emission reductions under the global carbon tax are from the BSR sector, with the remaining quarter provided by the dairy sector (Table 2). Notably, most of the reduction in ruminant emissions stems from reductions in output (71%), as the fall in consumer demand due to higher prices from the carbon tax dominate the reductions achieved by lowering emission intensities. This is most clearly the case in the BSR sector, where the combination of relatively high emission intensities and low capacity for abatement results in larger contraction in global output (5% for BSR compared to 1% for dairy). The Scenario 1 tax causes a value-weighted average reduction in global ruminant production of only 2%; however, the low-income regions experience a disproportionate fall in production, especially for the BSR sector

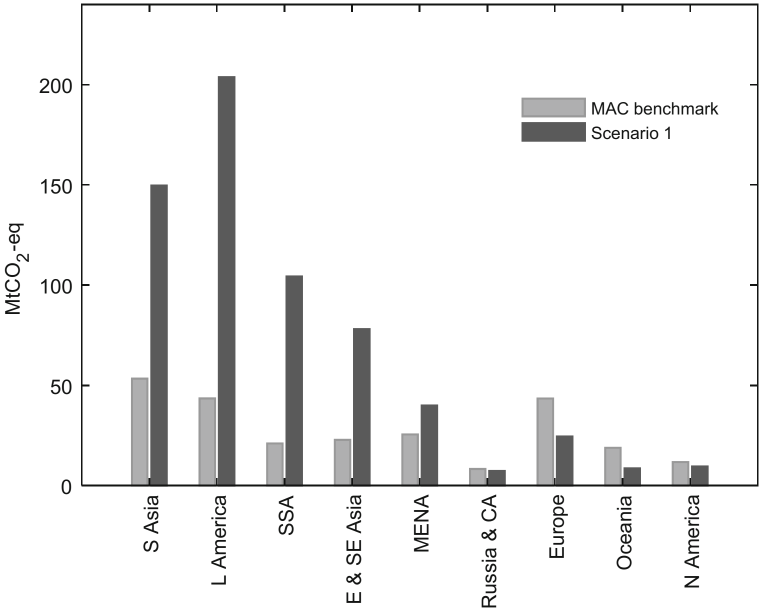

Fig. 2 Annual GHG mitigation without market interactions (MAC benchmark) and with market interactions under global carbon tax of $20 tCO_2-eq (Scenario 1), by region, for all ruminant sectors combined

(Fig. 3), because they tend to be more emission intensive. In contrast, output changes are either negligible or positive in N America, Europe, and Oceania (Fig. 3) because products from these regions become relatively cheaper, leading to trade-based substitution of these products into

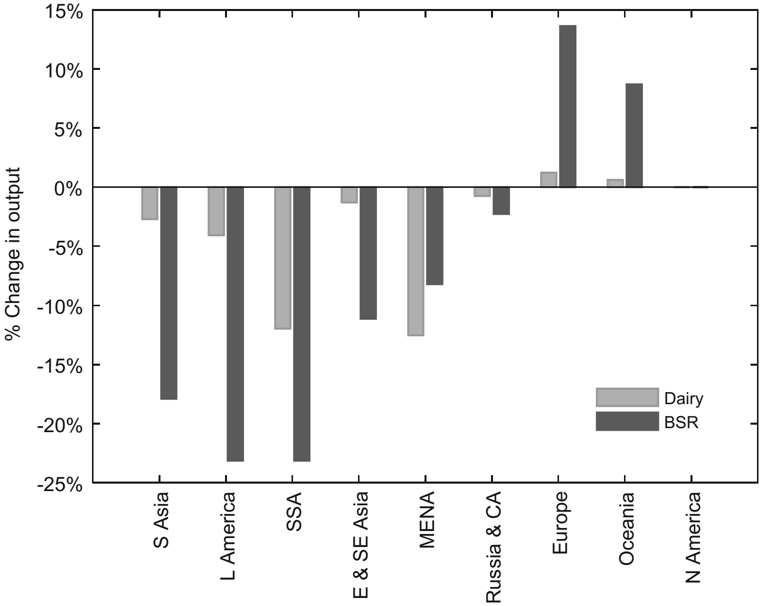

Fig. 3 Annual percentage changes in ruminant output under the global $20 tCO_2-eq carbon tax (Scenario 1), by sector and region

markets previously supplied with more emission-intensive products. Consequently, market interactions lower the abatement potential of the sector in these regions (Fig. 2).

The regional distributions of the emission reductions from the emission tax for each sector are shown in Figs. 4 and 5, where mitigation is decomposed into emission reductions from changes in output and changes in emission intensities. While most of the emission reductions from the dairy sector arise in S Asia, SSA, L America, and MENA, Europe is not far behind, and in terms of the volume of mitigation achieved by lowering the emission intensity of production, it is second only to S Asia. Naturally, in regions where dairy products are more emission intensive (e.g., S Asia, SSA, MENA, and L America), output reductions drive a much larger share of their mitigation potential. A similar regional pattern of mitigation emerges for the BSR sector, with S Asia, SSA, and L America again among the top 3 regional sources of emission reductions, although this time E and SE Asia displaces MENA in fourth position given the relatively large share of world's BSR production in E and SE Asia, particularly in China. In both sectors, the same three regions (Europe, Oceania, and N America) display either flat or slightly increasing output as higher export demand for products with relatively low emission intensities from these regions offset the additional costs imposed by the emissions tax.

We now turn our attention to the impact that a global ruminant carbon tax could have on reallocating the shares of meat supplied from the beef and dairy sectors. As mentioned, the dairy sector in this study includes the entire dairy herd, which operates as a multiproduct system supplying both milk and meat products. Since meat produced by the dairy sector is much less emission intensive than meat from the beef sector, the global carbon tax led to an increase in the share of cattle meat supplied by the dairy sector and an equivalent contraction in the share of meat supplied by the beef sector (Fig. 6 and Table 1). For S Asia and SSA, the shift towards meat supplied from the dairy sector is relatively large by 8%. In contrast, there is an offsetting influence in Oceania and Europe where beef production and exports increase to

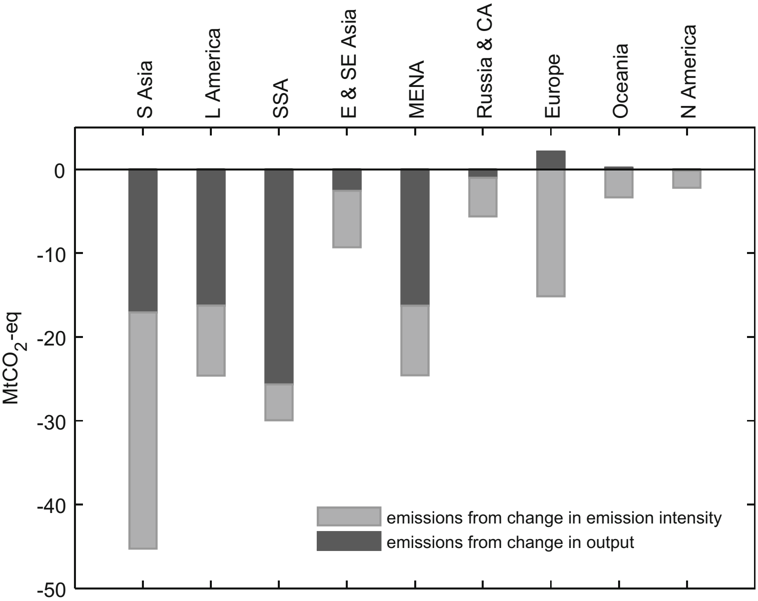

Fig. 4 Annual mitigation of dairy sector emissions in Scenario 1, decomposed into emission reductions from lower output and emission intensities, by region

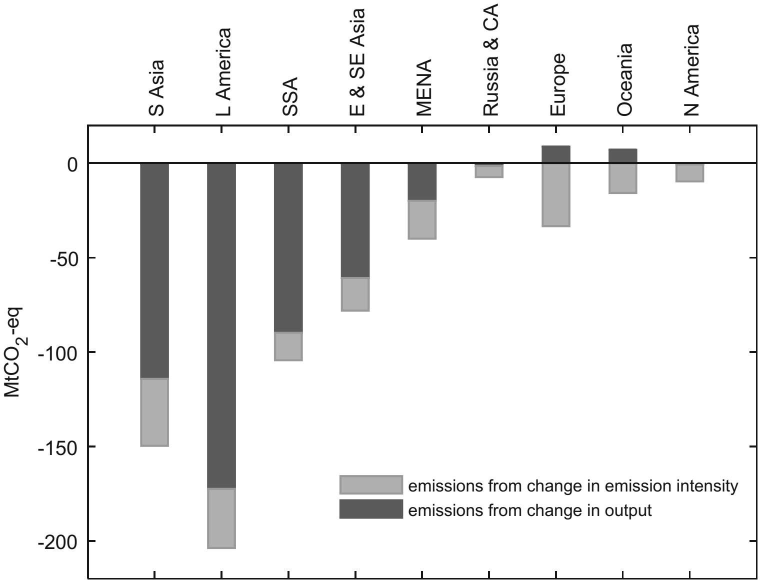

Fig. 5 Annual mitigation of BSR sector emissions in Scenario 1, decomposed into emission reductions from lower output and emission intensities, by region

make up for some of the fall in cattle meat production in low-income regions. The combined effect is a 1.3% increase in meat from dairy at the global level. While this shift towards a sector that is less emission intensive represents an improvement in resource use efficiency, the negative impacts on production in low-income regions calls into question the suitability and

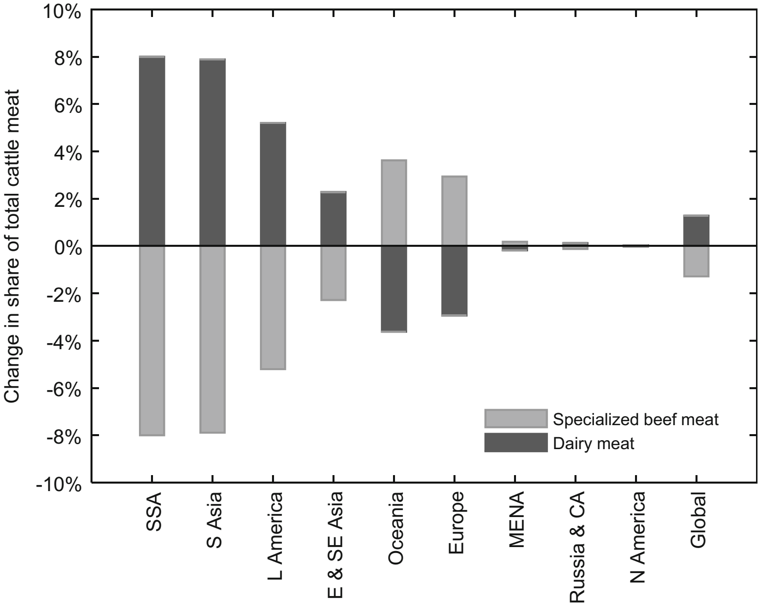

Fig. 6 Annual percentage changes in cattle meat supplied from dairy and beef sectors the global \$20 tCO$_2$-eq carbon tax (Scenario 1), by region

Table 1 The percentage shares (%) of cattle meat from dairy and beef sectors by region, in the baseline and in Scenario 1

	S Asia	L America	SSA	E and SE Asia	MENA	Russia and CA	Europe	Oceania	N America
Baseline									
Dairy meat	60	33	69	34	97	99	75	39	27
Beef meat	40	67	31	66	3	1	25	61	73
Scenario 1									
Dairy meat	68	38	77	36	97	100	73	36	27
Beef meat	32	62	23	64	3	0	27	64	73

political feasibility of such a blunt policy option. In addition, from a purely practical perspective, it would be very difficult to collect tax payments from lo-income producers given that they are unlikely to be able to afford the additional expense. Thus, for carbon policies to be feasible in these contexts, some form of compensation for affected producers will be necessary.

3.2 Scenario 2

With these concerns in mind, we now explore the impacts of the policy instrument in Scenario 2, which returns the emissions tax revenue to producers as an output subsidy. The results in Fig. 7, Fig. 8, Table 2, and Table 3 reveal the striking effectiveness with which this policy instrument can maintain output and consumption levels, while delivering reasonable mitigation outcomes. The total global reduction in emissions from this policy is 185 $MtCO_2$-eq year^{-1}, of which 99% is achieved by reducing emission intensities. While the carbon tax policy delivers much larger emission reductions, the amount of

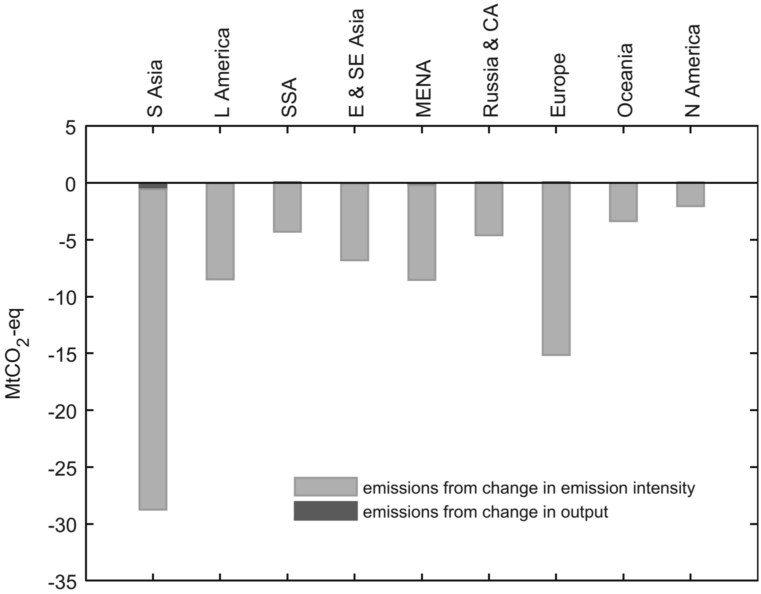

Fig. 7 Annual mitigation of dairy sector emissions in Scenario 2, decomposed into emission reductions from lower output and emission intensities, by region

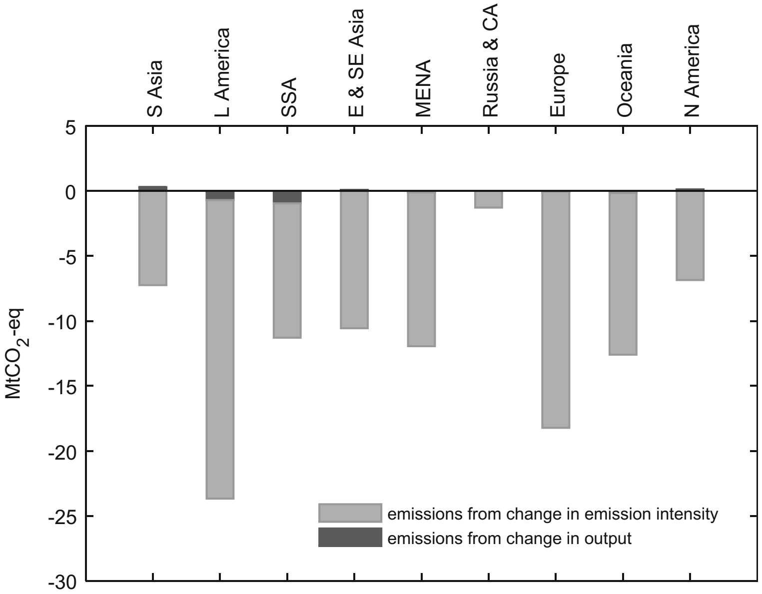

Fig. 8 Annual mitigation of BSR sector emissions in Scenario 2, decomposed into emission reductions from lower output and emission intensities, by region

mitigation achieved by lowering emission intensities is virtually identical to that achieved in Scenario 2. The largest differences in total mitigation between the two scenarios are for the BSR sector, where the overwhelming share of mitigation under the carbon tax came from a fall in production (Table 2).

As with Scenario 1, S Asia, L America, and MENA are in the top 4 mitigating regions for the dairy sector (Fig. 7). However, this time, Europe is in second spot and SSA makes a relatively

Table 2 Summary of the global GHG mitigation outcomes for the ruminant sectors under Scenario 1 and Scenario 2, decomposed into emission reductions from lower output and emission intensities

Sector	Source	Scenario 1 mitigation ($MtCO_2$-eq)	Scenario 2 mitigation ($MtCO_2$-eq)
Dairy	Dairy total	158	82
	Share of total reduction	(25%)	(44%)
	Emission intensity reduction	81	81
	Share of dairy reduction	(51%)	(99%)
	Output reduction	77	1
	Share of dairy reduction	(49%)	(1%)
Beef and small ruminants	BSR total	468	103
	Share of total reduction	(75%)	(56%)
	Emission intensity reduction	101	102
	Share of BSR reduction	(22%)	(99%)
	Output reduction	367	1
	Share of BSR reduction	(78%)	(1%)
Total	Total	626	185
	Emission intensity reduction	182	183
	Share of total reduction	(29%)	(99%)
	Output reduction	444	2
	Share of total reduction	(71%)	(1%)

Table 3 Percentage changes (%) in household consumption of unprocessed and processed (proc.) ruminant products under Scenario 1 and Scenario 2, by region

	S Asia	L America	SSA	E and SE Asia	MENA	Russia and CA	Europe	Oceania	N America
Scenario 1									
Milk	−2.9	−5.3	−13.2	0.7	−7.6	−0.9	0.8	−0.4	−0.9
Meat	−3.8	−11.7	−11.5	−7.2	−9.7	−2.3	−5.2	−5.3	−6.4
Proc. dairy	−1.2	−2.0	−2.4	−0.6	−3.5	−0.1	0.2	−0.2	−0.3
Proc. meat	−2.3	−7.6	−7.1	−1.6	−5.1	−2.0	−2.5	−2.2	−2.7
Scenario 2									
Milk	−0.1	−0.0	−0.0	0.0	−0.1	−0.0	−0.0	−0.0	0.0
Meat	0.0	−0.2	−0.1	−0.1	−0.3	−0.0	−0.1	−0.2	−0.1
Proc. dairy	−0.0	−0.0	−0.0	−0.0	−0.1	−0.0	−0.0	−0.0	0.0
Proc. meat	−0.0	−0.1	−0.1	−0.0	−0.1	−0.0	−0.0	−0.1	−0.0

Meat is a composite of meat from all ruminant sectors (dairy herd, specialized beef herd, and small ruminants)

minor contribution. This is mainly due to the greater mitigation opportunities in Europe (Henderson et al. 2015a). For the BSR sector, there are larger differences in the regional pattern of abatement for Scenario 2 (Fig. 8) compared with Scenario 1 (Fig. 5). While L America is still the dominant contributor, this time, Europe, Oceania, and MENA occupy the remaining top 4 places, instead of S Asia, SSA, and E and SE Asia. This again relates to the greater effectiveness and feasibility of mitigation options in these regions (Henderson et al. 2015a).

From a food security perspective, the Scenario 2 policy instrument does far better than the pure carbon tax in Scenario 1. The near maintenance of both dairy and BSR production (Figs. 7 and Fig. 8) is also reflected in the changes in household consumption of unprocessed and processed ruminant products shown in Table 3. Here, the relatively large falls in consumption under Scenario 1, particularly in low-income regions, are virtually eliminated in Scenario 2, as the output subsidy allows producers maintain their product prices at a near baseline levels.

In contrast to Scenario 1, the market interactions associated with policy Scenario 2 lower the quantity of emissions reduced when compared to the MAC benchmark (Fig. 9). The 185 MtCO$_2$-eq year^{-1} mitigation potential from Scenario 2 is around three quarters of that achieved under MAC benchmark, in the absence of market interactions. This occurs because the global scale of the mitigation effort has the effect of increasing the price of the resources associated with mitigating emissions. If instead the Scenario 2 policy was implemented in one sector and country at a time, the mitigation outcome would be nearly identical with the MAC benchmark. Further discussion about the role of market interactions under different policy settings is given in Section 4.

3.3 Sensitivity analysis

The sensitivity of the GHG mitigation results to the parameter variations for Scenario 1 is displayed by region and sector in Table 4. For ease of interpretation, we focus on the coefficient of variation (CV), which is the ratio of the standard deviation to the absolute value of the mean. A low CV corresponds to an outcome in which we can place greater confidence in the results. We consider a CV value of 0.5 (i.e., where the mean is twice the standard deviation) as a threshold to indicate whether the model results are robust or not. Under the assumption of normality, CV less than 0.5 indicates that 95% confidence interval does not include zero. On this basis, the results are robust with respect to the parameter variations, with coefficients of variation below 0.5 for all regions and sectors except for the BSR sector in

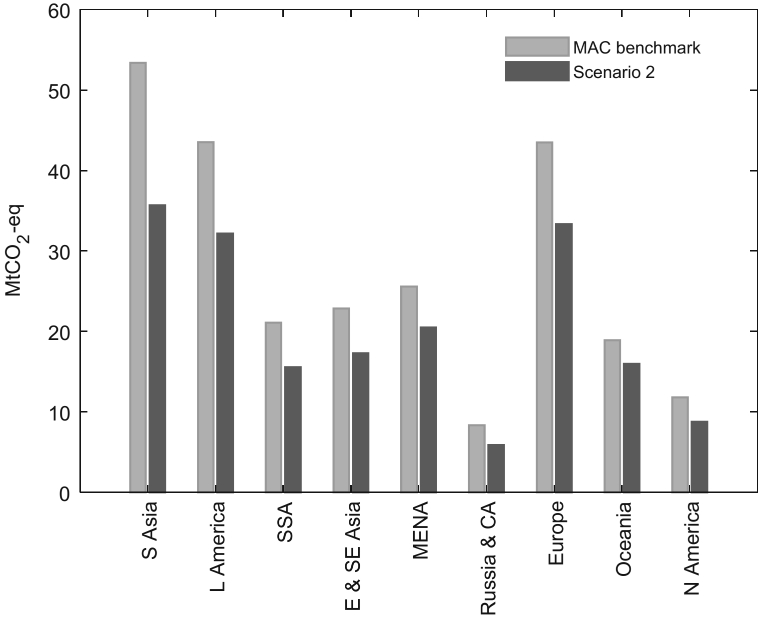

Fig. 9 Annual GHG mitigation without market interactions (MAC benchmark) and with market interactions under the global carbon tax/subsidy instrument (Scenario 2), by region, for all ruminant sectors combined

Oceania. This is a reassuring outcome that provides a reasonable degree of confidence in the overall performance of the model.

4 Discussion

4.1 Summary of findings and insights

The findings from this study reveal that the market impacts from carbon price policies substantially affect mitigation outcomes, especially when implemented at a global scale. These

Table 4 Sensitivity of the GHG mitigation results (MtCO$_2$-eq year^{-1}) by region and sector with respect to trade elasticities, MAC elasticities, and emission intensities

	Dairy sector			BSR Sector		
	Mean	St. deviation	CV	Mean	St. deviation	CV
S Asia	−45.78	12.96	0.28	−105.96	32.78	0.31
L America	−24.99	7.86	0.31	−180.34	53.05	0.29
SSA	−30.73	11.08	0.36	−74.96	21.34	0.28
E and SE Asia	−9.39	2.74	0.29	−70.14	25.26	0.36
MENA	−25.13	8.37	0.33	−15.60	4.12	0.26
Russia and CA	−5.64	1.64	0.29	−1.75	0.49	0.28
Europe	−13.21	3.72	0.28	−11.59	3.31	0.29
Oceania	−3.13	0.90	0.29	−5.56	3.21	0.58
N America	−2.21	0.61	0.28	−7.51	2.41	0.32

effects can work to enhance mitigation outcomes by encouraging the substitution of emission-intensive products for cleaner products or diminish mitigation outcomes by raising the use and prices of resources needed for mitigation. The strength of these counteracting effects depends on the nature of the policy instrument being implemented. Under the Scenario 1 emissions tax, the substitution incentives from significantly higher costs of ruminant production dominate the outcome, resulting in a dramatic 151% increase the total mitigation potential at \$20 tCO_2-eq^{-1} from 249 $MtCO_2$-eq year^{-1}, estimated in the MAC benchmark, to 626 $MtCO_2$-eq year^{-1}. This represents a 17% reduction of global ruminant emissions. On the other hand, the 185 $MtCO_2$-eq year^{-1}of mitigation potential from policy Scenario 2 is well short of the potential achieved in the MAC benchmark. In this case, the subsidy component in Scenario 2 nullified the market substitution effects, leaving higher prices of mitigation resources as the dominant market impact.

Apart from their differing global mitigation potentials, the two policy options have very different impacts on production and consumption. There are also contrasting motivations for their inclusion in this study. Taxes that are applied to every unit of pollution are more economically efficient than policies with compensating subsidies because they create more appropriate entry and exit conditions for the sector. While policymakers are unlikely to employ such an approach (e.g., Scenario 1), it is nonetheless instructive from a normative viewpoint to understand what an economically efficient reconfiguration of production might look like. We can see from Scenario 1 that this reconfiguration includes an increase in dairy cattle production at the expense of specialized beef production, with a corresponding increase in the proportion of cattle meat supplied by the dairy sector at the global level. This restructuring stems from the more efficient and less emission-intensive nature of the dairy production, and it is felt most strongly in low-income countries.

The strong economic efficiency credentials of the pure emissions tax are diametrically opposed to its negative impacts on food security, producer, and consumer welfare in low-income countries. By contrast, the more politically acceptable tax/subsidy instrument (Scenario 2) was remarkably effective in maintaining the supply and consumption of ruminant products, thus providing a more realistic assessment of what could be achieved with a globally coordinated mitigation policy for the ruminant sector.

4.2 Comparisons with other studies

A key strength of this study is its use of recent and improved MAC curves for the ruminant sector (Henderson et al. 2015a), which incorporate soil carbon sequestration (Henderson et al. 2015b) and heterogeneity in mitigation costs among producers within regions and production systems. To date, comparable global analyses that explore market interactions such as Golub et al. 2013 and Avetisyan et al. (2011) and Wollenberg et al. (2016) have relied on MAC curves from the US Environmental Protection Agency (US EPA 2006; US EPA 2013), which excluded soil carbon and used an average cost accounting approach. With regard to mitigating animal emissions (i.e., CH_4 and N_2O from enteric and manure sources), the marginal costs which we use are higher than those from US EPA (2006 and 2013). For example, at \$20 tCO_2-eq, the global mitigation potential according Henderson et al. (2015a) is 78 compared to 136 $MtCO_2$-eq yr.$^{-1}$ by US EPA (2013). The main reason for this discrepancy is that the former study applies stricter conditions for the inclusion and application of mitigation practices. A smaller portion of this discrepancy is due to the inclusion of some additional mitigation sources by US EPA (2013), namely manure CH_4 emissions from milk cows and pigs. The inclusion of soil carbon sequestration in our MAC curves brings the total mitigation potential, in the absence of market interactions, to 249 $MtCO_2$-eq year^{-1} at \$20 tCO_2-eq. Although this figure is considerably higher than the US EPA (2013) estimate of 136 $MtCO_2$-eq year^{-1}, the inclusion of soil carbon sequestration is not the game changer that many thought it might be following the IPCC Fourth Assessment Report's optimistic estimates about this key mitigation source (Smith et al. 2007).

The results from our assessment are comparable to those from the handful of published global economic assessments which use market-equilibrium models to estimate the economic mitigation potential for livestock. However, differences in carbon policy design and coverage confound these comparisons. The assessment in Golub et al. (2013) is based on a similar but older model; however, the closest policy scenario includes a \$27 tCO_2-eq^{-1} carbon tax on all regions and sectors of the economy, with a similarly structured compensation subsidy, although their subsidy component is only applied to low-income countries. In this case, 236 $MtCO_2$-eq year^{-1} of emissions were estimated to be reduced by ruminant producers, which falls between our two global estimates of 185 and 629 $MtCO_2$-eq year^{-1}. Avetisyan et al. (2011) use a similar model to Golub et al. (2013) and also assess the potential from \$27 tCO_2-eq^{-1} carbon tax, although this time applied only to livestock and without any compensating subsidy payments for producers. Under these policy settings, Avetisyan et al. (2011) report a total global mitigation potential 522 $MtCO_2$-eq year^{-1} for ruminants, which is lower than our estimate, despite their higher tax rate. The main reason is the additional potential in our assessment from including soil carbon sequestration as a mitigation option. Finally, Wollenberg et al. (2016) use the Global Biosphere Management Model (Havlík et al. 2011), which is an economic partial equilibrium model, to test the mitigation potential at \$20tCO_2-eq, based on options that intensify agricultural production. Under these settings, they estimate emission reductions of 0.21 $GtCO_2$-eq year^{-1}, from both crop and livestock sectors. It is not clear fhow much of this mitigation can be attributed to ruminant production systems; nonetheless, it is comparable to the Scenario 2 mitigation quantity estimated in this study.

4.3 Recommendations for further research

Further analysis into pragmatic policy designs, which can avoid or limit negative impacts on producers, is essential to provide policymakers with more practicable mitigation tools. As argued by Pezzey (2003a), political resistance of pure emission taxes without exemptions or recycled subsidies has been too great to overcome in the past. We address this concern in our study with a policy instrument which returns tax revenue to producers as an output subsidy. As outlined by Henderson (2010), these types of instruments have been used with varying degrees of success in managing nitrous oxide and sulfur dioxide emissions in France and Sweden. There are alternative policy designs that warrant further investigation and testing, one of which is a carbon tax that incorporates a tax-free threshold for a portion of emissions. Where this threshold is treated as a property right rather than a subsidy, this type of instrument could significantly reduce the tax burden for producers, while also increasing mitigation effectiveness by reducing incentives for expanding production (Pezzey 2003a; Pezzey 2003b). However, analysis of this instrument would require a different modeling framework, which allows the distinction to be made between new and existing producers. A tradeable permit scheme, in which permits are freely allocated rather than auctioned, could also be used to manage the tradeoff between food production and mitigation effectiveness, although the carbon price variability associated with these instruments can create industry resistance. The present study, which is based on interdisciplinary data synthesis and modeling, makes an important contribution to understanding the likely mean impacts of mitigation policies at a global scale. A valuable next step in this small but growing body of work is to assess the efficiency of different policy designs in the presence of risk aversion and uncertainty. As outlined by Herrero et al. (2016), this research needs to be conducted with due consideration to the broader goals of development, food and nutritional security, and adaptation to climate change. In particular, we need to develop the right policy settings and instruments to better manage these multiple and often competing goals.

5 Conclusions

With growing enthusiasm for action on climate change following the Paris Agreement and the establishment of the Carbon Pricing Leadership Coalition at COP 21, now is an opportune time to revisit the potential contribution that globally coordinated mitigation policies in agriculture could make. While ruminant production systems generate a substantial share of the world's GHG emissions, they can also play an important role in tackling climate change. This research provides policymakers with a quantitative basis for comparing policies that vary according the emphasis they place on mitigation effectiveness and economic efficiency versus producer and consumer welfare. The priority given to these objectives will naturally vary from country and result in a less uniform global application of policy designs and mitigation responses than assessed here. Nevertheless, there are several findings from this study that are relevant for a range of global policy configurations.

Firstly, we show that market-based mitigation policies can greatly amplify the mitigation potential identified in marginal abatement cost studies by harnessing powerful market forces such as product substitution and trade. A \$20 tCO_2-eq^{-1} carbon tax applied to ruminant emissions was shown to mitigate up to 626 $MtCO_2$-eq year^{-1}. However, the mitigation potential from the global carbon tax is some respects an upper bound because it causes global ruminant-based food production to fall and is therefore likely to encounter political resistance. This research also shows that carbon pricing could cause a restructuring of the cattle sector, by increasing dairy cattle production at the expense of specialized beef production, as cattle meat supplied by the dairy sector is less emission intensive. This insight can help policymakers and planners anticipate some of the structural changes that a more carbon-constrained future may bring, when mitigation policies are embraced more enthusiastically in the future.

To address the fall in ruminant production caused by the carbon tax, we introduced a producer subsidy to compensate producers for their tax expenses. This policy mechanism succeeded in preventing a decline in ruminant production in all global regions, but at the cost of a substantially reduced global mitigation potential of 185 $MtCO_2$-eq year^{-1} (5% of global ruminant GHG emissions). Given its obvious importance for food security and human welfare, the case for compromising on mitigation effectiveness to maintain production is arguably stronger for agriculture than for other sectors of the economy. Accordingly, our main global mitigation strategy recommendation is for policymakers and mitigation advocates to promote the uptake of hybrid tax-subsidy instruments, such as presented in Scenario 2 of this study. While the subsidy component of this instrument does water down the mitigation potential of the emissions tax, it does offer policymakers with a blueprint for meeting the Paris Agreement ambition to reduce agricultural emissions while protecting food production. Moreover, since this instrument can maintain ruminant production levels, it has the potential to accommodate a more ambitious carbon price that is closer to the marginal rate of damage for GHG emissions, such as the \$85 $tCO_2\text{-eq}^{-1}$ estimated by Stern (2007), without compromising its political expediency. However, as the carbon price increases, tradeoffs between mitigation and the welfare of producers and consumers will emerge, as the price of abatement and production resources rise.

Finally, whichever carbon policy approach is eventually pursued, it is clear from this and related research that carbon policies which target livestock producers are unlikely to reduce a very substantial share of global emissions. As shown by Herrero et al. (2016), dramatically higher emission reductions could be possible by reducing the share of red meat in human diets. For this reason, we also recommend that more research be done on designing feasible and equitable policy approaches to reduce demand for ruminant products, particularly in high income countries where there are negative health impacts associated with the overconsumption of red meat (Tilman and Clark 2014).

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