*Q Open*, 2023, **0**, 1–21
https://doi.org/10.1093/qopen/qoad021
Advance access publication date: 28 July 2023
**Article**

# Effects for global agriculture of country-specific climate policy regimes with a focus on methane

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**Received:** February 27, 2023. **Accepted:** July 18, 2023

## Abstract

While countries have agreed in the Paris-agreement on common rules to report greenhouse gas emissions, the design of domestic climate policy regimes remains in the national domain. This may cause different carbon prices for climate gasses across countries, between a country's emission sectors, and within the same sector. Our focus is on methane, which is a major emitter from agriculture, but also linked to livestock farming which is a core activity in agriculture worldwide. We analyse the potential effects of domestic carbon pricing regimes for agriculture in a non-cooperative game theoretic setting using a global agricultural sector model. Our results indicate no 'race to the bottom' to apply carbon pricing regimes that result in lowest implicit carbon prices for methane. Enforcing a uniform regime can reduce additional global warming with up to 0.02 °C, but runs the risk of agreeing to lower emission cuts than a nationally determined choice would suggest.

**Keywords:** Agriculture, Welfare, Carbon pricing, GHG accounting metrics, Non-cooperative game

**JEL codes:** Q17, Q18, Q54, Q56, Q58

## 1. Introduction

Greenhouse gas (GHG) emissions must be reduced to limit global temperature increase above the climate targets set out in the Paris-agreement. Mitigation targets include non-$CO_2$ GHG emissions from agriculture (i.e., methane and nitrous oxide), and a reduction of GHG from agriculture is deemed necessary to achieve global climate targets (Clark et al. 2020). However, current mitigation policies in agriculture fall short of achieving required GHG reductions compatible with limiting warming to 1.5–2 °C.

Agriculture is a major contributor to climate change through emissions of methane which accounts for about 16 per cent of total global GHG emissions (IPCC 2014) and 35 per cent of global GHG emissions of the food sector (Crippa et al. 2020). Methane emissions stem from mainly from livestock farming which is a core activity in terms of agricultural

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employment and value added in the agriculture of many countries worldwide. According to FAO (2006), the livestock sector employs 1.3 billion people globally and accounts for 40 per cent of the gross domestic product in agriculture.

Different GHG accounting metrics have been developed to evaluate the climate impact of different climate gases relative to each other. GHG emissions are commonly reported as '$CO_2$-equivalents' ($CO_2$-e) and calculated using the 100-year Global Warming Potential ($GWP_{100}$) (IPCC 1996; Eggleston et al. 2006; Leahy et al. 2020). Countries agreed at COP26 in the rulebook of the Paris-agreement to use $GWP_{100}$ as the common metric to report GHG-emissions (Åberg et al. 2021).

$GWP_{100}$ abstracts from the different behaviour over time of short-lived climate gases like methane and long-lived climate gases like $CO_2$ and $N_2O$. Its short life span implies that methane does not accumulate in the atmosphere (Cain et al. 2019). The climate impact of methane emissions is initially very high, but rapidly declines after 20 years. Constant emission rates for methane result in a relatively small contribution to additional warming beyond current temperatures. Increasing (decreasing) methane emission rates cause an additional increase (decrease) in global temperatures compared to current temperature developments. This dynamic behaviour is not captured by $GWP_{100}$, and alternative metrics, like $GWP^*$, have been proposed (Cain et al. 2019; Tanaka et al. 2020).

Although there exist internationally agreed rules for reporting emissions under $GWP_{100}$, there are no such rules which climate policies countries must apply domestically. This implies that countries can design their own climate policy regimes including carbon prices, other mitigation policies and accounting metrics. If countries apply other metrics than $GWP_{100}$ when setting domestic targets or policy measures, emissions must still be calculated and reported in terms of $GWP_{100}$ to comply with the Paris-agreement. This may lead to the reported reduction in emissions being less than the nationally determined commitments (NDCs) in which case additional reduction efforts in other emission sectors would be necessary. However, the choice of the accounting metric may have significant implications for emission reduction policies in agriculture and how the sector's contribution to climate change mitigation is perceived (Pérez-Domínguez et al. 2021).

To the best of our knowledge, New Zealand is currently the only country that discusses different climate policies for different climate gases at the political level. Under the so-called farm-level split-gas pricing system, the government has proposed that 'agricultural emissions would be priced via a farm-level, split-gas levy where biogenic methane and nitrous oxide gases would be priced differently' (Ministry for the Environment and the Ministry for Primary Industries 2022: 10).

Our contribution lies in informing policy makers and stakeholders about the impact on global warming of countries' use of different climate policy regimes for emission mitigation purposes. We are particularly interested in the effects of policies that result in different emission prices for methane between countries. This places our paper in the literature that focuses on the reduction of non-$CO_2$ agricultural emissions over time and their effective contribution to climate change. This research has so far focused on the impact for global agriculture if all countries use the same climate policy regime represented by a common global carbon price and a common GHG accounting metric (Frank et al. 2019; Pérez-Domínguez et al. 2021). Our focus is on the consequences for global agriculture if countries apply different climate policy regimes for their agriculture.

Differences in the applied or implicit emission price for methane can be caused by deliberately different carbon prices for different climate gases, the availability of supply-side mitigation options including their economic incentives, and accounting metrics. Any difference between countries' climate policy regimes leads to different implicit carbon prices faced by the agricultural sector. For example, if one country lacks the technology to set up biogas plants, the agricultural sector in that country may face higher abatement costs (i.e. implicit carbon prices) than farmers in a country in which biogas plants are readily available. Likewise, implicit carbon prices will differ if countries apply different accounting metrics. For example, the same carbon price measured in € per ton $CO_2$ yields a lower price when measured in € per t methane if GWP* is applied instead of $GWP_{100}$. Finally, countries can simply put a lower price on methane compared to $CO_2$ or $N_2O$ as the example from New Zealand indicates differences in climate policy regimes across world regions may therefore not only have considerable consequences for emission reduction efforts in the applying country but may also imply production- and trade-distorting effects for other countries. In this respect, we measure distortion in terms of a change in production and trade from a situation in which both countries apply the same climate policy regime to a situation in which one country deviates from a that same regime. We also study whether countries may be able to coordinate their climate policy regimes, and under which conditions that may be the case.

We apply an economic model for global agriculture with a special focus on Europe (CAPRI—Common agricultural policy regional impact modelling system). The scenarios are based on climate policy regimes aimed at incentivizing both agricultural producers to implement mitigation options in agriculture and consumers to change their eating habits. They differ with respect to the implicit carbon price provoked by the choice of the general carbon price and accounting metrics. The model results are put into a non-cooperative game theoretic framework to analyse the options for coordinating climate policy regimes between countries.

The reminder of the paper is organized as follows. The next section introduces climate policy regimes. Section 3 presents the model, while section 4 gives an overview of the scenarios. Results are presented in Section 5. The last section discusses the results and concludes.

## 2. Climate policy regimes

We consider a climate policy regime to define a wide array of climate policy instruments such as general carbon prices applied to all sectors and climate gases, exemptions from or deductions of the general price to specific sectors or climate gases, supply-side mitigation policies, accounting metrics, and informational policies to induce consumers to change their eating habits.

‘Carbon pricing’ is widely seen efficient to achieve the ambitions set out in the Paris-agreement given a reliable and costless monitoring system (Bowen 2011; Baranzini et al. 2017; World Bank 2017; Akerlof et al. 2019). A price on carbon incentivizes farmers to implement available mitigation options in the agricultural sector. The application of a price on carbon in agriculture is not straightforward since emissions from agriculture are not easily monitored. Emissions from agriculture differ from emissions from standardized industrial processes due to their biological nature, diverse land-use techniques, and different farm management practices leading to considerable variations in emission intensities for the same products (Lovett et al. 2008; Henriksson et al. 2011; Vellinga et al. 2011; Bonesmo et al. 2013; Cottle et al. 2016; Alemu et al. 2017; Samsonstuen et al. 2020). In addition, the spatial dispersion of farming renders the accurate monitoring of agricultural emissions at their source almost impossible. Carbon prices have therefore been applied in agricultural economic models as an approximation of other policies that incentivize farmers to implement mitigation options (or penalizes them for not adopting them), while the transaction costs caused by those policies have been neglected (Ripple et al. 2014; Frank et al. 2019).

A general carbon price across all sectors and climate gases is in many countries the exception rather than the rule. For example, the carbon tax rate on mineral oil in Norway depends on whether it is used in domestic aviation or other sectors, and whether the sectors belong to the European Emission Trading Scheme (ETS) (Norwegian Ministry of Finance 2022). Norway has also a distinct carbon tax rates for perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs). In the agricultural sector, $CO_2$-emissions from energy use (e.g., diesel, heating of greenhouses) are taxed, while emissions from methane and nitrous dioxide are not. There may be many reasons why countries apply different carbon tax rates across sector and climate gases. However, a thorough investigation into these matters is beyond the scope of this paper.

For our analysis, we introduce a methane deduction factor (MDF) defined as the relative difference between the applied or implicit price for methane and the general carbon price converted to methane using $GWP_{100}$. For instance, MDF = 25 implies that the effective price for methane is 25 per cent of that of $CO_2$ converted into methane using $GWP_{100}$ regardless of how that difference is brought about. The choice of the MDF affects the effective price for methane emissions, leaving the price for emissions from carbon dioxide, and nitrous dioxide unchanged. A higher MDF makes it less profitable for farmers to implement costly mitigation options targeted at methane.

GHG accounting metrics are used to convert the global temperature effect of non-$CO_2$ climate gases into the temperature effect of $CO_2$. $GWP_{100}$ converts climate gases applying specific emission conversion factors as shown in equation 1:

$$E_{CO_2-eq.(CH_4)} = GWP_{100} \times E_{CH_4(t)}, \tag{1}$$

where $GWP_{100}$ is 28 for methane and 265 for nitrous oxide according to the 5th Assessment Report of the IPCC (IPCC 2014).

The GWP* accounting metric reflects the dynamics of methane's behaviour in the atmosphere by distinguishing its short-term and long-term effects as shown in the formula below taken from Cain et al. (2019):

$$E_{CO_2-w.e.(CH_4)} = GWP_{100} \times \left(4 \times E_{CH_4(t)} - 3.75 \times E_{CH_4(t+20)}\right). \tag{2}$$

The formula implies that methane emissions in a particular year $t$ are priced twice: in that same year $t$ and 20 years later. We follow Pérez-Domínguez et al. (2021) in applying Hotelling's rule (1931) so that the carbon price in real prices remains the same in all years. Consequently, the net carbon price for methane emissions in year $t$ becomes 25 per cent of the carbon price applied to $CO_2$. The approach reflects the important fact that the total global temperature impact of methane is significantly lower than suggested by $GWP_{100}$. A constant relationship between the warming due to methane and the warming due to $CO_2$ remains. Therefore, the approach does not equally reflect the fact that rising (falling) emissions between $t$ and $t + 20$ lead to higher (lower) values for $E_{CO_2\text{-}w.e.}$.

Reported emissions can be linked directly to the global temperature response over any scenario and timeframe of interest (Denison et al. 2019; Tanaka et al. 2020). Following Cain et al. (2019), the added temperature from GHG emissions is computed according to equation 3:

$$AW_{CO_2-w.e.(t)} = E_{CO_2-w.e.(t)} \times TCRE, \tag{3}$$

where $AW_{CO_2-w.e.(t)}$ denotes the added warming (i.e., the temperature increase or decrease defined in °C) in year $t$ relative to year $t$–20 of GHG emissions measured in GWP*-terms, and $TCRE$ denotes the transient climate response to cumulated carbon emissions (Matthews et al. 2009). We apply a $TCRE$ value of 0.49 °C per $TtCO_2$ (Cain et al. 2019).

Dietary change towards a less animal protein diet is defined as a diet with a maximum intake of animal products corresponding to 430 kcal per capita per day based on recommendations by the United States Department of Agriculture (www.cnpp.usda.gov/USDAFoodPatterns). Animal products are defined as including meat from ruminants, meat from non-ruminants, and dairy products. The calorie target from animal products (excluding waste) is achieved gradually by 2070, such that calorie consumption from animal products will decrease linearly from the 2020 level to a maximum of 430 kcal per capita per day in 2070 in all countries. We refrain from an increase in the consumption of vegetable calories, but this might occur endogenously as a response to a change in relative food prices.

Less animal protein-based (LAP) diets have been identified as a promising strategy to reduce GHG emissions from the agriculture and global food systems (Tukker et al. 2011; Clark et al. 2020; Willett et al. 2019). This is in line with recommendations by the EAT-Lancet Commission, which proposes a healthier diet where whole grains, fruits, vegetables, nuts, and legumes comprise a greater proportion of foods consumed. This diet includes calorie intake targets by food group and a total calorie intake target of 2500 kcal (Willett et al. 2019).

## 3. Model

We use the CAPRI modelling system, which is an economic large-scale, comparative-static, and partial equilibrium model focusing on agriculture and the primary processing sectors. CAPRI consists of two interacting modules: (1) a set of mathematical programming models of regional agricultural supply in core European countries, and (2) a spatial multi-commodity model for global agri-food markets. The regional supply models maximize profit of representative farms in the EU-27, United Kingdom, Norway, and EU candidate countries. The models account for constraints related to land availability, nutrient balances for cropping and animal activities, and policy restrictions (Britz and Witzke 2014). The market module comprises a spatial, global multi-commodity model for about 60 primary and processed agricultural products. It distinguishes 77 countries in 40 trading blocks. Bilateral trade flows and attached prices are modelled based on the Armington assumption of quality differentiation (Armington 1969). The behavioural functions in the market model represent supply and demand for primary agricultural and processed commodities (including human and feed consumption, biofuel use, import demand from multilateral trade relations). They balance constraints and agricultural market policy instruments (i.e., import tariffs, tariff rate quotas, producer and consumer support estimates, etc.). Depending on scenarios behavioural functions are shifted to reflect productivity shocks or to implement preference shifts such as dietary changes. Information on prices for agricultural products is transmitted between the two modules. Iterations between the two modules achieve a new market equilibrium.

CAPRI calculates GHG emissions for supply model countries for the most important nitrous oxide and methane emission sources (e.g., enteric fermentation, manure management, manure and mineral fertilizer application to soils, grazing animals, crop residues, cultivation of histosoils, indirect emissions from the volatilization of ammonia, indirect emissions from leaching and runoff, and the burning of biomass) based on the inputs and outputs of agricultural production activities, following to a large extent the 2006 IPCC guidelines and a Tier 2 approach model (Pérez Domínguez et al. 2016; Fellmann et al. 2018). CAPRI contains a complete nutrient cycle for nitrogen and carbon. For phosphate and potassium, it considers nutrient balances for crops and feed. The model includes a wide range of technical and management-based GHG mitigation options for the EU and Norway such as fallowing histosoils, precision farming, nitrification inhibitors, anaerobic digestion, low nitrogen feed, feed additives, genetic improvements, and vaccination against methanogenic bacteria in the rumen (Pérez Domínguez et al. 2019). GHG mitigation for the rest of the world is represented by a change in emission factors and a matching change in output prices to reflect the increase in cost, derived from mitigation cost functions from the literature (Lucas et al. 2007).

A price on carbon incentivizes the uptake of available mitigation options in agriculture in the European Economic Area (EEA) and provokes a change in the emission factors in the rest of the world. The EEA consists of the European Union and the three EFTA (European

Free Trade Organization) countries Norway, Iceland, and Liechtenstein. Since Iceland and Liechtenstein are not single countries in the model, the EEA in CAPRI consists only of EU-27 and Norway, while the two remaining EFTA countries are part of the rest of Europe. The United Kingdom is treated as a country on its own. For the EEA, carbon pricing is considered to have zero income and budget effects. The monetary amount due to carbon pricing neither affects agricultural income nor does it enter government welfare as tax revenue. Farmers are perceived as being confronted by a price on carbon and behave as if a price on carbon is put in place. The approach allows for different interpretations: (1) Farmers are persuaded or otherwise incentivized to implement mitigation policies without the need to price carbon explicitly. (2) Farmers are paid a refund or subsidy that does not affect their behaviour and that equals the monetary amount of carbon pricing collected from their farms. Irrespective of the interpretation, mitigation costs are accounted and reduce agricultural income. In the rest of the world (i.e., Non-EEA), the carbon price affects producer prices. To ensure consistency and comparability with welfare analysis in the EEA, producer prices that enter the welfare analysis for Non-EEA are calculated net of carbon pricing. We interpret this correction in the same way as for farmers in the EEA.

Among the result indicators derived from the model runs are production, consumption, and trade quantities, market and producer prices, farm income, herd size and animal numbers, a wide range of environmental indicators including GHG emissions, and social welfare defined as the sum of producer, consumer, and taxpayer welfare.

Data for European agriculture are mostly taken from Eurostat while the international data are mostly from FAO. These data are supplemented by topic related sources and expert knowledge.

The welfare outcomes of the model simulations are further analysed in a game-theoretic setting. Game theory studies multiperson decision problems in which strategies chosen by one person affect the outcome or payoff for other persons (Gibbons 1992). We apply a static, non-cooperative game with perfect and complete information. That is, the game is played only once, the players know what strategies players can choose from, the players know exactly what payoff each player will achieve when choosing a particular strategy, and the players cannot coordinate their strategies. Instead, the players choose their strategy independent of the other player's strategy. The game we consider consists of two players, EAA and Non-EAA, the player's actions defined as the players' (i.e., world regions') climate policy regime, and the associated welfare outcomes. A strategy defines a player's own response for each of the second player's actions. That is, for each possible action taken by the second player, the first player defines which action to choose. As will become clear below, the strategies in the game correspond to the scenarios while the payoffs correspond to the scenarios' welfare outcomes. A Nash-equilibrium is defined of a pair of best strategies that contain the best response to the other player strategies so that no player has an incentive to deviate from that best response or strategy. In terms of the model simulations, we define non-cooperative game for each possible combination of general carbon price and dietary choice. The best strategy of anyone player within each game is defined as the highest welfare that player can achieve given the choice of MDF of the opponent player. In other words, a Nash-equilibrium is sustained if no world region can increase its welfare by choosing a different MDF given the choice of the MDF of the other world region.

## 4. Scenarios

The scenarios are built as counterfactuals to a long-term 'business as usual' (BAU) projection of agricultural commodity markets in which no particular climate policy regime is applied. The scenarios distinguish three elements of carbon policy regimes: (1) a general carbon price applied to all sectors stimulating the implementation of mitigation options, (2) informational policies inducing dietary change towards a less meat diet, and (3) a specific deduction for methane emissions from agriculture induced either using GWP* or by applying a deduction of the general carbon price.

We distinguish two carbon price paths: 150 2005-$ per t $CO_2$ and 500 2005-$ per t $CO_2$ following Rogelj et al. (2018). These carbon prices are in line with the 1.5 °C temperature target of the Paris-agreement. Since the model's base year is 2012, we convert the prices using an exchange rate of 0.9€ per $, and 1.9 per cent inflation for the 2005–2012 period. The discount rate used to calculate the optimal carbon price path following Hotelling's rule is set to 5 per cent. $N_2O$ emissions from agricultural production are priced according to the $GWP_{100}$ $N_2O$ price. $CO_2$ emissions or uptake from agricultural land use and land-use change are not considered. The carbon prices are shown in Table 1.

Dietary change is implemented in the model by manipulating the behavioural parameters of the demand for the animal products in question. This implies a downwards shift in the respective demand functions that is exogenous to the model. That is, we refrain from the explicit modelling of policies to stimulate consumers' eating habits and their related costs. The literature has identified a range of barriers and hindrances to change diets as eating habits are often based on social and cultural factors (Atkins and Bowler 2016; Vatn et al. 2022).

To keep a comprehensive number of scenarios we split the world into two regions: The EEA including the EU-27 and Norway, and the rest of the world (Non-EEA). Norway is part of the EU emission trading scheme (ETS) and participates also in the EU's Effort Sharing Decision that establishes climate targets at member state level (and Norway) for sectors not included in the ETS such as transport and agriculture.

Moreover, as our interest is in the effect of special treatment of methane emissions, we assume that the general carbon price rate and the informational policies towards a low animal-protein diet are the same in both world regions in each scenario. This leaves us with a total of 17 scenarios including the baseline as shown in Table 2. The scenarios are coded according to the methane deduction factor applied in the Non-EAA/EAA regions, the general carbon price rate, and the choice of diet.

With respect to the actions in the non-cooperative game based on the welfare outcomes of the scenarios, Non-EAA and EAA choose the size of the methane deduction factor (i.e., MDF25 or MDF100). A strategy then defines two actions: whether to MDF25 or MDF25 if the opponent player chooses MDF25 and MDF, respectively.

## 5. Results

We start by presenting the welfare outcomes of the different scenarios for the years 2030, 2050, and 2070. Table 3 shows the welfare outcomes by scenario for 2030. The scenarios are transformed into four games that differ with respect to the combinations of general carbon price and dietary choice. Comparing welfare outcomes, the EEA is always better off applying MDF100. Regardless of the general carbon price, dietary choice, and the MDF applied by Non-EEA, a higher price for methane (MDF100) yields higher welfare compared to a lower price for methane (MDF25). For instance, under a 150_REF carbon policy regime, if Non-EEA choses MDF100, EEA welfare becomes 16 885 mill € using MDF100 and 16 883 mill € using MDF25. Likewise, if Non-EEA chooses MDF25, the EEA achieves a welfare of 16 884 mill € applying MDF100 and 16 883 mill € applying MDF25. This means that applying MDF100 is the best strategy for the EEA irrespective of the choice of the Non-EEA. The opposite results is true for Non-EEA. With one exception, Non-EEA is always better off using MDF25. The exception is the 150_LAP carbon policy regime in which welfare is higher when applying MDF100, but only if the EEA also chooses MDF100.

Since applying MDF100 is the best strategy for EEA, the Nash-equilibrium depends on the scenario setting. In three of the four possible combinations of general carbon prices and dietary choice, (MDF25, MDF100) (i.e., Non-EEA applying MDF25, and EEA applying

**Table 1.** Carbon prices by general carbon price, methane deduction factor (MDF) and climate gas for 2030, 2050 and 2070 (€ per t climate gas).

| General carbon price | MDF | 2030 | | 2050 | | 2070 | |
|---|---|---|---|---|---|---|---|
| 150 2005-\$ per t $CO_2$ | 100 | All gases: | 20.67 | All gases: | 54.85 | All gases: | 145.54 |
| | 25 | $CO_2$, $N_2O$: | 20.67 | $CO_2$, $N_2O$: | 54.85 | $CO_2$, $N_2O$: | 145.54 |
| | | $CH_4$: | 5.79 | $CH_4$: | 15.36 | $CH_4$: | 40.75 |
| 500 2005-\$ per t $CO_2$ | 100 | All gases: | 68.91 | All gases: | 182.84 | All gases: | 485.13 |
| | 25 | $CO_2$, $N_2O$: | 68.91 | $CO_2$, $N_2O$: | 182.84 | $CO_2$, $N_2O$: | 485.13 |
| | | $CH_4$: | 19.29 | $CH_4$: | 51.20 | $CH_4$: | 135.84 |

**Table 2.** Scenario matrix.

| Methane deduction factor (MDF) | No carbon price<br>No dietary change | General carbon price rate 150 2005-\$/t $CO_2$-equu.<br>No dietary change (REF) | General carbon price rate 150 2005-\$/t $CO_2$-equ.<br>Low animal protein diet (LAP) | General carbon price rate500 2005-\$/t $CO_2$-equ.<br>No dietary change (REF) | General carbon price rate500 2005-\$/t $CO_2$-equ.<br>Low animal protein diet (LAP) |
|---|---|---|---|---|---|
| Non-EEA: 100<br>EEA: 100 | BAU | 100/100_150_REF | 100/100_150_LAP | 100/100_500_REF | 100/100_500_LAP |
| Non-EEA: 100<br>EEA: 25 | | 100/25_150_REF | 100/25_150_LAP | 100/25_500_REF | 100/25_500_LAP |
| Non-EEA: 25<br>EEA: 100 | | 25/100_150_REF | 100/25_150_LAP | 100/25_500_REF | 25/100_500_LAP |
| Non-EEA: 25<br>EEA: 25 | | 25/25_150_REF | 100/25_150_LAP | 25/25_500_REF | 25/25_500_LAP |

**Table 3.** Welfare outcome by scenario in 2030 (mill €).

| | | EEA | |
|---|---|---|---|
| **150_REF** | | **MDF100** | **MDF25** |
| Non-EEA | MDF100 | (97 771, 16 885) | (**97 772**, 16 883) |
| | MDF25 | (**97 772**, **16 884**) | (97 772, 16 883) |
| | | EEA | |
| 500_REF | | MDF100 | MDF25 |
| Non-EEA | MDF100 | (97 712, 16 887) | (97 713, 16 885) |
| | MDF25 | (**97 771**, **16 886**) | (97 773, 16 883) |
| | | EEA | |
| 150_LAP | | MDF100 | MDF25 |
| Non-EEA | MDF100 | (**97 801**, **16 877**) | (97 795, 16 876) |
| | MDF25 | (97 795, 16 877) | (97 805, 16 876) |
| | | EEA | |
| 500_LAP | | MDF100 | MDF25 |
| Non-EEA | MDF100 | (97 742, 16 881) | (97 745, 16 879) |
| | MDF25 | (**97 791**, **16 879**) | (97 800, 16 876) |

Note: Welfare outcomes are denoted (Non-EEA, EEA). Best strategies dependent on the other world region's strategy are underscored. Strategies supporting a unique Nash-equilibrium are underscored and bold.

MDF100) becomes the unique Nash-equilibrium. For instance, under the 500_REF regime, Non-EEA receives higher welfare from choosing MDF25 irrespective of the choice of the EEA. Likewise, the EEA cannot do better than using MDF100 irrespective of what Non-EEA does. For the remaining scenario, 150_LAP, the unique Nash-equilibrium is characterized as one in which both world regions apply MDF100.

The situation changes slightly when moving 20 years ahead to 2050. The EEA achieves the same or higher welfare outcome applying MDF25 under a 150_REF and 500_REF carbon policy regime if Non-EEA uses MDF100. However, Non-EEA is always best off applying MDF25, also under a 150_LAP and 500-LAP carbon policy regime. Therefore, the unique Nash-equilibrium turns out to be the same for all four combinations of general carbon price and dietary choice: Non-EEA applies MDF25, while EEA uses MDF100. Table 4 shows that Non-EEA's choice of MDF25, and EEA's choice of MDF100 establish a unique Nash-equilibrium regardless of general carbon price and dietary choice. Since welfare outcomes are presented in nominal prices, the absolute differences in welfare between the strategies increase somewhat.

The results for 2050 are confirmed for 2070. Table 5 shows that the strategies that support the Nash-equilibrium remain the same. It is still most profitable for Non-EEA to use MDF25 regardless of the EEA's choice of MDF and scenario assumptions about general carbon price and dietary choice. Given the Non-EEA's optimal strategy, the best response for the EEA is to apply MDF100. Under certain conditions (e.g., 150_REF, 500_REF, 500_LAP) the EEA would achieve a higher welfare level by implementing MDF25, but only if Non-EEA would apply MDF100. As this is not the best strategy to be made by Non-EEA, the EEA's choice of MDF25 cannot be sustained as a Nash-equilibrium.

The long-run Nash-equilibrium thus turns out to be a situation in which the two world regions choose different MDF. While Non-EEA applies MDF25 which leads to a lower price

**Table 4.** Welfare outcome by scenario in 2050 (mill €).

| | | **EEA** | |
|---|---|---|---|
| **150_REF** | | **MDF100** | **MDF25** |
| Non-EEA | MDF100 | (232 574, 31 878) | (232 577, 31 878) |
| | MDF25 | (**232 646**, **31 878**) | (232 650, 31 876) |
| | | EEA | |
| 500_REF | | MDF100 | MDF25 |
| Non-EEA | MDF100 | (231 774, 31 888) | (231 780, 31 893) |
| | MDF25 | (**232 636**, **31 880**) | (232 651, 31 876) |
| | | EEA | |
| 150_LAP | | MDF100 | MDF25 |
| Non-EEA | MDF100 | (232 806, 31 857) | (232 812, 31 856) |
| | MDF25 | (**232 873**, **31 856**) | (232 880, 31 853) |
| | | EEA | |
| 500_LAP | | MDF100 | MDF25 |
| Non-EEA | MDF100 | (231 999, 31 878) | (232 009, 31 877) |
| | MDF25 | (**232 862**, **31 864**) | (232 880, 31 853) |

Note: Welfare outcomes are denoted (Non-EEA, EEA). Best strategies dependent on the other world region's strategy are underscored. Strategies supporting a unique Nash-equilibrium are underscored and bold.

**Table 5.** Welfare outcome by scenario in 2070 (mill €).

| | | **EEA** | |
|---|---|---|---|
| **150_REF** | | **MDF100** | **MDF25** |
| Non-EEA | MDF100 | (505 825, 61 384) | (505 836, 61 392) |
| | MDF25 | (**507 009**, **61 378**) | (507 031, 61 376) |
| | | EEA | |
| 500_REF | | MDF100 | MDF25 |
| Non-EEA | MDF100 | (495 549, 61 433) | (495 561, 61 476) |
| | MDF25 | (**506 967**, **61 382**) | (507 032, 61 377) |
| | | EEA | |
| 150_LAP | | MDF100 | MDF25 |
| Non-EEA | MDF100 | (506 513, 61 369) | (506 529, 61 367) |
| | MDF25 | (**507 694**, **61 355**) | (507 718, 61 340) |
| | | EEA | |
| 500_LAP | | MDF100 | MDF25 |
| Non-EEA | MDF100 | (496 258, 61 455) | (496 281, 61 474) |
| | MDF25 | (**507 653**, **61 378**) | (507 719, 61 341) |

Note: Welfare outcomes are denoted (Non-EEA, EEA). Best strategies dependent on the other world region's strategy are underscored. Optimal strategies supporting a unique Nash-equilibrium are underscored and bold.

**Table 6.** Absolute change in EEA meat production and meat net exports by scenario in 2070 (1 000 t).

| From | To | 150_REF | 150_LAP | 500_REF | 500_LAP |
|---|---|---|---|---|---|
| Non-EEA: MDF25 | Non-EEA: MDF25 | −2 947 | −4 092 | −8 349 | −10 017 |
| EEA: MDF25 | EEA: MDF100 | −2 688 | −3 847 | −7 102 | −9 444 |
| Non-EEA: MDF100 | Non-EEA: MDF25 | −445 | −2 176 | −13 088 | −15 439 |
| EEA: MDF100 | EEA: MDF100 | −5 289 | −7 046 | −13 073 | −16 410 |
| Non-EEA: MDF100 | Non-EEA: MDF100 | 759 | 3 282 | 1 775 | 6 062 |
| EEA: 100 | EEA: MDF25 | 756 | 3 173 | 1 867 | 5 914 |
| Non-EEA: MDF25 | Non-EEA: MDF100 | 2 828 | 5 613 | 6 514 | 11 484 |
| EEA: MDF25 | EEA: MDF25 | 3 357 | 6 373 | 7 838 | 12 881 |

Note: Upper number in cells: EEA meat production, lower number in cells: EEA net exports

for methane, the best strategy for the EEA is to apply MDF100 which results in pricing methane equal to other climate gases, but also a higher price for methane.

This result may be counterintuitive as rising production costs to mitigate methane emissions are expected to lead to lower welfare. To investigate this issue further, we decompose the change in EEA welfare by interest group and scenario of a shift from MDF25 to MDF100. Producers and taxpayers benefit, while consumers, land owners, and the food industry loose. The gains for producers are larger under the low animal-protein diet and under the low general carbon price. These gains are accompanied by losses of consumers, landowners, and the food industry, but the net welfare effect is positive.

Further investigation shows that producer welfare increases for all commodity groups included meat which is most sensitive for methane prices. For meat, the combined effect of a shift from MDF25 to MDF100 on prices, costs, and premiums outperforms the negative effect of that shift on production. In other words, higher domestic meat prices have a larger effect on agricultural income than reduced production. Moreover, lower production also reduces the costs of production. In sum, while an increase in the price of methane leads to higher production costs, farmers pass on increased costs to consumers. Demand and production falls, but the net total welfare effect and the welfare effect for producers are positive.

We now present meat production and net trade to investigate possible production and trade distorting effects of the choice of the MDF. The rows in Table 6 mark the four situations in which the two world regions switch from using the same MDF to a using a different MDF, while the upper (lower) numbers in the cells show meat production (meat net exports). For instance, the upper row marks the situation in which EEA switches from MDF25 to MDF100 while Non-EEA keeps MDF25. EEA meat production decreases by 2,947 kt under the 150_REF scenario as meat production costs increase caused by higher price for methane. Net meat exports decrease by 2,688 kt. Similar results can be observed for the 150_LAP scenario. A higher general carbon price drives a wedge between production and net exports indicating a more pronounced reduction in meat demand.

EEA meat production and net exports decrease also if Non-EEA switches to MDF25 from a situation in which both world regions apply MDF100. This is because a reduction of the price of methane in the Non-EEA has similar effects on competitiveness as discussed above for the EEA. However, the effect on EEA net exports is much larger than the effect on production, at least under the lower general carbon price. Under the higher general carbon price, the difference between the reductions of production and net exports becomes much smaller. A switch in the Non-EEA from MDF100 to MDF25 first hits EEA net exports. With a higher price of methane, also EEA production is more affected.

EEA meat production and net exports increase following a change from either common usage of MDF100 or MDF25 to a situation in which the Non-EEA (EEA) applies MDF100

(MDF25). This situation is shown in the lower two rows of Table 6. In both cases, the additional production in the EEA closely follows the increase in net exports. The development is caused by a lower price for methane in the EEA compared to the Non-EEA. Whether the EEA changes from MDF1000 to MDF25 or the Non-EEA switches from MDF25 to MDF100 is of minor importance.

The results in Table 6 show that any change from uniform to non-uniform use of MDF in the two world regions clearly have production and trade effects. Our particular interest is in distortionary effects that emerge from the deviation of a common MDF applied by both world regions relative to the Nash-equilibrium in which different MDF are applied. The Nash-equilibrium is characterized by Non-EEA using MDF25 and EEA using MDF100. The corresponding EEA and Non-EEA meat production and net exports are shown in Table 7 distinguishing a situation in which either MDF25 or MDF100 is applied by both world regions.

EEA meat net exports decrease at most by 80 per cent, while EEA meat production is down by up to 36 per cent. Since production is larger than net trade in absolute terms, the relative changes are larger for net trade. This picture is more pronounced for the Non-EEA. The relative effects on production are rather small, while the relative trade effects show an increase of up to 85 per cent. The numerical results indicate significant trade effects of a change from common global MDF to nationally decided MDF.

We finally study how different climate policy regimes affect additional global warming. Figure 1 shows annual methane emissions for the four different combinations of MDF chosen by the two world regions. Emissions are averaged over carbon prices and dietary assumptions, and emissions between the base year (2010) and the simulation years (2030, 2050, 2070) are imputed. Irrespective of the choice of MDF, methane emissions are more than halved by 2070 from 200 000 t in the BAU to less than 100 000 t. The choice of the MDF in the Non-EEA matters most for global emissions due to the large size of that world region. Therefore, applying MDF25 in Non-EEA leads to significantly lower methane emission cuts than applying MDF100. The choice of MDF in EEA is of minor importance. In the baseline, the contribution of the EEA to global emissions from agriculture is 6.9 per cent in 2030, 5.2 per cent in 2050, and 4.6 per cent in 2070.

Including $N_2O$ emissions from agriculture does not considerably change that picture. Figure 2 shows the added global warming from agricultural Non-$CO_2$ emissions.

Any climate policy regime significantly reduces added global warming compared to the BAU. However, the MDF combination sustained in the Nash-equilibrium (MDF25/MDF100) is not the one that fully utilizes the global mitigation potential. This is because the Nash-equilibrium establishes MDF25 being chosen by Non-EEA. The difference in added global warming between the metric choice sustained by the Nash-equilibrium and the full potential (MDF100/MDF100) is more than 0.02 °C in 2070.

Figure 3 compares the cumulated Non-$CO_2$ emissions using the two GHG accounting metrices $GWP_{100}$ and GWP*. Note that GHG accounting is done outside the model by applying equations (1) for $GWP_{100}$ and (2) for GWP* to the model results for $CH_4$ and $N_2O$ emissions. In the BAU, and without a particular carbon policy regime, the GWP-values defined in $CO_2$*-eq.* (GWP100) and $CO_2$*-w.e.* (GWP*), are somewhat smaller if emissions are accounted using GWP* compared to GWP100. However, the general picture is the same: increasing methane emissions (jf Fig. 1) lead to increased GWP-values. The difference between accounting GHG emissions using GWP100 and GWP* becomes evident when methane emissions decrease over time. Using GWP100, $CO_2$-eq.-values still increase, although a lower rate compared to the BAU. The discrepancy between rising $CO_2$-eq. values and falling added global temperature (jf. Fig. 1) for the same Non-$CO_2$ emissions illustrates the potential error made by accounting methane emissions using GWP100. On the contrary, the GWP*-values for the average of all scenarios show the same development over time as the added global temperature effect in Fig. 1.

**Table 7.** Relative change in EEA and Non-EEA meat production and meat net exports by scenario in 2070 (1 000 t).

| From | To | Region | 150_REF | 150_LAP | 500_REF | 500_LAP |
|---|---|---|---|---|---|---|
| Non-EEA: MDF25 | Non-EEA: MDF25 | EEA | −6 | −11 | −17 | −26 |
| EEA: MDF25 | EEA: MDF100 |  | −26 | −26 | −69 | −63 |
| Non-EEA: MDF100 | Non-EEA: MDF25 |  | −10 | −16 | −24 | −36 |
| EEA: MDF100 | EEA: MDF100 |  | −41 | −39 | −80 | −74 |
| Non-EEA: MDF25 | Non-EEA: MDF25 | Non-EEA | 0 | 0 | 0 | −1 |
| EEA: MDF25 | EEA: MDF100 |  | 6 | 17 | 11 | 27 |
| Non-EEA: MDF100 | Non-EEA: MDF25 |  | −3 | −5 | −4 | −7 |
| EEA: MDF100 | EEA: MDF100 |  | 33 | 43 | 76 | 85 |

Note: Upper number in cells: Meat production, lower number in cells: Meat net exports

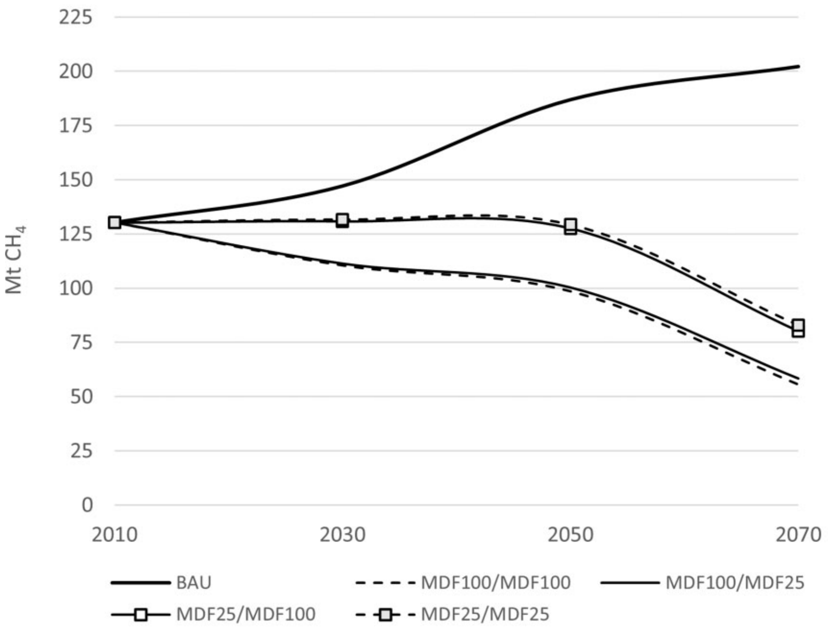

**Figure 1.** Annual global methane emissions as an average over carbon price and dietary choice by Non-EEA/EEA MDF combinations in 2030, 2050, and 2070 (1 000t).

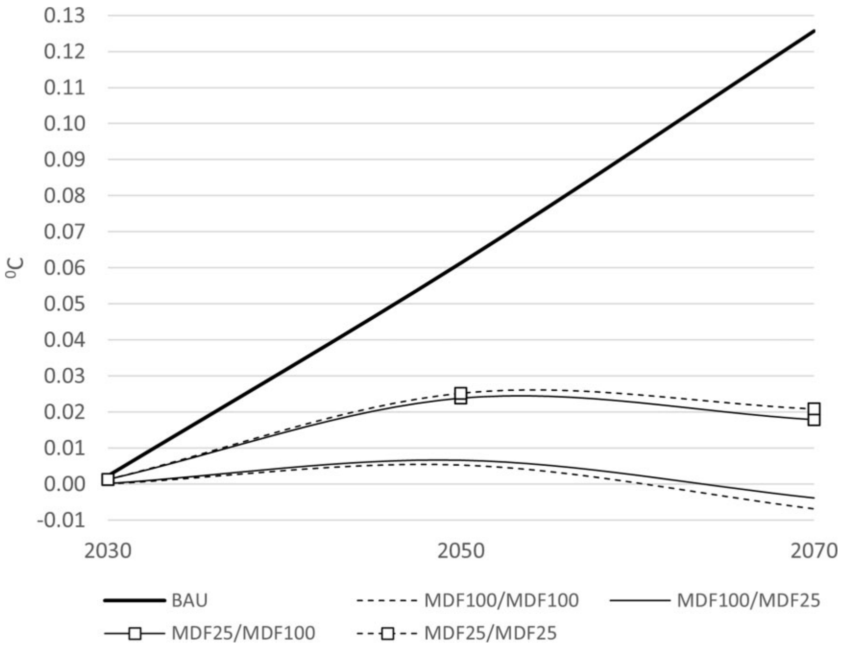

**Figure 2.** Added global warming from Non-$CO_2$ emissions from agriculture as an average over general carbon price and dietary assumptions by methane deduction factor applied by Non-EEA/EEA in 2030, 2050, and 2070 (°C).

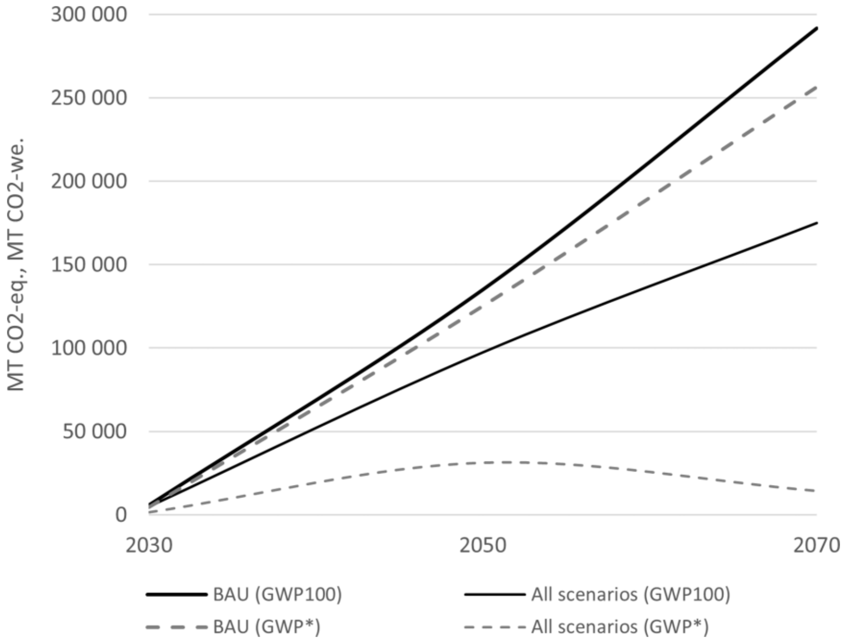

**Figure 3.** Cumulated Non-$CO_2$ emissions from global agriculture for the BAU and an average of scenarios by GHG accounting metric in 2030, 2050 and 2070 (MT $CO_2$-eq. and MT $CO_2$-w.e.).

Figure 4 compares the marginal effects of MDF, general carbon price, and dietary assumptions on added global temperature. Shown in Fig. 4 are the difference in added global temperature for each scenario compared to the BAU. The general carbon price and dietary assumptions play a larger role than the choice of the MDF. A high general carbon price guarantees larger emission cuts compared to a low general carbon price irrespective of dietary assumptions and application of the MDF. This can be seen in Fig. 4 by comparing the light grey bars (high general carbon price) with the dark grey bars (low general carbon price). A general carbon price of 500$ per t $CO_2$ ensures at least −0.13 °C of added global warming even if MDF25 is applied globally and no dietary change occurs (i.e., 25/25_500_REF). A general carbon price of 150$ per t $CO_2$ achieves at most −0.114 °C of added global warming under a low animal-protein diet and MDF100 globally applied (i.e., 100/100_150_LAP).

The additional effect of dietary assumptions on added global warming is at most −0.0145 °C in the presence of a low carbon price, MDF25 applied in Non-EEA, and MDF 100 applied in EEA (i.e. temperature difference between 25/100_150_REF and 25/100_150_LAP). In comparison, the highest additional effect of MDF application is −0.033 °C. This reduction is achieved if countries switch from MDF100 to MDF25 globally under a low general carbon price and a low animal-protein diet (i.e. temperature difference between 100/100_150_LAP and 25/25_150_LAP).

Overall, the marginal effect of a dietary change on added global warming decreases with an increase in the general carbon price level. Under a low general carbon price, the marginal effect of a low animal protein-based diet is at most −0.007 °C, while it is at least −0.013 °C under a low general carbon price. The same is true for the marginal effect of MDF application. The marginal effect of a change from MDF25 to MDF100 (i.e., applying a higher implicit price on methane emissions) on added global warming is higher under a low general carbon price. These results are related to the exhaustion of mitigation options and in line with the literature (Frank et al. 2019). Under a high general carbon price regime, the

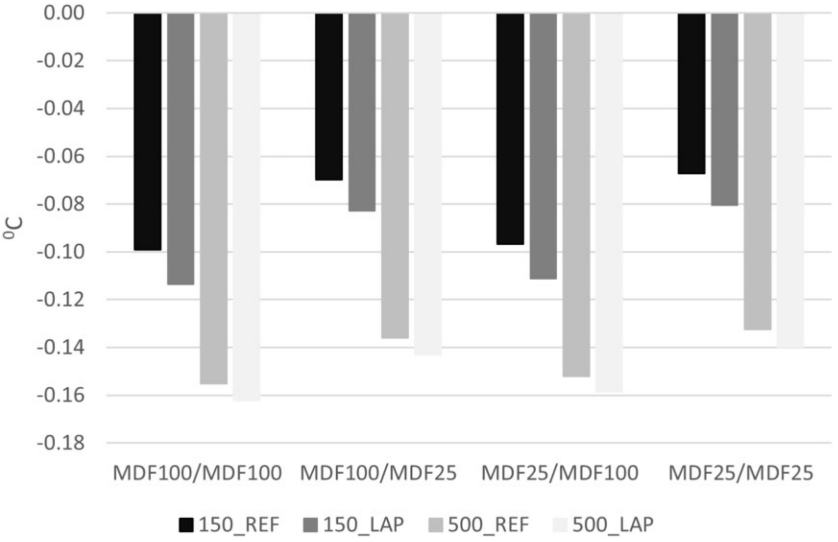

**Figure 4.** Added global warming from Non-$CO_2$ emissions from agriculture compared to the BAU by methane deduction factor (MDF) applied in Non-EEA/EEA world regions, general carbon price, and dietary assumptions in 2070 (°C).

agricultural sector has fewer options to implement additional mitigation options induced by a stricter carbon policy regime for methane (i.e., a change from MDF25 to MDF100) or by adjustments in the agricultural sector due to dietary change.

## 6. Discussion and conclusion

Our study anticipates a discussion of providing a 'rebate' to methane emissions from agriculture using a methane deduction factor and assesses likely consequences for global agriculture. Countries currently hardly discuss such choices, but such a discussion may evolve in countries where animal husbandry is a major emitter, and the farm lobby is strong.

Countries' choice of the methane deduction factor as a basis for pricing methane emissions within their territory may have severe impacts on the efforts to reduce Non-$CO_2$ emissions globally. The non-uniform application of MDF for carbon pricing purposes provides production and mitigation incentives to farmers that differ by world region. These incentives depend also on the stringency of the mitigation policy to be achieved and demand side policies leading to dietary changes.

The choice of the MDF also affects production decisions and trade. In principle, countries that apply large deduction factors for methane gain in terms of production and trade as it provides a competitive advantage for the domestic agricultural sector through a lower implicit carbon price for methane. Similarly, countries with weaker mitigation options may implement a large MDF with the aim to protect domestic agriculture from foreign competition. Hence, non-uniform application of MDF by countries has limited effects on global mitigation efforts, leading instead to emission leakage through an adjustment of agricultural production and trade.

A country's best strategy for choosing MDF depends also on other countries' decisions. In our example, Non-EEA always chooses the MDF with the lower implicit carbon price for methane (i.e., MDF25). Given that choice, EEA opts for MDF100 which results in higher total welfare compared to MDF25. By doing so, meat production and net exports decrease and provide production and trade opportunities for Non-EEA. We conclude that a free choice of MDF does not necessarily lead to a 'race to the bottom' in which all countries apply MDF25. The benefits for EEA agricultural producers and taxpayers due to higher prices induced by a higher implicit carbon price for methane outperform the reduction in consumer welfare. Our results suggests that for the EEA pricing methane differently from $N_20$ and $CO_2$ is not beneficial nonetheless what Non-EEA is planning.

From a global emission reduction point of view, the absence of common rules of setting a MDF is suboptimal for global efforts to combat climate change as emissions unfold their global warming potential regardless of their origin in the EEA or Non-EEA area. Hence, the marginal cost of reducing emissions should be uniform in any objective involving global warming.

Our analysis shows that applying a low MDF (i.e., MDF100) globally would cut emissions most. However, enforcing countries to agree on a common MDF globally could also result in the 'lowest common denominator' which would be MDF25 as Non-EEA would face a welfare loss if opting for MDF100. Hence, enforcing a globally applied MDF may run the risk of achieving less emission cuts than a situation in which countries may choose their MDF freely.

Any choice of MDF for carbon pricing of methane affects production and trade. In equilibrium, Non-EEA expands production and trade compared to a situation with a uniform MDF. Hence, although EEA distorts production and trade through its unilateral change of MDF, Non-EEA experiences a welfare gain.

Our analysis also shows that supply-side mitigation options induced by carbon pricing remain most important to achieve emission cuts in agriculture. A high general carbon price reduces emissions more than a dietary change or a change in the MDF.

Our conclusions are based on simplifying assumptions. Firstly, we assume that carbon pricing and dietary change can be enforced globally, although these measures are part of a country's domestic climate policy regime. Since there is no agreement on a global MDF, countries will most likely decide on individual carbon prices and dietary policies, which have specific impacts on production, consumption trade and emissions (see e.g., Frank et al. 2019). Further analysis could extend the simulation work to study policy coordination problems and distortionary effects associated with them.

We also assume that climate policy regimes achieve emission cuts in an efficient way. This is problematic, because emissions from agriculture are difficult to measure at their source due to the spatial dispersion of farming and variety of farming practices. Similarly, as we abstract from the welfare implications of a change in dietary preferences, consumer welfare associated with the reference diet and in the low animal protein-based diet is incomparable. Further, the benefits of a dietary change due to longer, more productive lives and decreasing healthcare costs are not considered in the welfare analysis. These questions must be left for future research.

Our model analysis abstracts from other sectors in the economy. The Effort Sharing Decision (ESD) in the EEA sets out an overall GHG emission target for sectors not included in the EU emission trading system such as agriculture, transport, buildings, and waste. MDF that lead to lower emission reductions in agriculture must be offset by larger reductions in other sectors covered by the ESD. The net welfare outcome for the whole economy is unclear. For example, Norway has set a quantitative GHG emission reduction target for agriculture. However, research shows that the marginal abatement costs to achieve that target are higher than the marginal abatement costs of additional reduction efforts in other ESD-sectors (Kokemohr et al. 2022). Therefore, reduced ambitions in agriculture could improve total welfare. Whether that example extends to other countries depends on whether specific emissions targets exist for sectors covered by the ESD and the likely social costs associated with them. General equilibrium modelling could help to shed light on this issue.

## Conflict of interest

This paper is based on results from the research project MIND STEP, which is funded by European Union's Horizon 2020 research and innovation programme under grant agreement No. 817566. The authors are solely responsible for the content of the paper. The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

## Funding

This work has received funding from the European Union's research and innovation programme under grant agreement No. 817566.

## Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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