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Impacts of national vs European carbon pricing on agriculture

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Abstract

The agricultural sector has the potential to contribute to reaching both global and national climate targets. Lately, frequent discussions emerge among academics as well as policymakers regarding whether the agricultural sector should be subject to carbon pricing under different emission trading systems. Germany has set ambitious climate targets envisaging to reach carbon neutrality by 2045, and the EU plans reaching carbon neutrality by 2050. However, the current GHG emission mitigation trends are not in line with this goal. In this study, we quantitatively analyze the environmental and economic effects of the possible inclusion of the agricultural sector into a carbon pricing scheme, once for Germany only, and second for the EU. Moreover, we evaluate the role of already existing and novel technological mitigation options in the GHG emissions mitigation quest. Our findings demonstrate that even the unilateral action by Germany leads to net agricultural emissions reduction, although, the effect obtained by the EU-wide implementation of carbon pricing in agriculture is fivefold larger. The results also highlight the importance of stimulating the use and transferability of the technological options not only in mitigating GHG emissions but also in alleviating the emission leakage to third countries and easing the economic consequences of such a policy.

1. Introduction

In light of the COP27 summit in Sharm el-Sheikh and in the run-up to the COP28 with a focus on a global stocktake of greenhouse gas mitigation efforts, many national governments are facing international scrutiny to revisit and strengthen their climate targets to align with the Paris agreement. Moreover, considerable effort is still required to achieve these targets. The EU has committed to reach carbon neutrality by 2050 and to reduce its greenhouse gas (GHG) emissions by 55% until 2030 compared to the 1990 levels. The cornerstone of the EU climate change mitigation policy is the EU Emission Trading System (EU ETS) established in 2005. It covers around 11 700 installations in 31 participating countries (EEA 2022) which account for about 40% of the EU's total GHG emissions (Verde and Borghesi 2022). With stricter regulating mechanisms such as the so-called invalidation rule the EU ETS will be further strengthened in the coming years (Bruninx and Ovaere 2022). The crucial role of emissions trading in achieving climate targets has generally been acknowledged (Fujimori *et al* 2016). In 2019, the EU managed to reduce its emissions by 24% and by 34% in 2020 compared to the 1990 levels as a result of the Covid-19 pandemic (BMWK 2022). If the current trends continue the EU will miss its 2030 target by 15 percentage points (667 $MtCO_2eq$) (EEA 2020). This is the reason the European Commission has put forward the Fit for 55 package consisting of a set of measures that will ensure that the EU meets the target in 2030. The package includes implications for the agricultural sector up to 2030, such as increasing emission reduction targets for Effort Sharing sectors, including agriculture, and increasing targets for net removals from the land use, land-use change and forestry (LULUCF) sector. Additionally, a new agriculture, forestry and other land use (AFOLU) sector is proposed after 2030, with its own emission targets, with the aim of reaching net zero emissions by 2035 and negative emissions (net removals) thereafter (EC 2021). Notably, the proposed and ambitious quantitative targets with the revision of the LULUCF regulation, setting quantities for emission reductions and carbon removals in the land use, land use change and forestry will draw the attention even more to sectors which are currently not under a carbon pricing scheme.

Apart from the EU climate change mitigation targets, Germany has set even higher ambitions for carbon neutrality which is laid out by the Climate Change Act (German Federal Government 2021). The German Government plans to reduce GHG emissions by 65% by 2030 and 88% by 2040. Moreover, climate neutrality is envisaged by 2045. These targets will be achieved through a large number of sector-specific individual measures and the gradual implementation of a cross-sectoral national emissions trading system (nETS). The nETS targets the sectors not covered by the EU ETS, i.e. the heating and transport sectors. The carbon price of the nETS was fixed at 25€/tCO_2 until 2021, and it will gradually increase to 55€/tCO_2 until 2025. Starting in 2026 it will shift to an auctioning process. Since 1990 Germany has shown a promising rate of emission reduction. In 2020 the estimated reduction of GHG emissions in Germany was 41.3% reaching approximately 729 MtCO_2eq (BMWK 2022). This reduction, however, is a result of the collapse of East German energy-intensive industry after reunification, the Covid-19 pandemic as well as favorable weather conditions. Following the economic recovery in 2021, the GHG emissions in the country have increased to 762 MtCO_2eq (UBA 2022). This was the first increase in GHG emissions for the last decade since at this time the average annual reduction in emissions was about 15 MtCO_2eq. Nevertheless, for the national emission reduction target in 2030 to be reached, this rate should double in the coming years and then triple in the run-up to 2030. Such a reduction rate requires contributions from all economic sectors, including the agricultural sector. In 2020, the German agricultural sector was responsible for 9% of total GHG emissions in the country which is equivalent to around 62.4 MtCO_2eq (BMWK 2022). According to the Federal Government's 2021 Projection Report, the cumulative gap in the sector between the 2022 emissions and the 2030 target is around 36 MtCO_2eq (Bundesregierung 2021).

While the common agricultural policy (CAP) plays a central role in designing agricultural mitigation policies at the EU level, the framework of the CAP can be adapted to enable more ambitious national policies in Member States. This can be achieved through a combination of mandatory requirements (conditionality), the design of eco-schemes, and the design of second pillar environmental measures. For instance, Germany has proposed a set of ten different measures to reduce greenhouse gas emissions from agriculture and LULUCF within its 'Climate Action Program 2030', in addition to the CAP (Bundesregierung 2019). This highlights the existence of a variety of policy instruments for climate mitigation in agriculture, raising the question of whether a unified market instrument would lead to more efficient results in climate policies, including for agriculture.

Isermeyer *et al* (2021) examine the feasibility of including the agricultural sector into a CO_2 pricing mechanism in Germany. Although, without any quantitative assessment the study identifies two potential challenges in doing so. The first challenge is associated with the administrative burden considering the variety of emission sources in the sector. And second, a unilateral carbon pricing policy in Germany could lead to leakage effects. However, it is important to distinguish between the leakage within the EU and that outside the EU. As long as all EU member states comply with mitigation targets in the ESR pillar (effort sharing regulation, including agriculture)[3] and the LULUCF pillar (according to LULUCF regulation)[4], they have to counterbalance increased emissions from increasing agricultural activities. In that sense, there is no leakage within a domestic market regulated by a common climate policy. Displacements of production due to unilateral action within the EU are thus impacting competitiveness of the national farm sectors, but not the achievement of the EU mitigation targets. Relevant leakage occurs when production is reallocated to third countries outside the EU. This is a well-covered phenomenon in the literature and it has been shown that a possible inclusion of the agricultural sector under carbon pricing mechanisms in one region may provoke a considerable leakage of emissions of the third countries (Himics *et al* 2018, van Meijl *et al* 2018, Jansson *et al* 2020, Frank *et al* 2021). Moreover, Thube *et al* (2021) show that the average carbon price required to achieve the climate targets is considerably lower in the case of coordinated global action as opposed to unilateral actions.

Against this background, the objectives of this study are twofold (a) to quantitatively assess the environmental and economic effects of integrating the agricultural sector into carbon pricing schemes only in Germany versus the EU-wide implementation; (b) to evaluate the effects of technological GHG mitigation options under German and EU-wide CO_2 (equivalent) price implementation.

2. Methods

For this study, we have applied the well-known Common Agricultural Regionalized Impact Analysis (CAPRI) model[5] in combination with the most recently updated database (EC 2022). CAPRI is a global, comparative static partial equilibrium (PE) model for the agricultural sector designed for policy

[3] Effort sharing regulation (ESR)—regulation (EU) 2018/842.
[4] LULUCF regulation—regulation (EU) 2018/841.
[5] Model revision number: 10 235; date of release: 30 May 2022.

impact assessment of CAP and trade policies (Britz and Witzke 2014). CAPRI is a combination of a detailed European-focused supply module and a global market module.

The supply module consists of independent non-linear programming models for each of 280 NUTS 2[6] regions of EU 27, Norway, Western Balkans, and Turkey representing around 50 animal and crop activities. The individual supply models are based on the positive mathematical programming approach allowing for high flexibility in capturing important interactions between production activities and the environment (Gocht *et al* 2017). Each supply model maximizes the regional agricultural income subject to land constraints, nutrient balances, and policy requirements.

The market module is a comparative static, deterministic, spatial, global PE model depicting around 60 primary and secondary agricultural products. It represents 80 countries and country blocks worldwide. International trade is modeled based on a two-stage Armington assumption which means that the goods are differentiated by place of origin following the consumer preferences derived from the historical trade patterns. On the top level, the model determines the total demand from imports and domestic sales by considering the relation between the domestic price and the average import price, and then determines the import shares from different origins and defines the average import price in a lower stage. To address the issue of the Armington aggregator defining a utility aggregate and not a physical quantity, the shares are adjusted to physical quantities in the post-model stage. This approach allows the modeling of bilateral trade flows between countries as well as various bilateral and multilateral trade instruments (Britz and Witzke 2014).

Market equilibria in CAPRI are reached by iterations between the supply and market modules. These two modules iteratively exchange information on prices, supply and feed demand until convergence is reached.

CAPRI endogenously accounts for CO_2 and non-CO_2 emissions and removals in the agricultural sector. The model is designed to capture the links between the EU agricultural production activities in great detail and thus based on production activities, input, and outputs the agricultural GHG emission effects are defined. The model also includes a detailed nutrient flow model per agricultural activity and region. Then based on this information GHG emissions are quantified following the (IPCC 2006) guidelines (mostly uses a Tier 2 approach but for emission sources for which necessary information is missing a Tier 1 approach is used) (Pérez Domínguez *et al* 2020). For the non-EU regions, the emission accounting is done on a product basis (Jansson and Säll 2018). For scenario analysis, the emission factors per commodity previously estimated for each non-EU region are multiplied with production to calculate the total emissions per region.

[6] Regions belonging to the second level of the Nomenclature of Territorial Units for Statistics.

Table 1. Technological GHG mitigation options available for adoption in CAPRI.

Sector	Mitigation technologies
Livestock	Anaerobic digestion at farm scale, low nitrogen feed, linseed as feed additive, nitrate as feed additive, vaccination against methanogenic bacteria in the rumen
Crop	Better timing of fertilization, nitrification inhibitors, precision farming, variable rate technology, increasing legume share on temporary grassland, rice measures, fallowing histosols (organic soils),
Ammonia	Low emission housing, manure storage with basin in concrete, low ammonia application (low and high efficiency).

CAPRI explicitly accounts for a number of already existing or innovative GHG mitigation technologies for EU agriculture. A detailed description of the modeled technological option can be found in Pérez Domínguez *et al* (2020). The underlying assumptions on mitigation potential, implementation costs, initial implementation shares, implementation limits, and cost saving of the mitigation technologies are mainly taken from the GAINS database. The implementation share of each mitigation technology is determined endogenously for each region as an economic decision based on a non-linear mitigation cost function. The linear part of the mitigation cost function is taken from cost databases, whereas the non-linear part implicitly accounts for factors influencing the uptake of technologies going beyond pure profitability considerations. All technologies are modeled in competition with each other, therefore, the decision on which technology to adopt and at which rate depends on such region-specific factors as costs, benefits, manure availability, etc. The considered mitigation technologies are listed in table 1.

3. Scenario description

Four scenarios are analyzed in comparison to a reference scenario (table 2), which reflects the state of the art of the EU agricultural sector in 2030 covering all the future developments as well as policy changes already foreseen by the current legislation. The reference scenario is calibrated to the European Commission's agricultural outlook and accounts for

Table 2. Simulated scenarios.

1.	Ref.	Reference scenario
2.	CPDE	100€/tCO_2 eq. tax is applied to agricultural activities in Germany without the effect of mitigation technologies.
3.	CPEU	100€/tCO_2 eq. tax is applied to agricultural activities in the EU 27 without the effect of mitigation technologies.
4.	CPDE-Tech	100€/tCO_2 eq. tax is applied to agricultural activities in Germany with the effect of mitigation technologies.
5.	CPEU-Tech	100€/tCO_2 eq. tax is applied to agricultural activities in the EU 27 with the effect of mitigation technologies.

trends in technological progress such as yield growth or increases in feed and fertilizer efficiency, inflation, gross domestic product (GDP) changes, population growth, and so on (EC 2019). The simulated policy scenarios use all specifications of the reference scenario and in addition, include the simulated shocks. The scenarios are further specified by integrating a carbon price and additionally whether mitigation technologies are enhanced or not. For the carbon price, we simulate a scenario of 100€/tCO_2eq for two reasons[7]: first, the carbon price in German nETS is fixed at 55 €/tCO_2eq until 2025 and afterwards will shift to auctioning process. Second, the carbon price of the EU ETS has been fluctuating between 50 and 100€/tCO_2eq for 2022 (Statista 2022). Therefore, it is reasonable to assume that by 2030 the carbon prices of both German nETS and EU ETS will converge and that the average carbon price in 2030 will be around the upper limit of the 2022 price.

CAPRI accounts for about 98.4% of the total EU agricultural GHG emissions officially reported to the UNFCCC (table A2) (Pérez Domínguez *et al* 2020)[8]. The assumed carbon price is applied to the CO_2 equivalents of all emissions from agriculture. In CAPRI, it is assumed that farmers have carbon permits corresponding to their emissions observed in the reference scenario. Therefore, the simulated tax is applied to the difference between their actual emission levels and permits. If the emissions in the region decrease compared to the reference scenario the tax turns into a subsidy.

4. Results

The mitigated emissions in the EU agricultural sector as a result of simulated scenarios are presented in table 3. The 100€/tCO_2eq carbon tax in Germany without the consideration of the impact of mitigation technologies (CPDE) reduces the emissions in the EU by about 5 MtCO_2eq (−1.28%) compared to the reference scenario. Whereas with the consideration of mitigation technologies (CPDE-Tech), the amount of mitigated agricultural emissions in the EU reaches around 18 MtCO_2eq (−4.53%). Of course, the impact of the EU-wide carbon tax implementation is more significant, i.e. 39 MtCO_2eq (−9.82%) without (CPEU) and 93 MtCO_2eq (−23.4%) with the mitigation technologies (CPEU-Tech). More details of emissions reductions from various gases are presented in table 4. Although, under the CPDE scenario, the GHG emissions from agricultural input industries in Germany decrease by about 0.8 MtCO_2eq as a result of reduced mineral fertilizer use (−10%), on the EU level the reduction is only around 0.55 MtCO_2eq since the mineral fertilizer use in the rest of the EU increases. Under the CPDE-Tech scenario, the mitigated emissions in Germany and in the EU, respectively, are even higher due to the effect of mitigation technologies in place which are specifically targeting N_2O emissions. Interestingly, the total ammonia emissions in both scenarios increase. This increase is provoked by the consideration of mitigation technologies, especially more and wider application of organic fertilizer, and thus more manure applied, which leads to more ammonia losses that occur during manure management and manure application.

Table 3. Mitigated emissions from the EU agricultural sector under the simulated scenarios.

	Value in baseline (in MtCO_2 eq)	Abs. change (in MtCO_2 eq)	% change
CPDE	396	−5	−1.28%
CPEU	396	−39	−9.82%
CPDE-Tech	396	−18	−4.53%
CPEU-Tech	396	−93	−23.40%

As presented in figure 1, under the CPDE scenario, the emissions decrease only in Germany and increase in the rest of the EU. The largest changes are observed in France, Spain, and Ireland. Which is explained by the fact that these countries increase their production to cover the unsatisfied demand in Germany. Under the CPDE-Tech scenario, the picture is similar, except that the mitigated emissions in Germany are higher by around a factor of 3 compared to the CPDE scenario, and the increase of emissions in other member states is more modest. Under the CPEU scenario, the emissions decrease in all member states with the largest mitigation observed in France,

[7] In order to determine the future value of the carbon price in 2030, an annual interest rate of 1.9% has been assumed.

[8] The current model version does not account for LULUCF emissions and removals.

Table 4. Emission reduction in the EU 27 compared to the reference scenario (in 1000 t).

	CPDE	CPEU	CPDE-Tech	CPEU-Tech
Total NH_3	−17.12 −0.79%	−156.30 −7.17%	48.47 2.20%	96.36 4.38%
Total N_2O	−8.63 −1.24%	−65.24 −9.40%	−34.45 −4.92%	−175.75 −25.07%
Total CH_4	−119.76 −1.46%	−881.35 −10.74%	−337.00 −4.12%	−1835.78 −22.43%
GHG emission from ag. input industries in CO_2 eq.	−555.11 −1.01%	−5413.17 −9.89%	−1572.05 −2.94%	−12 385.24 −23.19%

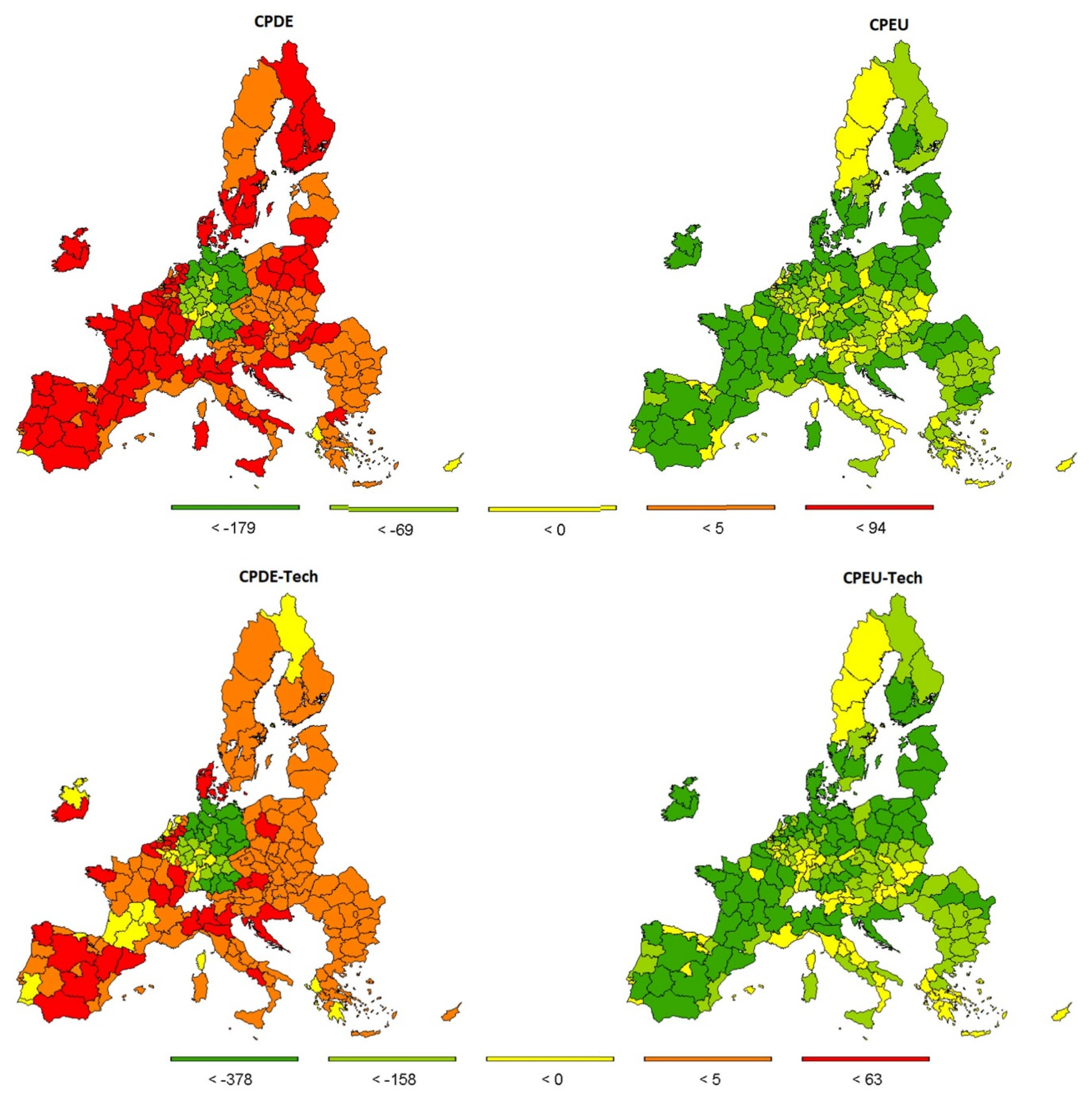


Figure 1. Absolute changes of GHG emissions from agriculture at Nuts2 level compared to the reference scenario with no carbon tax (in 1000 tCO_2eq).

Germany, Ireland, Poland, and Spain which is not surprising considering their livestock production levels. Under the CPEU-Tech scenario, the mitigated emissions in the EU are more than twice as much as under the CPEU scenario. Consequently, the mitigation in individual member states is also larger.

Figure 2 shows the contribution of each GHG mitigation technology to the total EU emissions reduction under the CPDE-Tech and CPEU-Tech scenarios. The first observation is that under the CPDE-Tech scenario, around 34% of mitigated emissions are due to production effects and 66% due to mitigation technologies. Whereas under the CPEU-Tech scenario, around 47% of the mitigated emissions are due to production changes and 53% due to the effects of the mitigation technologies. Under both

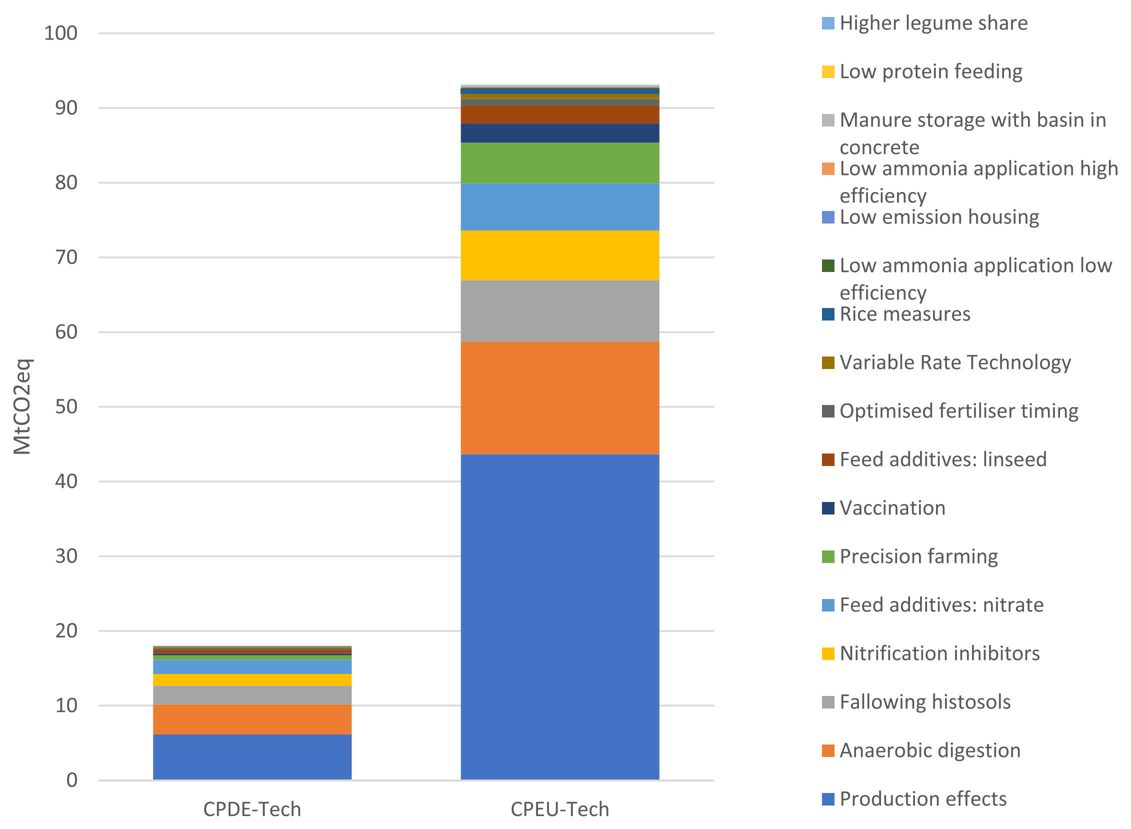


Figure 2. The sources of mitigation in EU 27.

scenarios, anaerobic digestion at the farm scale is the most uptaken mitigation option and therefore, has the highest mitigation impact. Under the CPDE-Tech scenario, it contributes with 4MtCO_2eq emissions reduction (22.5% compared to the total reduction), and under the CPEU-Tech with 15MtCO_2eq emissions reduction (16% compared to the total reduction). The uptake of anaerobic digestors is due to their high mitigation cost efficiency considering that it generates additional revenues by producing renewable energy.

The CPDE scenario reduces the German utilized agricultural area (UAA) by 0.55 million ha, whereas the CPEU scenario reduces the UAA in Germany by 0.42 million ha (by 2.57 million ha in the EU). Under the latter scenario, set aside and fallow land in the EU increases by about 17% (1.57 million ha). When considering the effects of mitigation technologies, the carbon tax only in Germany causes a reduction of the UAA in Germany and the EU by 0.13 and 0.08 million ha, respectively. Under the EU-wide carbon tax implementation, the reduction is 0.15 and 1.4 million ha in Germany and the EU, respectively. These reductions in UAA is mainly caused by arable land taken out of production since pasture land cannot be converted due to CAP obligations for biodiversity conservation. As a consequence, under all four scenarios, grassland extensification is observed.

As a result of this reduction in UAA, under the CPDE scenario, the total use of mineral N fertilizer decreases by 10.32% in Germany and 1.05% in the EU, accordingly (table A1). The use of manure, on the other hand, reduces in the EU by 0.9% which is mainly driven by the reduction in Germany (8.73%). The average overall reduction of crop production in the EU draws down fertilization with crop residues by 1.34%. A similar effect is observed regarding biological fixation (−1%) which is mainly explained by the reduction in the production of intensive grassland and fodder from arable land in the EU. The effects of the CPEU scenario are in the same direction but more pronounced. Under this scenario, the total use of mineral fertilizer in the EU decreases by 10% (1.03 Mt), and the highest absolute reduction of mineral fertilizer is observed in Poland (0.17 Mt/13.5%), Germany (0.12 Mt/7.9%), France (0.11Mt/5.8%), and Ireland (0.1 Mt/27.81%) (figure 3). Fertilization with manure and crop residues in the EU reduce by 7.17% (0.6 Mt of N) and 11.74% (1.03 Mt of N), respectively. When considering the effects of mitigation technologies, the reduction of fertilizer application from different sources is considerably higher due to higher nitrogen use efficiency.

Following the reduction of overall UAA, the production of cereals and oilseeds in the EU reduces in all four scenarios (figure 4). The reduction under the scenarios with mitigation technologies is relatively lower than without mitigation technologies which are explained by the positive yield and increased nutrient

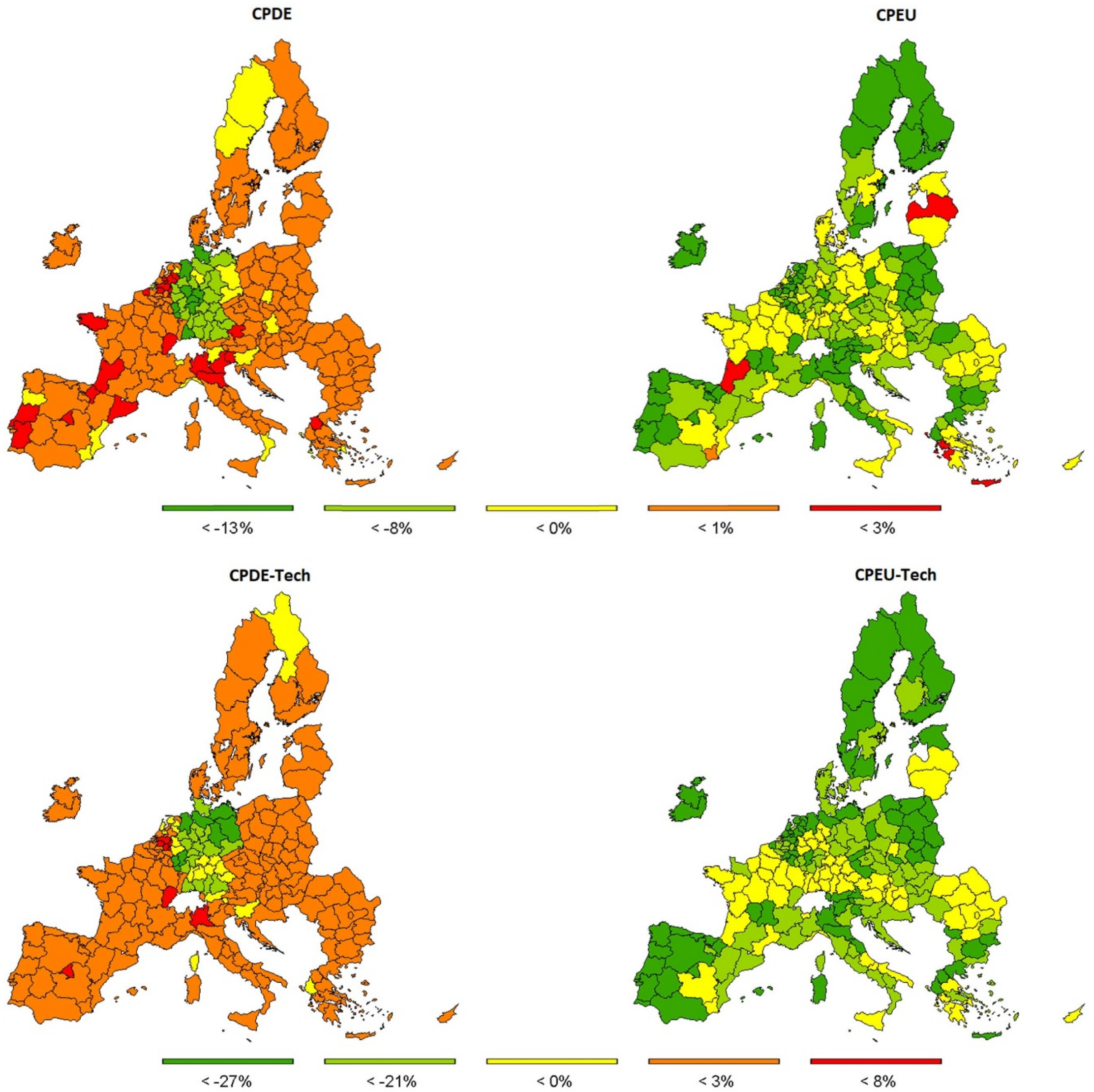
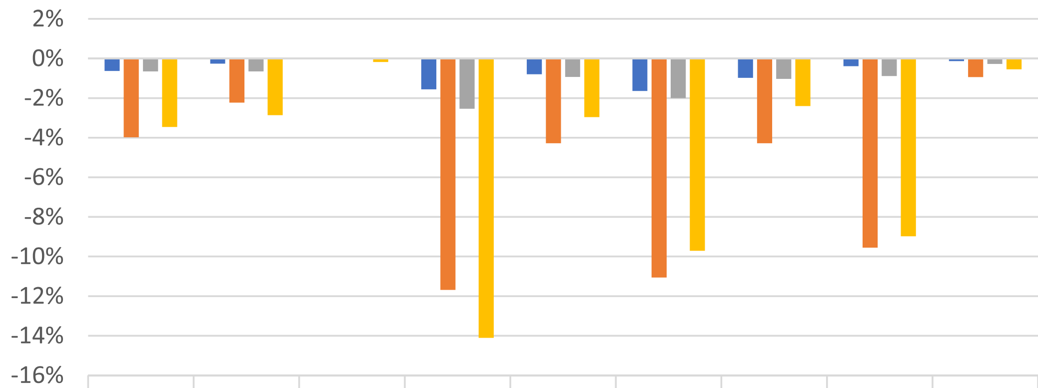


Figure 3. Relative changes in mineral fertilizer use compared to the reference scenario.

efficiency effects of some technological options. The EU beef herd size under the CPDE and CPEU scenarios decrease by 2.4% (376 210 heads) and 21% (3388 020 heads) leading to a reduction in beef production by 1.6% and 11.1%, respectively, which is the main contributor of methane emissions from agriculture. The impact of the carbon tax on pork and poultry meat production is more modest, however, since the emission intensities of these products are considerably lower compared to beef production, these changes have only minor impacts on EU GHG emissions. The reduction in sheep and goat meat production is 0.4% and 9.5% under the CPDE and CPEU scenarios, and 0.9% and 8.9% under the CPDE-Tech and CPDE-tech scenarios, respectively. This reduction in EU supply is partially substituted by increased imports from the rest of the world, hence, leading to a negative net trade position for the EU. In all scenarios, there is considerable leakage due to beef production reallocation. Under the CPDE and CPEU scenarios 63% and 64% and under the CPDE-Tech and CPEU-Tech scenarios 73% and 62% of leaked emissions to non-EU countries, respectively, are due to reallocation of beef production.

As shown in figure 5, both the German and the EU mitigation efforts under CPDE and CPDE-Tech, and CPEU and CPEU-Tech scenarios, respectively, are partially offset due to emission leakage to the rest of the world. The leakage rate under CPDE and CPDE-Tech scenarios is 59% and 17%, respectively, and under CPEU and CPEU-Tech scenarios is 44% and 15%, respectively. The literature distinguishes between two channels of leakage: competitiveness and international price (Böhringer *et al* 2012). The competitiveness channel occurs when higher costs lead to domestic producers losing competitiveness and being replaced by imports. The international price channel, on the other hand, arises when a regulating



	Cereals	Oilseeds	Veg. & Perm. crops	Fodder	Meat	Beef	Pork meat	Sheep and goat meat	Poultry meat
CPDE	-0.63%	-0.26%	0.01%	-1.56%	-0.80%	-1.64%	-0.98%	-0.39%	-0.13%
CPEU	-3.98%	-2.23%	0.00%	-11.69%	-4.28%	-11.06%	-4.28%	-9.55%	-0.94%
CPDE-Tech	-0.65%	-0.65%	0.03%	-2.54%	-0.93%	-2.00%	-1.03%	-0.89%	-0.28%
CPEU-Tech	-3.46%	-2.86%	-0.18%	-14.11%	-2.96%	-9.71%	-2.40%	-8.98%	-0.55%

CPDE CPEU CPDE-Tech CPEU-Tech

Figure 4. Percentage change of the EU agricultural supply compared to the reference scenario.

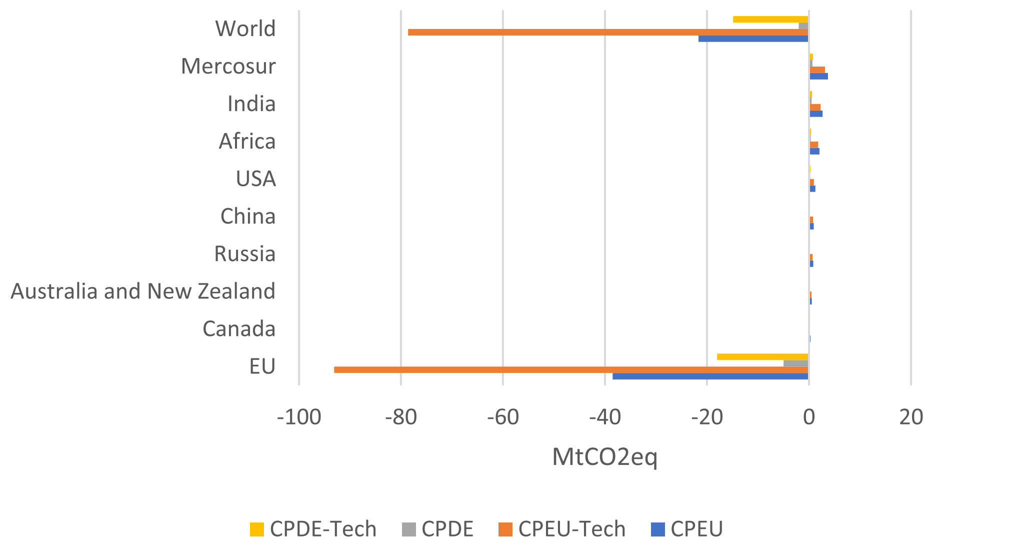


Figure 5. Absolute change in global agricultural emissions compared to the reference scenarios.

country is a price setter. In this case, demand in the regulating country shrinks, causing international prices to drop and increasing demand in the rest of the world. The leakage observed in this analysis is mainly through the competitiveness channel, as the demand changes observed in the EU are relatively small.

The sectoral economic welfare effects of the implemented scenarios in the EU are presented in table 5. All simulated scenarios harm consumer welfare slightly and improve producer welfare in the EU and Germany. The welfare changes are mainly explained by higher prices as well as by the subsidies that farmers receive by reducing their GHG emissions compared to the reference situation.

The prices of animal products are the most affected ones. Figure 6 shows the changes of consumer and producer changes as a result of the simulated scenarios.

The above-mentioned price spikes trigger changes in the human consumption of those products in the EU (figure 7). As one can see beef is the most affected commodity in the EU as it shows the highest price increases. In all scenarios, beef is substituted by poultry meat and under the EU-wide implementation scenarios beef is also substituted by pork.

Table 5. Sectoral economic welfare effects in the EU and Germany in absolute (million Euro) and percentage change compared to the reference scenarios.

	EU		Germany	
	Consumer welfare	Producer welfare	Consumer welfare	Producer welfare
CPDE	−2510 −0.01%	3132 1.24%	−535 −0.01%	464 1.45%
CPEU	−13 280 −0.07%	15 084 6%	−2539 −0.05%	2349 7.32%
CPDE-Tech	−2806 −0.01%	3441 1.41%	−591 −0.01%	91 0.3%
CPEU-Tech	−10 488 −0.05%	9868 4.04%	−1977 −0.04%	1668 5.4%

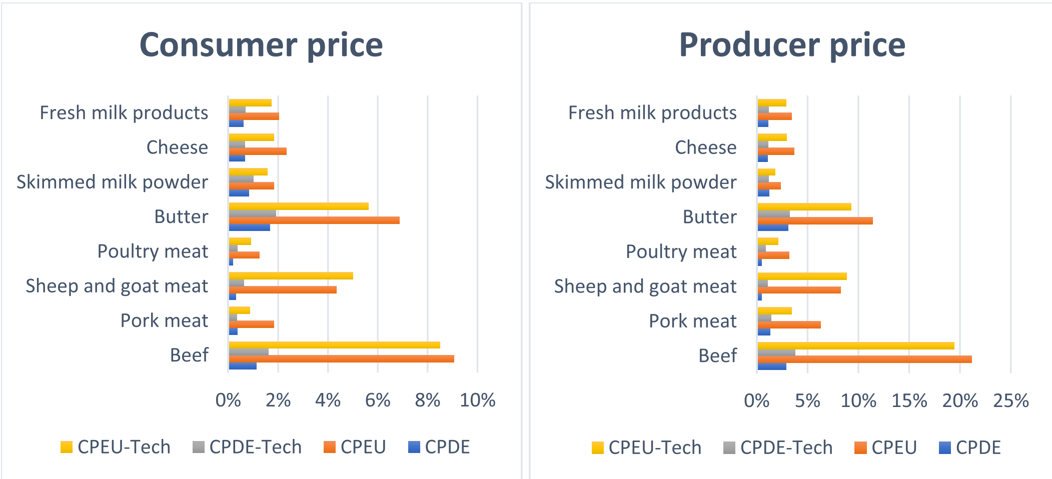


Figure 6. Consumer and producer price changes of animal products in the EU compared to the reference scenarios.

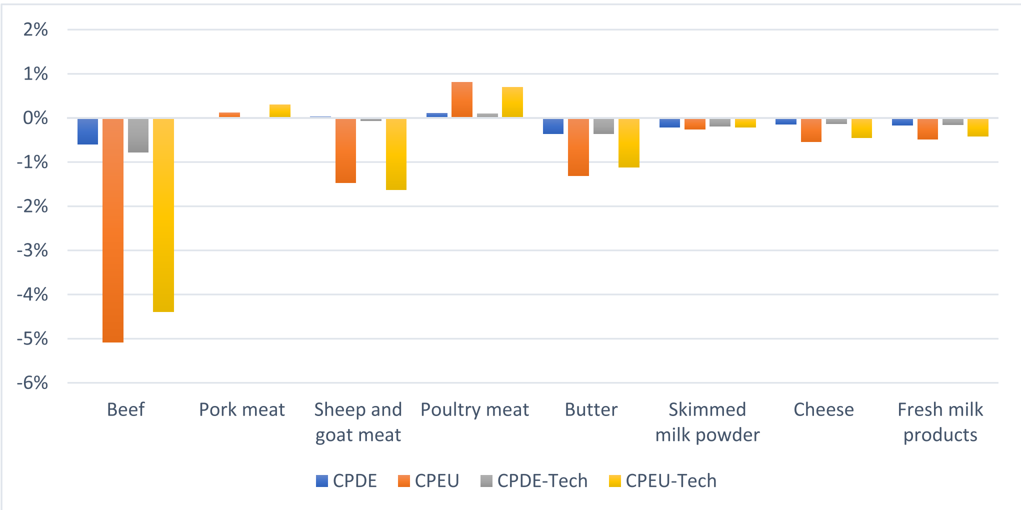


Figure 7. Human consumption changes of animal products in the EU compared to the referenced scenario.

5. Discussion and conclusions

This study quantitatively evaluates the environmental and economic impacts of incorporating the agricultural sector into a carbon pricing scheme in Germany as a possible solution for bridging the gap between the actual emissions and the 2030 national target. For comparison, the EU-wide integration of the agricultural sector into a carbon pricing scheme is also analyzed. Both scenarios are analyzed in two modeling frameworks—with and without consideration of the utilization of already existing or possible innovative mitigation technologies in the sector. The latter step is crucial in determining the importance of such technological options in reaching climate targets.

The results reveal several important implications of such a policy option. First, even if Germany chooses to take this step unilaterally, a net emission reduction effect is reached in the agricultural sector and the gap between the total projected and targeted 2030 emissions in Germany is reduced by 10%. Although this effect is notably more substantial if the entire EU adopts a similar policy. Moreover, the EU gap in 2030 is also reduced by 14%. Second, the consideration of the effects of already existing or novel mitigation technologies has a significant impact on the results and even further contributes to emission reduction in Germany or the EU. The scenarios that ignore the possible uptake of such technological options are proven to underestimate the mitigation potential of the simulated policy options by about a factor of two. This is not surprising, as it was found that both in German and EU-wide implementation of the policy scenario the analyzed technological options are responsible for more than 50% of the mitigated emissions. EU producers, as a result of simulated policy scenarios, lose their competitiveness which is stronger pronounced in the case of ruminants and cereal production. This leads to reduced exports from the EU and increased imports to the EU causing emission leakage in all scenarios. The leakage rate is lower in the case of EU-wide implementation of the policy, however, again the scenarios that neglect the potential of technological mitigation options overestimate this rate by a factor of three. These large leakage rates need to be reflected under the assumption that there is no exogenous consumption change in agricultural products, especially meat consumption; and that we do not consider any additional trade mechanisms such as a carbon border tax for imported products.

Although the sectoral welfare effects on the consumer side are negative in all scenarios, in relative terms they are negligible, ranging from 0.01% to 0.07%. On the other hand, the producers gain as a result of increased prices and premiums received by cutting down their emissions. This phenomenon is also observed by Himics *et al* (2018). However, the sectoral welfare effects must be taken with caution, as the administrative costs associated with the implementation of such policies are not considered due to the limitations of our modeling approach.

The sensitivity analysis results (figure A1) validate our assumption regarding the chosen carbon price level. When mitigation technologies are considered (CPDE-Tech and CPEU-Tech), the rate of change in mitigated emissions decreases after a carbon price of 100 €/t CO_2, as most of the mitigation technologies reach their maximum implementation limits at this price point. Any further reductions in emissions are, therefore, due to changes in activity levels. Further sensitivity analysis results regarding the market effects are presented in figures A2 and A3.

Our results further indicate the importance of investing in the R&D of cost-efficient and easily transferable mitigation technologies for the EU agricultural sector considering both their economic and environmental effects.

The production losses identified and the land taken out of agricultural production can also be seen as a way forward with the extensification strategy and the aim to increase organic farming under the new CAP and the farm-to-fork strategy. The arable land taken out of production could even be considered as an option for afforestation or photovoltaics, making the instrument even more efficient for climate mitigation.

A limitation of this study is that it only accounts for agricultural emissions, and it does not incorporate the emissions/removals from the LULUCF sector in the analysis. Furthermore, we emphasize in the Introduction that due to the compliance with the ESR and LULUCF pillars of the EU climate policy there will be no intra-EU leakage effect under Germany's unilateral carbon pricing policies. This is attributed to the requirement that any increased emissions from the agricultural sector have to be counterbalanced by reducing emissions from other sectors within the pillars. However, it is important to note that CAPRI, being a PE model, cannot precisely identify the specific sectors that will need to counterbalance the increased agricultural emissions in the rest of the EU.

Above all, with our quantitative analysis for Germany and for the European Union, we can conclude that a carbon pricing scheme for the agricultural sector could be a valuable and cost-efficient instrument to reach national or EU-wide mitigation targets under manageable side effects. Given the option that leakage rates can be further reduced by policies on the consumer side, by border taxes, the results are even more promising to further assess the option for carbon pricing for this sector. This is also identified as further research needs. In the light of the 'fit for 55' package of the European Union and the integration of transport and buildings into a revised EU ETS our results provide another example of how also new or remaining sectors could be integrated into an ETS, either on a national or directly on a European level.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Appendix

Table A1. Sources and remains of nitrate used in EU agriculture.

			Total (in 1000 t)			Per ha (in kg)		
			Value in baseline	Abs. change	% change	Value in baseline	Abs. change	% change
CPDE	Source	Mineral fertilizer	10 300.63	−108.19	−1.05%	64.78	−0.46	−0.72%
		Manure	8114.02	−73.10	−0.90%	51.03	−0.29	−0.57%
		Crop residues	8826.61	−118.67	−1.34%	55.51	−0.56	−1.01%
		Biological fixation	1500.66	−15.07	−1.00%	9.44	−0.06	−0.67%
		Atmospheric deposition	1803.43	−5.53	−0.31%	11.34	0.00	0.00%
	Remains	Absorption by crop	19 925.65	−216.39	−1.09%	125.31	−0.94	−0.75%
		Surplus total	10 599.35	−104.16	−0.98%	66.66	−0.43	−0.65%
		Gaseous loss	2924.75	−24.30	−0.83%	18.39	−0.10	−0.54%
		Run off mineral	426.15	−3.66	−0.86%	2.68	−0.01	−0.52%
		Run off manure	445.20	−4.60	−1.03%	2.80	−0.02	−0.70%
		Surplus at soil level	6803.25	−71.62	−1.05%	42.78	−0.31	−0.72%
CPEU	Source	Mineral fertilizer	10 300.63	−1029.11	−9.99%	64.78	−5.52	−8.51%
		Manure	8114.02	−581.91	−7.17%	51.03	−2.88	−5.65%
		Crop residues	8826.61	−1035.83	−11.74%	55.51	−5.71	−10.29%
		Biological fixation	1500.66	−173.17	−11.54%	9.44	−0.95	−10.09%
		Atmospheric deposition	1803.43	−31.39	−1.74%	11.34	−0.01	−0.13%
	Remains	Absorption by crop	19 925.65	−1721.40	−8.64%	125.31	−8.95	−7.14%
		Surplus total	10 599.35	−1130.00	−10.65%	66.66	−6.13	−9.18%
		Gaseous loss	2924.75	−211.16	−7.22%	18.39	−1.05	−5.71%
		Run off mineral	426.15	−40.38	−9.48%	2.68	−0.21	−7.99%
		Run off manure	445.20	−30.05	−6.18%	2.80	−0.15	−5.22%
		Surplus at soil level	6803.25	−848.40	−12.45%	42.78	−4.72	−11.01%
CPDE-Tech	Source	Mineral fertilizer	10 027.18	−313.96	−3.13%	63.02	−1.94	−3.08%
		Manure	8112.42	−94.99	−1.17%	50.98	−0.57	−1.12%
		Crop residues	8834.76	−217.38	−2.46%	55.52	−1.34	−2.41%
		Biological fixation	2721.30	−32.84	−1.21%	17.10	−0.20	−1.16%
		Atmospheric deposition	1804.95	−0.64	−0.04%	11.34	0.00	0.00%
	Remains	Absorption by crop	19 960.55	−342.72	−1.72%	125.45	−2.09	−1.67%
		Surplus total	11 519.71	−317.09	−2.75%	72.40	−1.96	−2.70%
		Gaseous loss	2942.12	18.74	0.64%	15.75	0.12	0.76%
		Run off mineral	206.03	−17.93	−8.72%	1.29	−0.11	−8.68%
		Run off manure	306.87	−13.24	−4.32%	1.93	−0.08	−4.27%
		Surplus at soil level	8064.68	−304.66	−3.77%	50.68	−1.89	−3.73%
CPEU-Tech	Source	Mineral fertilizer	10 027.18	−2414.91	−24.09%	63.02	−17.75	−23.42%
		Manure	8112.42	−571.09	−7.04%	50.98	−3.17	−6.22%
		Crop residues	8834.76	−1256.95	−14.23%	55.52	−7.48	−13.47%
		Biological fixation	2721.30	−393.59	−14.14%	17.10	−2.34	−13.71%
		Atmospheric deposition	1804.95	−16.85	−0.93%	11.34	−0.01	−0.06%
	Remains	Absorption by crop	19 960.55	−1986.80	−9.95%	125.45	−11.49	−9.16%
		Surplus total	11 519.71	−2666.58	−23.13%	72.40	−16.27	−22.45%
		Gaseous loss	2942.12	−40.81	−1.39%	15.75	−0.09	−0.57%
		Run off mineral	206.03	−117.76	−57.28%	1.29	−0.74	−56.90%
		Run off manure	306.87	−70.33	−22.94%	1.93	−0.43	−22.27%
		Surplus at soil level	8064.68	−2437.68	−30.18%	50.68	−15.01	−29.56%

Table A2. GHG emission sources accounted for by CAPRI.

Emissions	Sources modeled in CAPRI
CH_4	• Enteric fermentation • Manure management • Rice cultivation
N_2O	• Synthetic fertilizer • Manure management (application) • Excretion on pasture • Crop residues • Histosols • Deposition of ammonia • Emissions due to leaching of nitrogen
CO_2	• Liming

Source: Pérez Domínguez *et al* (2020).

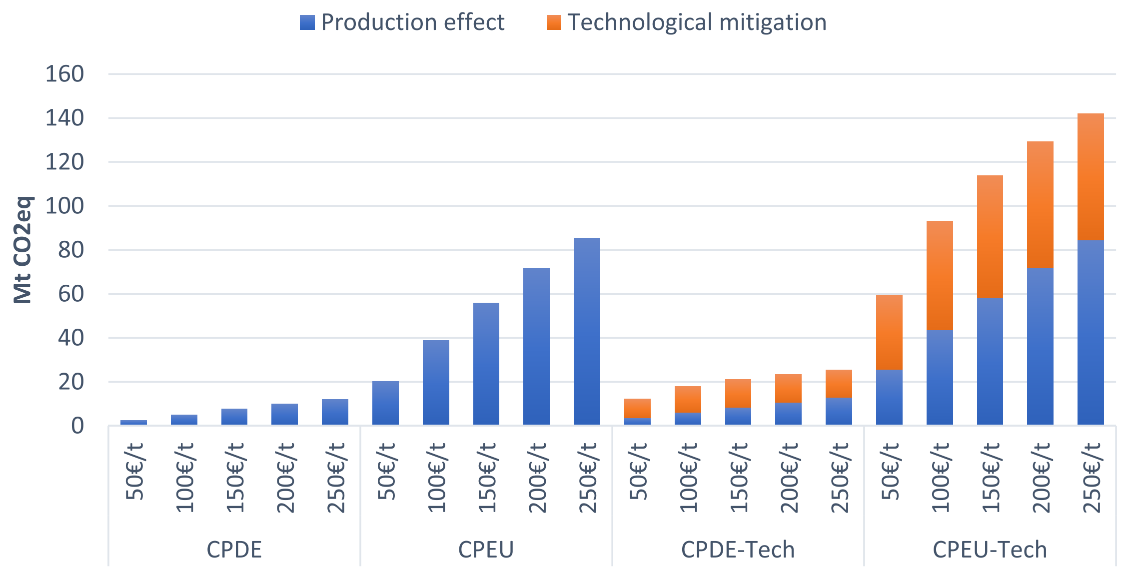

Figure A1. Sensitivity analysis of mitigated agricultural emissions in the EU across four scenarios at varied carbon prices.

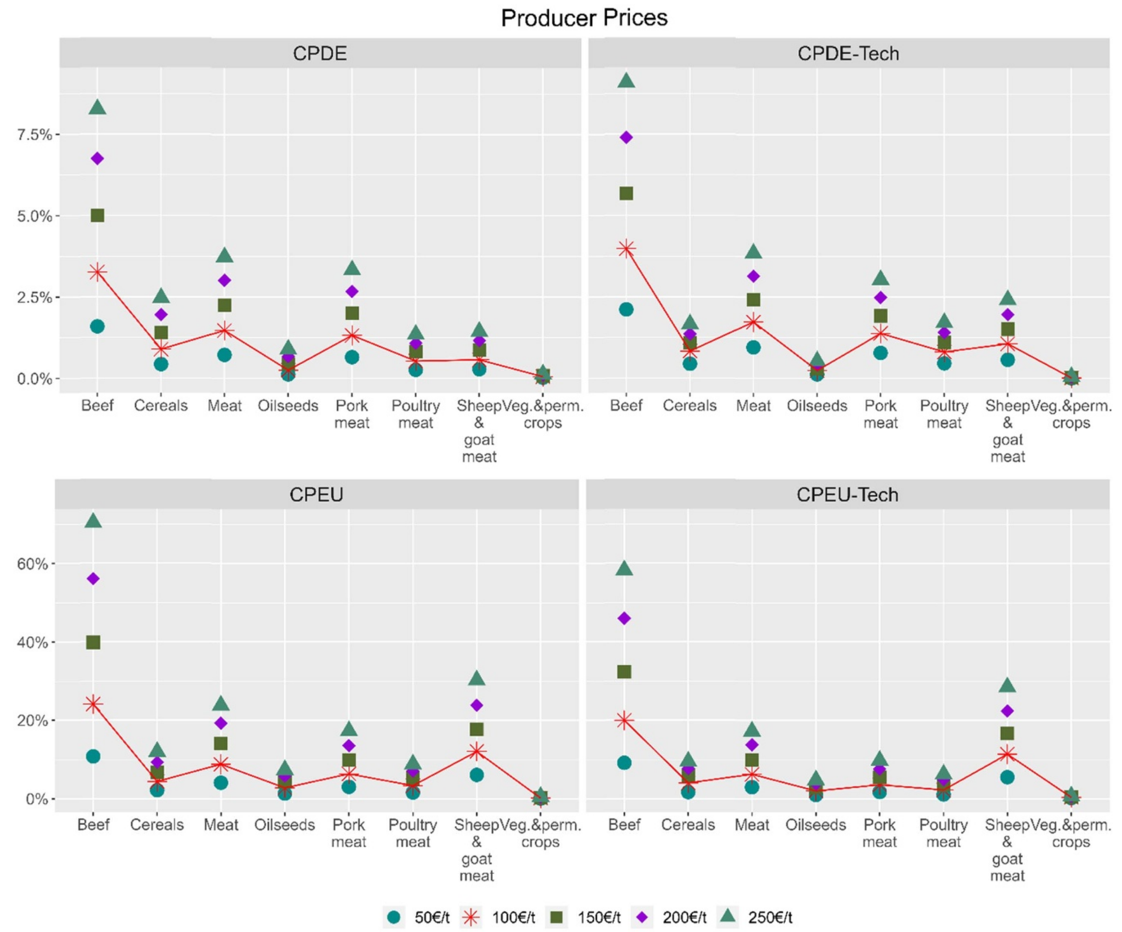

Figure A2. Sensitivity analysis of producer prices in the EU across four scenarios at varied carbon prices.

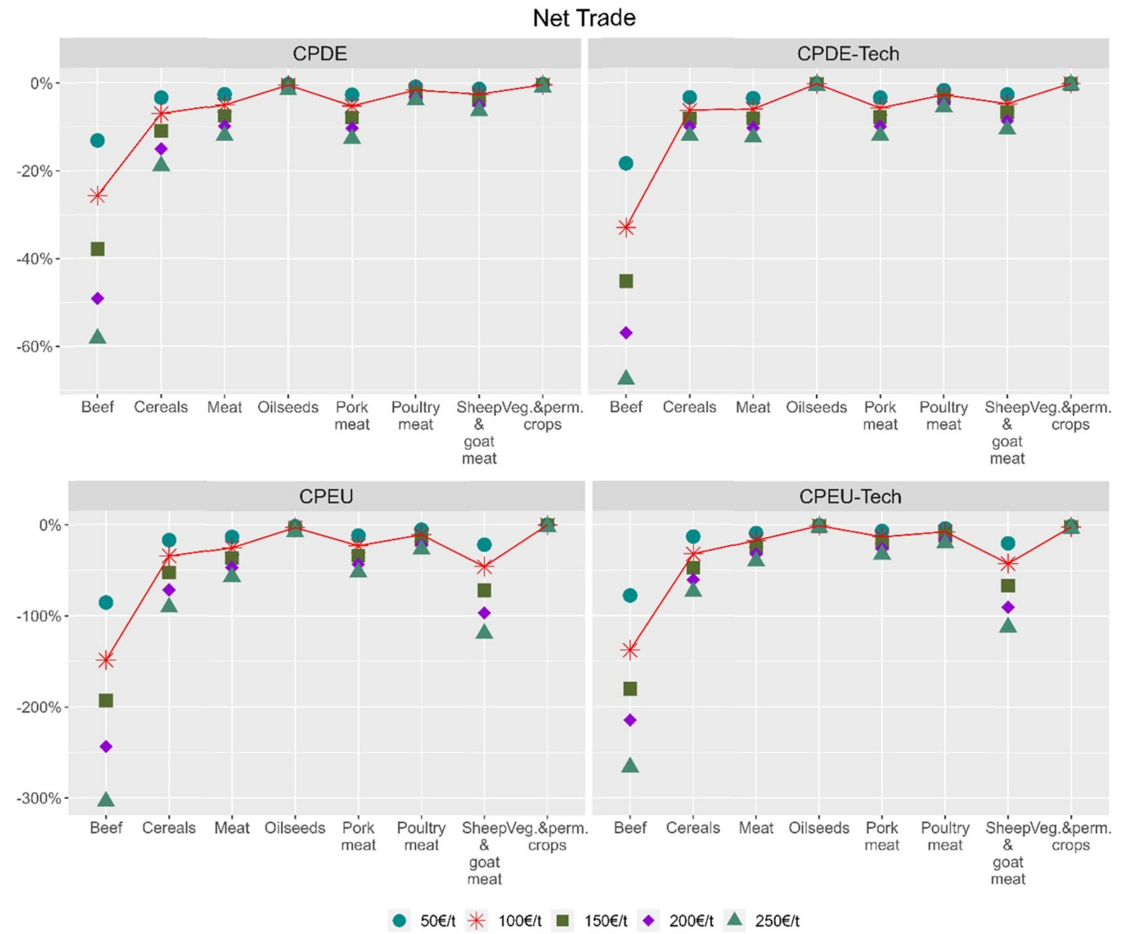

Figure A3. Sensitivity analysis of net trade in the EU across four scenarios at varied carbon prices.

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