BAE
Bio-based and Applied Economics

AIEAA
ASSOCIAZIONE ITALIANA DI ECONOMIA AGRARIA E APPLICATA

Citation: Dell'Unto, D., Coderoni, S. & Cortignani, R. (2026). Applying the Global Methane Pledge to the italian livestock sector. *Bio-based and Applied Economics* 15(2): 63-75. doi: 10.36253/bae-18002

Received: June 13, 2025
Accepted: January 22, 2026
Published: August 2, 2026

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

Editor: Fabio Bartolini
Associate editor: Riccardo d'Alberto

ORCID
DDU: 0000-0003-2721-8352
SC: 0000-0001-8751-7376
RC: 0000-0002-2685-9783

Silvia Coderoni serves as editor in chief of the journal. She declares to have not had any role in the peer review or editorial processes related to this paper.

Applying the Global Methane Pledge to the italian livestock sector

Davide Dell'Unto[1], Silvia Coderoni[2,*], Raffaele Cortignani[1]

[1] *Department of Agriculture and Forest Sciences (DAFNE), University of Tuscia, Via San Camillo de Lellis, 01100, Viterbo, Italy*
[2] *Department of Biosciences and Agricultural and Environmental Technologies, University of Teramo, Via Renato Balzarini, 1, 64100, Teramo, Italy*
*Corresponding author. Email: scoderoni@unite.it

Abstract. The Global Methane Pledge was launched by the EU and the US with the aim to cut 30% of methane (CH_4) emissions by 2030. Livestock systems are major contributors to CH_4 emissions. This study assesses a combined tax and subsidy policy tool applied at the farm level that would allow to reach the 30% reduction target for livestock CH_4. The simulation is performed with the Positive Mathematical Programming model AGRITALIM calibrated using the Italian commercial livestock farms as represented by the Farm Accountancy Data Network. The micro-based model simulates at the farm level the imposition of a tax on each unit of emissions that exceeds the targeted amount, or the grant of a subsidy for each unit of emissions that is reduced above the target. The simulation exploits the heterogeneity of farmers' behaviour to reach a market-clearing permit price of one tonne of emissions to obtain a self-sustaining policy tool that would equate the amount of taxes and subsidies paid. Results point that with a price of EUR 110.50t-1CO_{2eq}. the system would self-sustain itself. Higher negative impacts are foreseen for less productive beef and mixed cattle farms as a result of the profitability and emission intensity of their activities. Findings could be used to help policymakers understand the diversified impacts of the target on farms and evaluate possible compensation they could provide for a more just transition.

Keywords: GHG emissions, mathematical programming model, carbon tax, carbon subsidy, carbon price, short-lived GHG.

1. INTRODUCTION

Establishing plans to reduce the greenhouse gas (GHG) emissions produced by the world's livestock systems is essential, given the expanding global population and the anticipated 20% increase in demand for terrestrial animal products by 2050 (FAO, 2023).

Despite continuous advancements in production efficiency, GHGs from livestock systems continue to pose a serious problem, as they account for a large portion of global emissions (Cerutti et al., 2023). In particular, the Intergovernmental Panel on Climate Change (IPCC, 2021) has identified agricultural production, primarily livestock, and the use of fossil fuels as

Firenze University Press | www.fupress.com/bae

major contributors to the rise in atmospheric methane (CH_4) emissions. These emissions are second only to carbon dioxide (CO_2) in their overall contribution to climate change (Milich, 1999). On a molecular level, CH_4 is more powerful than CO_2; thus, although it is less persistent in the atmosphere, it has a significant effect on climate change (IPCC, 2021; Gernaat et al., 2015).[1] Additionally, CH_4 contributes to the formation of tropospheric ozone, a potent local air pollutant with serious health effects (European Commission, 2020). Consequently, cutting CH_4 emissions improves air quality and slows the rate of climate change.

In recent years, there has been a worldwide political focus on CH_4 (European Commission, 2020; Minister of Environment and Climate Change, 2023; Magnapera et al., 2025). The United States (US)-China Joint Glasgow Declaration specifically points the urgent need for greater action to reduce CH_4 (Wang et al., 2021). In New Zealand, the Zero Carbon Amendment Bill targets a net zero budget for GHG, including a separate target to reduce biogenic CH_4 emissions (New Zealand Ministry for the Environment, 2024).

To put forward a global action, in 2021, the European Union (EU) and the US launched the Global Methane Pledge (GMP) at the 26th Conference of Parties in Glasgow to cut CH_4 emissions by 30% by 2030. As part of its commitment to the GMP, the EU submitted the Methane Action Plan (European Union, 2022), which outlines existing policies and further activities under development that are expected to reduce CH_4 emissions until 2030 and beyond. The plan describes the expected impact on CH_4 emissions from agriculture because of the proposed revision of the Industrial Emissions Directive (IED)[2] that, for the first time, was intended to target cattle farms as well as the pig and poultry farms already subject to the (old) Directive. The proposal to include cattle farms in the revised IED did not pass after much debate within the co-decision mechanism. However, by the end of 2026, the EU Commission plans to publish a report with solutions that will more comprehensively address emissions from the rearing of livestock, focusing on cattle.[3]

In this context, this work aims to simulate a combined tax and subsidy scheme to illustrate the likely impacts of the GMP's proposed CH_4 reduction target of 30%. The simulation applies this target to the same livestock categories (i.e., specialised cattle, pig and poultry farms) targeted by the proposed revision of the IED, as it appears to be the most likely policy objective, based on recent developments.[4]

The assessment requires a model that is based on micro-level (i.e. farm-level) data that allow representing farms' heterogeneity in terms of productive and structural features (Baldi et al., 2024; Heckelei et al., 2012). In this study we use the agroeconomic supply model called AGRITALIM (AGRIcultural TerritoriAL tIme economic; Dell'Unto et al., 2025; Cortignani and Coderoni, 2022; Dell'Unto et al., 2023). The model is calibrated with microdata surveyed of the Farm Accountancy Data Network (FADN) that include information on aspects regarding economic, financial, productive, market, policy and structural features of farms. The model was recently implemented to account for GHG emissions at the farm level (Coderoni et al., 2024a). Impacts are evaluated focusing on the number of livestock units (LSUs) reared, the level of CH_4 emissions and the operating income (OI) of farms.

Compared to the literature to date, this is the first assessment of a hybrid policy tool that proposes the simultaneous application of tax and subsidy to the sole livestock sector of one important livestock-producing country (Italy).[5] Previous works have considered either a tax to incentivise farms to reduce emissions or a subsidy for those farms that reduce this negative externality (see, among others: Acosta et al., 2023; Fellmann et al., 2018; Himics et al., 2018; Pérez Domínguez et al., 2016).

Moreover, we conduct our assessment using a micro-based modelling approach, allowing us to capture farms' heterogeneous abatement costs (Cai et al., 2016). At this stage of the analysis proposed, the only mitigation strategy allowed is the reduction of LSU as the aim of the study is not to assess the possible benefits and costs of eventual mitigation options, but to show the impact of the application of the GMP to the Italian livestock sector in a short-term scenario, with no possible changes to the production technology. However, the GHG estimation approach here adopted, allows the model to capture farms' optimizing behaviours characterized by different

[1] CH_4 is a so-called short-lived GHG (i.e., it has a strong initial climate impact that rapidly drops after 20 years, unlike CO_2). This attribute has significant consequences for calculating its effect on global warming and some stakeholders have urged that a distinct regime is needed for long-lived and short-lived GHGs. At present, however, CH_4 and CO_2 emissions belong to the same policy frameworks at the EU and national level.

[2] COM (2022)156 final, at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0156 (accessed 08/11/25).

[3] https://environment.ec.europa.eu/topics/industrial-emissions-and-safety/industrial-and-livestock-rearing-emissions-directive-ied-20_en#farming-under-the-ied-20 (accessed 08/11/2025).

[4] Specialised sheep and goat farms, along with non-specialised livestock farms, fall outside the scope of the original directive, and including them in the revised IED has never been part of the debate for its revision.

[5] Running a search on the Scopus database (search string: "emission trading system" OR "ets" AND livestock AND "eu*") did not yield any paper that addressed the same issue with a similar approach.

emission intensities at the baseline, that reflect management intensity, even in the absence of explicit mitigation strategies (see Section 3).

The simulation also aims to exogenously identify the price that could yield a predetermined reduction target through a self-financing scheme[6] by exploiting the heterogeneous abatement costs of farms. In contrast, previous studies mainly imposed a price on emissions and evaluated environmental and economic impacts (see, among others: Coderoni et al., 2024a; Pérez Domínguez et al., 2020).

The rest of the paper proceeds as follows: Section 2 reviews some pertinent literature on the economics behind the proposed approach, Section 3 presents the models, data used and the simulated scenarios, Section 4 presents the results, Section 5 discusses their implications, and Section 6 presents our conclusions.

2. BACKGROUND OF THE ANALYSIS AND LITERATURE REVIEW

Although there has been substantial political attention on curbing CH_4 emissions, reaching this objective remains difficult. GHG emissions are environmental externalities that lack a market price; thus, farmers are unable to internalize their global impact on society (Acosta et al., 2023; Millock and Nauges, 2006). Consequently, in Europe, the Scientific Advisory Board on Climate Change (2024) recommends that, through a legislative proposal set to begin after 2030, the EU should extend the pricing regime of GHG emissions to all key emitting sectors, including agricultural, food and land use. This change would give farmers a definite financial incentive to lower emissions and increase removals. This vision advances what the European Court of Auditors (2021) previously recommended that the EU should assess the potential of applying the polluter pays principle (PPP) to agricultural emissions.

Many challenges exist in applying the PPP in agricultural GHG mitigation, including the difficulty of MRV for a non-point source of pollution that is also linked to high levels of heterogeneity of farms environmental performances (European Commission et al., 2023; Coderoni, 2023). Farmers' performances can in fact vary according to many structural features (farm size, typologies, etc.) that inevitably translate into behavioural heterogeneity. Consequently, homogenous policies will produce heterogeneous responses (Stetter et al., 2022; Esposti, 2022; Coderoni et al., 2024b). Moreover, even when farms show similar structural and behavioural characteristics, site-specific agronomic, ecological and biophysical variables can lead to uneven environmental effects (OECD, 2022).

These multiple and complex sources of heterogeneity are among the reasons that over the last two decades, analysts and stakeholders have advocated for agri-environmental policies with a more tailored design (Erjavec and Erjavec, 2015; Mahmoud and Hutchings, 2020). However, not all farm characteristics are easily targetable due to practical or political constraints (Coderoni et al., 2024b). Moreover, information asymmetries prevent policymakers from tailoring policies to those farms that can more effectively mitigate emissions, as they are unaware of farms' individual abatement costs.

In the context of information asymmetries, economic theory indicates that market-based policy instruments, like a tax or a tradable permit system for emission rights (a so-called emissions trading system-ETS), are the most cost-effective way to abate emissions without knowing the cost structure of each farm (NERA, 2007). Both ETS and carbon taxes leave the decision of how much to pollute to the regulated parties, which are better informed about the costs and benefits of mitigation options (NERA, 2007). Thus, regulated parties will abate the amounts of GHG that equal their marginal costs of abatement. In the absence of uncertainty, an efficient level of abatement could be achieved under either policy, even if their distributional effects are different (Walter 2020; McKibbin and Wilcoxen, 2002)[7]. A pure emissions tax would generally induce large transfers of income from firms to the government general funds, while the ETS would generate revenue for the governments only through the (eventual) initial auction of emission permits (Carl and Fedor, 2016). Additionally, it would represent a financial transfer from more to less polluting entities. Thus, some ETS-type of instruments have been shown to be less regressive than carbon taxes, and even slightly progressive (Roberts and Thumin, 2006). As a result, ETSs are usually more politically acceptable than carbon taxes. Moreover, an ETS allows for reaching an environmental objective by setting a GHG reduction target in a cost-effective way, without knowing the abatement costs of each firm (as convenience assessments are left to individual cost-benefit analysis). Instead, to reach a desired emission reduction, a carbon tax should be fixed at its optimal level; otherwise, the environmental outcome is uncertain (NERA, 2007).

[6] It is worth specifying that Monitoring Reporting and Verification (MRV) costs and transaction costs were not considered in this study.

[7] As showed by Weitzman (1974), however, in the presence of uncertainties on marginal benefits and costs, taxes and permits are not equivalent. In this case, the relative slopes of the two curves determine which policy would cause a minor welfare loss for society.

To attain a more desirable balance of trade-offs, alternative market-based policy designs could capitalise on the advantages of both the carbon tax and the ETS. Hybrid tax-subsidy schemes offer a potential solution (OECD, 2019; Povitkina et al., 2021).[8] One of these hybrid approaches could take the form of a joint tax and subsidy that applies both the PPP and the provider gets principle (PGP) to CH_4 emissions mitigation. This scheme would apply an environmental standard (in this case, the reduction of 30% CH_4 emissions) to each farm and establish a tax on each unit (tonne) of emissions that exceeds the imposed reduction target or pay a subsidy for each unit of emissions that is reduced above the target.

Farmers can decide to pay the tax while continuing to emit above their threshold, or they can receive the subsidy by reducing emissions below this threshold, according to their economic convenience. If this approach is designed so that the total amount of taxes paid by polluting farms equals the subsidies paid by the government to farms, there would be no burden on government funds (apart from the MRV costs).

This combined policy tool mimics an ETS in terms of incentives, as it leaves farmers free to decide their most convenient action. Meanwhile, policymakers can continue to ignore individual abatement costs. Unlike the ETS, however, this system does not generate government revenue, as taxes are recycled back to subsidised farmers. Moreover, if the price of the incentive (tax or subsidy) is fixed in advance by the regulatory scheme, the uncertainty that usually exists in the likely future permit price can be reduced, thus encouraging investment decisions (Pezzey, 2003).

3. MATERIALS AND METHODS

The data used in this study are derived from the 2020 Italian FADN, the only harmonised microeconomic database that merges data on farm structure, input use, output produced and economic variables (European Council, 2009) with reference to specialised cattle, pig and poultry farms.

To estimate GHG emissions, we adopt an approach already used in the literature to achieve a farm-level indicator of GHG emissions adapting the IPCC methodology at the micro level (Coderoni and Vanino, 2022; Dabkiene et al., 2020; Baldoni et al., 2017). We performed the analysis using the AGRITALIM model, an agroeconomic supply model that uses much of the information reported in the FADN dataset on economic, financial, productive, market, political and structural aspects. The model allows to consider information about farms' geographical areas, altimetric levels and farm types (Cortignani et al., 2022; Dell'Unto et al., 2023); however, for the purpose of this study, results are shown only for farm specialization, OI and LSU.[9] The estimation of CH_4 emissions from livestock farms is a feature only recently included in the model (Cortignani and Coderoni, 2022) and, for the purposes of this study, we further enrich it by implementing an integrated tax and subsidy system to achieve a reduction of 30% of CH_4 emissions from the baseline, to mimic the objective set by the GMP. Our study assumes that this reduction target is equal among all CH_4-emitting units.

To reach this target, we used an alternative system of tax or subsidy, modulating the unitary amounts of the incentive to achieve the mitigation target and an equilibrium between the total amount of tax paid and subsidies received by farmers. The model is constructed so that, at the farm level, two alternatives exist: (1) maintain the productive level (and emissions) and pay a tax on each unit of emissions (tonne of CO_{2eq}) exceeding the 30% target reduction, or (2) reduce emissions more than by 30% and receive a subsidy for each unit of emissions avoided above the target.

The methodology used to estimate CH_4 emissions and the mathematical structure of the model for each farm are presented in Appendix A-Supplementary materials.

4. RESULTS

The results of the simulation involve various technical-productive and economic aspects. All results distinguish between the group of farms that would pay the tax and the group of farms that would receive the subsidy, with reference to the different livestock categories.

Table 1 reports the total emissions produced at the baseline by the different farm types, the quantity of emissions curbed to meet the mitigation target, and the emissions produced above (ΔE^+) and below (ΔE^-) the mitigation target (tonnes of CO_{2eq}). To ensure completeness, we also report the total amount of taxes and subsidies paid.

The total emissions curbed (under Tax and Subsidy, i.e.: 134,964 t^{-1} CO_{2eq}) represent, as expected, 30% of baseline emissions (Table 1).

[8] Such a scheme could encourage the adoption of low-emission technologies by returning emissions tax income to firms (Ollier and De Cara, 2024).

[9] Other results are available upon request.

Table 1. Baseline emissions, emissions curbed under simulation scenario and deviations from the mitigation target (t CO_{2eq}) and total amounts paid for farms opting for the tax or the subsidy.

	Tax				Subsidy			
	Baseline CO_{2eq}	CO_{2eq} curbed	ΔE^+	Total taxes (€)	Baseline CO_{2eq}	CO_{2eq} curbed	ΔE^-	Total subsidies (€)
Dairy cattle	198,234	34,976	24,494	2,706,554	123,347	56,378	19,374	2,140,795
Beef cattle	35,791	6,894	3,843	424,657	38,948	22,992	11,307	1,249,470
Mixed cattle	14,014	3,443	762	84,163	10,910	5,677	2,403	265,583
Pig	18,965	1,649	4,040	446,455	3,151	1,715	770	85,035
Poultry	4,865	437	1,023	112,997	1,441	804	371	41,031
Total	271,870	47,400	34,161	3,774,825	177,797	87,564	34,225	3,781,914

Source: Authors' elaborations.

The unit value of emissions that is calibrated to achieve the mitigation target, is of course the same for tax and subsidy and is equal to EUR 110.50 t^{-1} $CO_{2eq.}$ This would be like the clearing-market price, if there was a market. Thus, the total taxes paid by farms that produce emissions exceeding their threshold (EUR 110.5 × ΔE^+) nearly equals that of subsidies granted to farms that reduce emissions below their threshold (EUR 110.5 × ΔE^-).[10] This result suggests a neutral impact on public finances (without considering implementation and transaction costs).

It is worth noting that farms opting for the tax produce 60% of baseline emissions but contribute only 35% to the mitigation effort. The majority (68%) of the mitigation effort is sustained by dairy cattle farms. Despite this, this category continues to produce the highest volume of emissions exceeding the mitigation threshold (ΔE^+). In contrast, beef and mixed cattle farms exhibit a large prevalence of emissions reduced below the mitigation threshold (ΔE^-). As for pig and poultry farms, the quota of ΔE^+ emissions largely exceeds that on ΔE^- emissions.

Table 2 reports the impacts on the LSU yielded by the different farm types and overall, along with their CO_{2eq} emissions. Moreover, it provides information on the percentage incidence of the amount of the subsidy received and the tax paid, and the percentage of farms opting for the subsidy, both within each type and overall. The absolute values of LSU number and CO_{2eq} emissions for the different farm types at the baseline and under simulation are graphically represented in Figure A.1 (Appendix B-Supplementary materials).

A strict relationship binds the reduction of CH_4 emissions and the number of LSUs, in the absence of any feasible mitigation option that reduces the amount of CH_4 emitted per LSU, like modifications of manure management practices, vaccination against methanogenic bacteria, feed rations supplementation (Magnapera et al., 2025), etc. Such options were not considered at this stage of the analysis, because the objective here is not to appraise the possible benefits and costs of these mitigation options; thus, curbing emissions was possible only by reducing the number of LSUs. Therefore, impacts shown must be considered as a worst-case or short-term scenario, in which it is not possible to change the production technology.

In the overall results, farms opting for the tax reduced their emissions (and number of LSUs) much less than those opting for the subsidy.

Regarding the different farm types, cattle farms (in particular, mixed and beef cattle) are most likely to opt for the subsidy. Thus, cattle farms are the only type to receive an amount of subsidies that exceeds the taxes paid, due to the relevant reduction of emissions they achieve. On opposite, only a limited share of pig and poultry farmers opt for the subsidy. Pig farms were the least likely to adopt the subsidy, and they received the lowest number of subsidies compared to the taxes paid. To understand the technical and economic motivations behind these farms behaviours, Table 3 and the corresponding Figure A.2 in Appendix B show the values of three key indicators for the different farm types and overall: (*i*) methane emission intensity (MEI; i.e., tonnes of CH_4 in CO_{2eq} divided by the LSUs), (*ii*) profitability per LSU (PLSU; i.e., OI divided by the number of LSUs)

[10] Perfect equality between the two values (taxes and subsidies) cannot be achieved for technical reasons. Since price calibration is external to the model, a more precise calibration (e.g., to the level of EUR cents) would theoretically bring the total amount of taxes and subsidies to perfectly balance, but this would also cause issues in model resolution. In practice, as farms cannot simultaneously be subject to both the tax and the subsidy, and given their inherent heterogeneity, it is highly unlikely (though theoretically possible) that the two groups of farms (those paying the tax and those receiving the subsidy) would be perfectly identical, for example, in terms of LSU.

Table 2. Impacts on the LSU number and on CO_{2eq} emissions of farms opting for the tax, for the subsidy and average (Δ% under the simulation with respect to baseline) and percentage incidence of the amount of the subsidy received and the tax paid and of farms opting for the subsidy on total farms.

	Tax		Subsidy		Average		Subsidy/Tax	Subsidised farms
	LSU	CO_{2eq}	LSU	CO_{2eq}	LSU	CO_{2eq}	%	%
Dairy cattle	-17.6	-17.6	-45.7	-45.7	-28.5	-28.4	79.1	41
Beef cattle	-18.8	-19.3	-57.7	-59	-39.4	-40.0	294.2	41.2
Mixed cattle	-23.6	-24.6	-51.5	-52	-36.2	-36.6	315.6	56.2
Pig	-8	-8.7	-56.5	-54.4	-15.9	-15.2	19	11.4
Poultry	-7.2	-9	-57.5	-55.8	-18.7	-19.7	36.3	16.7
Total	-13	-17.4	-51.4	-49.2	-25.5	-30	100.2	38.7

Source: Authors' elaborations.

Table 3. Average values of MEI, PLSU and MeP for the two groups of farms that opt for paying the tax or receiving the subsidy, under the Baseline and the Simulation.

	Tax			Subsidy		
	MEI	PLSU	MeP	MEI	PLSU	MeP
Baseline						
Dairy cattle	3.25	903	278	3.18	562	177
Beef cattle	2.12	751	355	2.05	356	173
Mixed cattle	2.74	682	249	2.61	350	134
Pig	0.33	323	995	0.28	100	357
Poultry	0.19	427	2,189	0.19	151	780
Total	1.63	606	371	2.21	400	181
Simulation						
Dairy cattle	3.25	1,004	309	3.18	1,010	318
Beef cattle	2.11	868	412	1.99	865	434
Mixed cattle	2.71	824	304	2.58	713	276
Pigs	0.32	342	1,059	0.29	231	788
Poultry	0.19	454	2,375	0.20	355	1,761
Total	1.55	653	421	2.30	815	354

Source: Authors' elaborations.

and (*iii*) methane productivity (MeP; i.e., the OI generated by one tonne of CH_4 in CO_{2eq}).

The first section of the table (Baseline) shows the value of the indicators at the baseline for the two groups of farms that opt for paying the tax or receiving the subsidy; the second section (Simulation) reports the same information for the same groups under the simulation.

The results in the last row of the Baseline section reveal that farms opting for the subsidy tend to have a lower value of PLSU and MEI than those opting for the tax, and this is true across all the different farm types. The higher share of cattle farms among those opting for the subsidy leads the average value of MEI to be higher for farms opting for the subsidy, even though the values of the different farm types are lower than those opting for the tax.

Relevant differences also emerge among farm types. Dairy cattle farms exhibit the highest MEI and PLSU, while the highest MeP is found among beef cattle farms opting for the tax, as they tend to have a low MEI compared to the other cattle farms in this group. The highest value of MeP within the whole sample is associated with poultry farms, which have the lowest MEI and an intermediate level of PLSU. Pig farms exhibit an intermediate MEI, which, in combination with the lowest PLSU, leads to intermediate MeP values.

Similar considerations are seen when analysing the values of the indicators of the different farm types under the Simulation scenario. It is worth highlighting that PLSU and MeP increase compared to the baseline, even doubling in the case of the farms opting for the subsidy. This result is partly explained since 35% of farms opting for the subsidy would have a negative OI in the baseline, if the contribution from the Common Agricultural Policy (CAP) First Pillar payments were not included. Thus, these farms probably prefer to cut production, forgoing the CAP coupled support and opting for the CH_4 reduction subsidy. These farms also demonstrate a slight increase in MEI values in contrast with the farms opting for the tax.

When analysing the impacts on the single farm types opting for the tax, it is necessary to consider how reducing the number of LSUs (and emissions) affects mixed cattle farms, in comparison with other types of farms. As shown in Table 3, these farms exhibit the lowest value of MeP along with a still-high value of MEI (second only to dairy cattle farms). When looking at the farms opting for the subsidy, the drop in production activities is particularly dramatic for beef cattle, poultry and pig farms.

Table 4. Impacts on OI of farms opting for the tax, for the subsidy and average, with and without the impacts of taxes and subsidies on farms' budget (Δ% under the simulation with respect to baseline).

	With taxes and subsidies			Without taxes and subsidies		
	Tax	Subsidy	Average	Tax	Subsidy	Average
Dairy cattle	-8.4	-2.4	-6.7	-3.5	-12.2	-5.9
Beef cattle	-6.3	2.8	-3.1	-2.9	-15.8	-7.4
Mixed cattle	-7.8	-1.2	-5.9	-5.4	-19.4	-9.5
Pig	-2.8	0.7	-2.7	-0.5	-6.9	-0.8
Poultry	-1.3	-0.2	-1.2	-0.2	-3.8	-0.5
Total	-6.3	-1.1	-5.0	-2.6	-12.8	-5.0

Source: Authors' elaborations.

Table 4 shows the impacts on OI of the different farm types and overall. The left section reports actual impacts on OI, including the economic cost of reducing production activities, as necessary to meet the mitigation target, and the financial impacts of taxes and subsidies on farms' budgets. In the right section of Table 4, we considered only the impacts of activities that reduced production, excluding the financial impact of taxes and subsidies on farms' budgets. The absolute values of OI generated by the different farm types under baseline and simulation are graphically reported in Figure A.3 (Appendix B).

The overall results in the left section of Table 4 indicate that farms opting for the subsidy are nearly compensated for OI losses due to the reduction in their production activities (–1.1%), while tax burden reduces the OI of the farms opting for this instrument by 6.3%. When excluding the financial impacts of tax and subsidy, the situation is reversed. The much milder reduction of production activities undertaken by the farms opting for the tax would determine equally mild impacts on their OI (–2.6%). Instead, the negative impacts on OI are much stronger for the farms opting for the subsidy (–12.8%), although this impact is far less than proportional to the level of reduction of productive activities these farms undertake (–51.4% of LSU, as reported in Table 2). This less-than-proportional reduction of OI with respect to the level of production activities is due to the strong increase of PLSU and MeP that occurred for these farms in the simulation (Table 3).

When examining the different farm types and considering the financial impact of tax and subsidy, cattle farms (particularly dairy cattle and mixed cattle) are the most negatively affected due to having the highest MEI and lowest MeP (Table 3). Even when excluding the financial impact of tax and subsidy, the worst impacts again affect mixed cattle farms, since these farms more frequently opt for the subsidy and receive the highest amount of subsidies with respect to taxes paid. For the same reason, the opposite occurs considering the average impacts on OI of pig and poultry farms, which make less recourse to – and thus receive a lower share of – the subsidy.

To provide evidence of the wide heterogeneity between farms' performances, Table 5 shows baseline values of OI and CH_4 emitted and the impacts on these variables from the application of the combined economic policy tool, together with their Coefficients of Variation (CV).

As evidenced by the high values of CV, a large heterogeneity characterises the farm types under analysis at the baseline, with beef and mixed cattle farms being the most heterogeneous both in terms of OI and of CH_4 emitted. Instead, dairy cattle farms show the lowest heterogeneity in terms of emissions, indicating that the high level of emissions is a characteristic inherent to this type of farming (in line with the value MEI values reported in Table 4). Under simulation, these farms experiment the worst impact on OI with the highest level of heterogeneity, closely followed by beef cattle farms. Instead, both the extent of the impacts and their variability gradually reduce in mixed cattle, pig and poultry farms. Thanks to the lowest MEI, these latter two farm types

Table 5. Average value of OI (EUR ,000) and CH4 (t) at the baseline and Δ% under simulation, and respective Coefficients of Variation (CV).

	Baseline OI		Baseline CH_4		Δ% OI		Δ% CH_4	
	Average	CV	Average	CV	Average	CV	Average	CV
Dairy cattle	82.6	231.4	345.4	141.9	-27.0	-897.7	-29.9	-62.8
Beef cattle	41.7	334.8	160.4	237.9	-26.2	-787.4	-32.6	-75.0
Mixed cattle	32.3	387.1	162.9	291.1	-6.4	-412.0	-37.7	-65.1
Pig	126.6	166.8	140.0	145.1	-5.9	-360.5	-13.3	-137.0
Poultry	151.0	215.5	80.8	199.5	-2.4	-167.3	-13.8	-138.4
Total	74.5	250.7	251.8	176.2	-22.1	-926.3	-29.1	-75.1

Source: Authors' elaborations.

show lower CH_4 reductions, although with the highest heterogeneity. For the opposite reason, cattle farms (particularly mixed ones) reduce the most their emissions, with a halved level of variability.

Relevant heterogeneity also exists among different geographical location of Italy (see Table A2 in the Appendix C).

A sensitivity analysis was finally performed to evaluate the eventual different impacts derived from imposing d reduction targets (-25% and -35% with respect to baseline level of emissions). The overall results indicate that the extent of the impacts on OI, LSU and emissions increase in a consistent way as the mitigation target becomes more ambitious (Table A3 in Appendix D).

5. DISCUSSIONS AND POLICY IMPLICATIONS

This study simulates the application of the GMP mitigation target to the Italian livestock sector through a mechanism alternatively combining taxes and subsidies. The proposed policy instrument is exogenously built to approach financial self-sufficiency. The heterogeneity of farms' characteristics and productivity, shown in Table 5, make this outcome likely. As the degree of homogeneity increases, the instrument might become less efficient in reaching this objective, as farms' relative convenience would converge.

The choice to reduce emissions or pay taxes drives the optimisation behaviour based on farm-level abatement costs (represented in this case by the opportunity cost of production, i.e., PLSU) and emissions' performances (MEI and MeP).

When examining the impacts generated, it is worth noting that a reduction of emissions is currently possible in the model only by reducing the number LSU. As specified, in fact, our model does not consider any simulated mitigation option for reducing emissions per LSU while retaining animals. Indeed, as stressed by European Commission et al. (2023), for cattle farms in particular, GHG abatement using technical options has limited emissions reduction potential. Therefore, these farms primarily need to reduce livestock numbers, as it is inherently tied to the level of GHG emissions (USDA, 2004). Reducing LSUs thus represents the most direct (and drastic) mitigation measure. Of course, impacts on OI are much lower in this study than those estimated by Coderoni et al. (2024a) for the introduction of a tax (of a maximum of 100 EUR per tonne of CO_{2eq}) alone, as, in this case, farmers can choose to opt for mitigating emissions or paying taxes. However, impacts on LSUs are almost identical. In particular, the simulated impacts on production (specifically of farms opting for the subsidy) are remarkable. The average reduction in LSUs in farms opting for the subsidy exceeds 50%, with peaks of –56.5% and –57.5% for pig and poultry farms. For these farm types, it is notable that almost 30% showed high dependence on the CAP First Pillar payment in the baseline, indicating that they are inefficient in producing OI without the subsidy. In the presence of such taxation, they have opted to reduce their herd size and receive the subsidy.

In this scenario, however, it is likely that many of the most impacted farms will be forced to exit the market or drastically modify their productive specialisation in the medium to long run. These impacts must be considered as the bottom line in case no policy intervention is undertaken to facilitate the adoption of alternative mitigation options by farmers and no spontaneous adoption by the latter occurs. Indeed, it may not be realistic to expect farmers to spontaneously adopt mitigation options, particularly in the short run. Implementing these measures could contribute, on the one hand, to mitigating the impact on production levels, but on the other hand, it requires having financial resources available to invest, and thus increases production costs.

Usually, in the presence of a price on carbon, rational farmers adopt technologies for mitigating GHG emissions if these technologies improve their economic sustainability; thus, what really matters in implementing these measures is the interplay between mitigation potential (that would reduce the amount of tax to pay or increase the subsidy to receive) and the costs of its implementation (Auld et al., 2014; Blandford and Hassapoyannes, 2018; Bakam et al., 2012). In addition, if the reduction targets are relevant, impacts on LSUs are as well, unless not all farms apply the mitigation measures (Coderoni et al., 2024a). Thus, the policy should provide support to cover the cost of mitigation technologies and ensure the effectiveness of the strategy.

Our results show that the choice to reduce productive activities, as well as the level of reduction with respect to the mitigation target, can be explained by considering three proxies of productivity and efficiency performance at the farm level, with respect to CH_4 emissions produced. The first (MEI) pertains to CH_4 emission intensity. The second (PLSU) relates to the profitability (in terms of OI) of each LSU. The third (MeP) combines the information from the first two, quantifying the productivity or profitability (OI) of each unit of CH_4 emissions (expressed in CO_{2eq}). The modelling tool's optimisation of OI involves increasing PLSU and MeP in the presence of taxes and subsidies. In general, the higher PLSU in the farms opting for the tax prevents them from reducing the LSUs to the level necessary to achieve the mitigation target. On the contrary, farms with lower PLSU opt for the subsidy because it is convenient to reduce emissions far below the mitigation target, along with reducing their production level. This makes it possible for these farms to (*i*) receive the subsidy on the quota of curbed emissions below the threshold and (*ii*) reduce the production costs in the presence of a lower baseline PLSU. This means that only farms with higher productivity will continue to emit more than the mitigation target (paying the tax), while the others will reduce their emissions below the target (receiving the subsidy).

An interesting aspect is that farms opting for the tax manage to reduce their CH_4 emissions more than proportionally to the number of LSUs, while reducing emissions is more "costly" in terms of LSUs for the farms opting for the subsidy (although they reach higher levels of reduction). However, subsidised farms achieve a less-than-proportional reduction of emissions with respect to the number of LSUs. This is because their lower baseline MEI, which slightly increases under the simulation.

It is also interesting to note the strong increase, under the simulated scenario, of the average value of PLSU and MEI, particularly for farms opting for the subsidy. This increase could also result from reducing the herd size for those farms that would have not been profitable (without CAP support) in the baseline and thus opt for reducing inefficient production units if taxed.

Results in terms of GHG reduction with respect to the GHG price are not directly comparable to other studies that simulate the introduction of an ETS or the pricing of GHG emissions. We only address CH_4 emissions from the Italian livestock sector, while other studies usually consider applying an ETS or an emission price to the whole agricultural sector (at the European or country level) (see among others: Pérez Domínguez et al., 2020). However, some comparisons are possible with other works in the literature. For example, the market-clearing price derived in this study, which would permit reaching the 30% GHG reduction target, is 110.50 EUR t^{-1} CO_{2eq}. Isbasoiu et al. (2020) and Pérez Domínguez et al. (2020), who calculated a similar GHG price (100 EUR t^{-1} CO_{2eq}), estimate a GHG reduction of 25%. Furthermore, in terms of subsidies, this emission price is similar to other payments made under the Italian CAP (e.g., agro-environmental payments to reduce ammonia emissions or livestock-related eco-schemes).

5.1 Policy implications

The results presented here, being the first ex-ante modelling of the application of the GMP to Italian livestock sector, could be useful to appraise the impacts of such target on different specialisations, to provide a policy to support the transition to more heavily affected farms. Besides, they could provide a preliminary indication of the tentative price to be applied to livestock emissions to reach this ambitious target.

In terms of policy tool efficiency and efficacy, the analysed instrument combining a tax and a subsidy, like an emission standard, allows for reaching a desired reduction target, but unlike the standard, it also compensates virtuous behaviour with the subsidy (thus pursues the PGP).

Similarly to the ETS, this tool allows for reaching the environmental objective by addressing the heterogeneity of farms' performances in terms of mitigation potentials, thus overcoming information asymmetries between the polluter (farm) and the policymaker. Unlike ETS, this system does not foresee a mechanism for the market of credits; thus, part of the implementation costs should be lower (as, for example, there is no need for a registry for the credits), although MRV issues remain. MRV matters are linked to two main (interlinked) problems: complexities and costs. MRV complexities are present because agricultural emissions are challenging to quantify. The sector is a non-point source of pollution, and emissions derive from all agricultural activities across the rural landscape (Smith et al., 2014). Usually, there is a direct proportion between estimation accuracy and the cost of estimation itself. This brings us to the second relevant issue: MRV costs. MRV costs per tonne of GHG reduction are primarily driven by the size of the source. Significant transaction costs associated with MRV are thought to be fixed expenses that are independent of farm size (Bellassen et al., 2105). This fact heavily influences the discussion on the cost-effectiveness of including small farms in the system. An "on farm" ETS option, like the one simulated here, although excluding small non-professional farms, would include farmers as direct participants, bringing much higher complexity and administrative costs compared to "downstream" and "upstream" options that involve dairy and meat processors or fertiliser and feed sellers as participants (European Commission et al., 2023). Although the availability of proxy data can reduce these costs, as some data required for MRV is already collected under existing agricultural regulations and applications for subsidies under the CAP – and synergies could be established with the IED (European Commission, 2022) – significant information remains to be collected to have a proper estimation at the farm level.[11]

[11] Indeed, a proper estimation of agricultural GHG emission is a very complex issue and the private sector initiatives have worked extensively on data quality for the agricultural measures to be included the Science

Another aspect to consider in implementing such a policy tool is that subsidising farmers to reduce their emissions might be less efficient and potentially more market distortive than the alternative approach based on taxation, beyond the risk of overcompensating farmers for reducing emissions (OECD, 2019; 2022). In this approach, the potential for creating a distorting effect is partly counterbalanced by the fact that the money needed to pay the subsidy is self-financed from the environmental tax implemented by the same scheme. This method yields a neutral impact on public finances (excluding MRV), as well as an income transfer between farms. Here, funds are transferred from pig and poultry farms to cattle farms. The latter benefit most from the subsidy, both in terms of the number of farms and the amount of subsidy received, but a similar redistributive effect also occurs among these farms (e.g. from dairy to beef and mixed farms).

In terms of policy implications, it is also necessary to reflect on impacts on employment[12], territorial protection and control of the territory by more extensive livestock farms, as well as on carbon leakage. We consider these factors in the absence of relevant modifications of consumers' behaviour towards the consumption of animal products.[13] Sustained internal demand is likely to lead, at least in part, to relocating production to countries where no emissions mitigation policy is in place, with a consequent increase in imports from outside the EU.

Finally, the overall policy coherence should be assessed (Coderoni, 2023). While such a policy framework could be coherent with the IED and the Farm to Fork Strategy, it may conflict with coupled income support for livestock under the CAP (European Commission et al., 2023).

5.2 Limitations of the study

Among the limitations of the study, the AGRITALIM model cannot consider changes in internal demand and international trade dynamics. However, the impacts it estimates – with a 25.5% reduction of reared LSUs for Italy alone – will hardly avert such a phenomenon, which a substantial body of literature warns about (Pérez Domínguez et al., 2016; Dumortier et al., 2012; Caro et al., 2017). This risk could be reduced through multilateral agreements with countries exporting in the EU, free allocation of GHG permits to farms or a Carbon Border Adjustment Mechanism (European Commission et al., 2023).

Another limitation of the study is the assumption that the emissions distribution across farms in a particular year (in this case, 2020) represents an adequate baseline on which to base a tax and subsidy regime, as individual farmers could claim that the baseline year chosen is not representative of their farms. While not fully relevant to the ex-ante simulation here proposed, this issue should be adequately considered in case of actual implementation of such policy tool.

Another means of improving the modelling tool would be to incorporate technological mitigation options that could function as an alternative to reducing the number of LSUs.

6. CONCLUSIONS

The present study employed a micro-level economic modelling approach to assess the results of a combined policy tool to curb CH_4 emissions from Italian cattle, pig and poultry specialist farms.

The results highlight the heterogeneity of farmers' behaviour, as influenced by the profitability and emission intensity of their livestock activities. In general, the analysed policy instrument would yield a stronger negative impact on less productive farms (i.e., beef and, particularly, mixed cattle). These farms are characterised by a much higher MEI than pig and poultry farms and a lower PLSU than dairy cattle farms. Consequently, the share of farms opting for the subsidy is highest among these farms, with dramatic production losses. Insights from this research could be used to help policymakers understand the diversified impacts of such a policy framework on livestock farms and the possible compensation they could provide to specific specialisations and territories.

Future research could replicate the study by simulating different minimum farm sizes (in terms of LSUs or income) to be included in the framework to assess the cost-effectiveness of the policy, according to different point of obligations design. Moreover, the model could be implemented considering alternative and combined technical mitigation options to assess the mitigation potential of the sector and more properly estimate impacts on productions allowing technological progress. This could be more easily implementable with database improvements that could capture the presence and

Based Target initiative (SBTi) (https://sciencebasedtargets.org/blog/the-sbti-flag-updates) (accessed 08/11/2025).

[12] European Commission et al. (2023) identifies the presence of livestock as an important risk-reduction strategy for vulnerable rural communities, the use of a threshold level of LSUs for the smallest farms should be carefully considered.

[13] For an assessment of the importance of integrating economic and environmental policies to enhance global food sustainability see Frontuto et al. (2025).

impacts of different mitigation measures (e.g. with the transition to the Farm Sustainability Data Network). Lastly, future studies should simulate the impacts of a likely CAP reform that divert financial resources to direct support to agricultural incomes, to direct support for GHG emissions reduction.

REFERENCES

Acosta A., Cicowiez M., Nicolli F., Rostan F. (2023). Economic, social and environmental effects of reducing dairy methane emissions through market-based policies: An application of the Livestock Policy Simulation Model. *Journal of Policy Modeling*, 45(2023), 345-361, https://doi.org/10.1016/j.jpolmod.2023.02.006.

Arvanitopoulos, T., Garsous, G. and Agnolucci, P. (2021). Carbon leakage and agriculture: A literature review on emissions mitigation policies. OECD Food, Agriculture and Fisheries Papers 169, OECD Publishing: Paris, France.

Baldi, L., Calzolai, S., Arfini, F., Donati, M. (2024). Predicting the effect of the Common Agricultural Policy post-2020 using an agent-based model based on PMP methodology. *Bio-based and Applied Economics*, 13(4), 333-351, https://doi.org/10.36253/bae-14592.

Baldoni E., Coderoni S., Esposti R. (2017). The productivity and environment nexus through farm-level data. The Case of Carbon Footprint applied to Italian FADN farms. *Bio-based and Applied Economics*, 6(2), 119-137, https://doi.org/10.13128/BAE-19112.

Bakam I., Balana B.B. and Matthews R. (2012). Cost-effectiveness analysis of policy instruments for greenhouse gas emission mitigation in the agricultural sector. *Journal of Environmental Management*, 112(2012), 33-44, https://doi.org/10.1016/j.jenvman.2012.07.001.

Bellassen, V., Stephan, N., Afriat, M. et al. (2015). Monitoring, reporting and verifying emissions in the climate economy. *Nature Clim Change*, 5, 319-328, https://doi.org/10.1038/nclimate2544.

Blandford, D. and Hassapoyannes K. (2018), The role of agriculture in global GHG mitigation, OECD Food, Agriculture and Fisheries Papers, No. 112, OECD Publishing, Paris, https://doi.org/10.1787/da017ae2-en.

Cai B., Bo X, Zhang L., Boyce J., Zhang Y., Lei Y. (2016). Gearing carbon trading towards environmental co-benefits in China: Measurement model and policy implications, *Global Environmental Change*, (39), 275-284, https://doi.org/10.1016/j.gloenvcha.2016.05.013.

Carl J., Fedor D. (2016). Tracking global carbon revenues: A survey of carbon taxes versus cap-and-trade in the real world. *Energy Policy*, 96(2016), 50-77, https://doi.org/10.1016/j.enpol.2016.05.023.

Caro, D., Frederiksen, P., Thomsen, M., Branth Pedersen, A. (2017). Toward a more consistent combined approach of reduction targets and climate policy regulations: The illustrative case of a meat tax in Denmark. *Environmental Science & Policy*, 76, 78-81, https://doi.org/10.1016/j.envsci.2017.06.013.

Cerutti, N., Lamb, W.F., Crippa, M., Leip, A., Solazzo, E., Tubiello, F.N., Minx, J.C. (2023). Food system emissions: a review of trends, drivers, and policy approaches, 1990–2018, *Environmental Research Letters*, 18(2023), 074030, https://doi.org/10.1088/1748-9326/acddfd.

Coderoni S. (2023). Key policy objectives for European agricultural policies: Some reflections on policy coherence and governance issues. *Bio-based and applied economics*, 12(2), 85-101, https://doi.org/10.36253/bae-13971.

Coderoni S., Dell'Unto D., Cortignani R. (2024a). Curbing methane emissions from Italian cattle farms. An agroeconomic modelling simulation of alternative policy tools. *Journal of Environmental Management*, 351(2024), 119880, https://doi.org/10.1016/j.jenvman.2023.119880.

Coderoni S., Esposti R., Varacca A. (2024b). How differently do farms respond to agri-environmental policies? A probabilistic machine-learning approach. *Land Economics*, 100(2), 370-397, https://doi.org/10.3368/le.100.2.060622-0043R1.

Coderoni S., Vanino S. (2022). The farm-by-farm relationship among carbon productivity and economic performance of agriculture, *Science of the Total Environment*, 819, 153103, https://doi.org/10.1016/j.scitotenv.2022.153103.

Cortignani, R., Buttinelli, R. and Dono, G. (2022). Farm to Fork strategy and restrictions on the use of chemical inputs: Impacts on the various types of farming and territories of Italy. *Science of the Total Environment*, 810, 152259, https://doi.org/10.1016/j.scitotenv.2021.152259.

Cortignani, R. and Coderoni, S. (2022). The impacts of environmental and climate targets on agriculture: Policy options in Italy. *Journal of Policy Modeling*, 44(6), 1095-1112, https://doi.org/10.1016/j.jpolmod.2022.11.003.

Cortignani R., Severini S. (2012). A constrained optimization model based on generalized maximum entro-

py to assess the impact of reforming agricultural policy on the sustainability of irrigated areas. *Agricultural Economics*, 43(6), 621-633, https://doi.org/10.1111/j.1574-0862.2012.00608.x.
Dabkienė, V., Baležentis, T. and Štreimikienė, D. (2020). Calculation of the carbon footprint for family farms using the Farm Accountancy Data Network: A case from Lithuania. *Journal of Cleaner Production*, 262, 121509, https://doi.org/10.1016/j.jclepro.2020.121509.
Dell'Unto D., Dono G., Cortignani R. (2023). Impacts of Environmental Targets on the Livestock Sector: An Assessment Tool Applied to Italy. *Agriculture*, 13, 742, https://doi.org/10.3390/agriculture13040742.
Dell'Unto, D., Selvaggi, R., Pappalardo, G. and Cortignani, R. (2025). Adoption of precision livestock farming devices in the dairy cattle sector: An assessment based on agroeconomic modelling. *Science of the Total Environment*, 1002, 180555.
Dumortier, J., Hayes, D. J., Carriquiry, M., Dong, F., Du, X., Elobeid, A., Fabiosa, J.F., Martin, P.A., Mulik, K. (2012). The effects of potential changes in United States beef production on global grazing systems and greenhouse gas emissions. *Environmental Research Letters*, 7(2), 024023, https://doi.org/10.1088/1748-9326/7/2/024023.
Erjavec, K., Erjavec, E. (2015). Greening the CAP – Just a fashionable justification? A discourse analysis of the 2014–2020 CAP reform documents. *Food Policy*, 51, 53-62.
Esposti, R. (2022). The Coevolution of Policy Support and Farmers Behaviour and Performance. An investigation on Italian agriculture over the 2008-2019 period. *Bio-Based and Applied Economics*, 11(3), 49-82, https://doi.org/10.36253/bae-12912.
European Commission et al. (2023). Pricing agricultural emissions and rewarding climate action in the agri-food value chain, Publications Office of the European Union. https://data.europa.eu/doi/10.2834/200.
European Commission (2022). Proposal for amending Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions and Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste, COM(2022) 156 final/3, Strasbourg, 5.4.2022.
European Commission (2020). An EU strategy to reduce methane emissions COM(2020) 663 final, Brussels.
European Commission (2019). The European Green Deal. COM(2019) 640 final, Brussels.
European Council (2009). Council Regulation (EC) No 1217/2009 of 30 November 2009 setting up a network for the collection of accountancy data on the incomes and business operation of agricultural holdings in the European Community. OJ L 328, 15.12.2009.
European Court of Auditors (2021). Special Report: The Polluter Pays Principle: Inconsistent application across EU environmental policies and actions.
European Scientific Advisory Board on Climate Change (2024). Towards EU climate neutrality. Progress, policy gaps and opportunities. Assessment Report 2024, Luxembourg: Publications Office of the European Union, 2024, ISBN 978-92-9480-612-3, doi:10.2800/216446
European Union (2022). European Union Methane Action Plan, available at the following url: https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/methane-emissions_en, accessed on 10/10/2024.
FAO (2023). Pathways towards lower emissions – A global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems. Rome https://doi.org/10.4060/cc9029en
Fellmann, T., Witzke, P., Weiss, F., ... and Leip, A. (2018). Major challenges of integrating agriculture into climate change mitigation policy frameworks. *Mitigation and Adaptation Strategies for Global Change*, 23, 451-468, https://doi.org/10.1007/s11027-017-9743-2.
Frontuto V., Felici T., Andreoli V., Bagliani MM., CorsiA. (2025). Is there an Animal Food Kuznets Curve, and does it matter? *Bio-Based and Applied Economics, Bio-Based and Applied Economics*, 14(1), 19-35, https://doi.org/10.36253/bae-16172.
Gernaat D.E.H.J., Calvin K., Lucas P.L., Luderer G., Otto S.A.C., Rao S., Strefler J., van Vuuren D.P. (2015). Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Global Environmental Change*, (33), 142-153, https://doi.org/10.1016/j.gloenvcha.2015.04.010.
Heckelei, T., Britz, W. and Zhang, Y. (2012). Positive mathematical programming approaches–recent developments in literature and applied modelling. *Bio-based and Applied Economics Journal*, 1(1), 109-124. https://doi.org/10.13128/BAE-10567.
Himics, M., Fellmann, T., Barreiro-Hurlé, J., Witzke, H. P., Domínguez, I. P., Jansson, T. and Weiss, F. (2018). Does the current trade liberalization agenda contribute to greenhouse gas emission mitigation in agriculture? *Food policy*, 76, 120-129.
IPCC (2021). Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. First edi-

tion. Cambridge University Press. https://doi.org/10.1017/9781009157896.

Isbasoiu, A., Jayet, PA, De Cara, S. (2021). Increasing food production and mitigating agricultural greenhouse gas emissions in the European Union: impacts of carbon pricing and calorie production targeting. *Environmental Economics and Policy Studies*, 23, 409-440, https://doi.org/10.1007/s10018-020-00293-4.

Magnapera C., Kazemekaityte A., Raffaelli R., Cerroni S. (2026). Farmers, experts and students' subjective probability distributions on methane emission reductions in livestock farming: An experimental comparison across elicitation methods. *Bio-Based and Applied Economics*, 15(2), https://doi.org/10.36253/bae-17310.

Mahmoud N., Hutchings, N.J. (2020). The advantages of using field- and farm-scale data to target agri-environmental measures-an example of afforestation. *Environmental Science & Policy*, 114: 14-21, https://doi.org/10.1016/j.envsci.2020.07.019.

McKibbin, W. J., and Wilcoxen. P. J. (2002). The Role of Economics in Climate Change Policy. *Journal of Economic Perspectives*, 16(2), 107-129.

Milich L. (1999). The role of methane in global warming: where might mitigation strategies be focused? *Global Environmental Change*, 9, 179-201, https://doi.org/10.1016/S0959-3780(98)00037-5.

Millock, K. and Nauges C. (2006), Ex Post Evaluation of an Earmarked Tax on Air Pollution. *Land Economics*, 82(1), 68-84, https://doi.org/10.3368/le.82.1.68.

NERA (2007). Market Mechanisms for Reducing Greenhouse Gas Emissions from Agriculture, Forestry and Land Management – NERA's Interim conclusions. NERA Economic Consulting, London.

New Zealand Ministry for the Environment (2024), Review of methane science and target, available here https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/emissions-reductions/emissions-reduction-targets/review-of-methane-science-and-target/ (accessed on 17/07/26).

Minister of Environment and Climate Change (2023). Reducing Enteric Methane Emissions from Beef Cattle. Federal Offset Protocol Public Consultation Draft, December 2023. His Majesty the King in Right of Canada, ISBN: 978-0-660-69074-2.

OECD (2019), Enhancing Climate Change Mitigation through Agriculture, OECD Publishing, Paris, https://doi.org/10.1787/e9a79226-en.

OECD (2022), Agricultural Policy Monitoring and Evaluation 2022: Reforming Agricultural Policies for Climate Change Mitigation, OECD Publishing, Paris.

Ollier M., De Cara S. (2024). Give and take: An analysis of the distributional consequences of emission tax-and-rebate schemes with an application to greenhouse gas emissions from European agriculture. *Ecological Economics*, 219(2024), 108154, https://doi.org/10.1016/j.ecolecon.2024.108154.

Pérez Domínguez, I., Fellmann, T., Witzke, P., Weiss, F., Hristov, J., Himics, M., ... and Leip, A. (2020). Economic assessment of GHG mitigation policy options for EU agriculture: A closer look at mitigation options and regional mitigation costs (EcAMPA 3) (No. JRC120355). Joint Research Centre.

Pérez Domínguez, I. P., Fellmann, T., Weiss, F., Witzke, P., Barreiro-Hurlé, J., Himics, M., ... and Leip, A. (2016). An economic assessment of GHG mitigation policy options for EU agriculture. JRC Science for Policy Report, EUR, 27973(10.2791), 843461.

Pezzey, J. (2003), Emission Taxes and Tradeable Permits A Comparison of Views on Long-Run Efficiency. *Environmental and Resource Economics*, 26(2), 329-342, https://doi.org/10.1023/a:1026393028473.

Povitkina M., Carlsson Jagers S., Matti S., Martinsson J. (2021). Why are carbon taxes unfair? Disentangling public perceptions of fairness. *Global Environmental Change*, (70), https://doi.org/10.1016/j.gloenvcha.2021.102356.

Roberts S., Thumin J. (2006). A Rough Guide to Individual Carbon Trading – Report to Defra, Centre for Sustainable Energy, November, London, UK.

Stetter, C., Mennig, P., & Sauer, J. (2022). Using Machine Learning to Identify Heterogeneous Impacts of Agri-Environment Schemes in the EU: A Case Study. *European Review of Agricultural Economics*, 49(4), 723-739, https://doi.org/10.1093/erae/jbab057.

USDA (2004). Agriculture and Forestry Greenhouse Gas Inventory: 1990–2001. Washington, DC: US Department of Agriculture.

Walter, J. M. (2020). Comparing the effectiveness of market-based and choice-based environmental policy. *Journal of Policy Modeling*, 42(1), 173-191, https://doi.org/10.1016/j.jpolmod.2019.07.006.

Wang W., Deng X., Wang Y. (2024). Changes in Non-CO_2 Greenhouse Gas Emissions From Livestock Production, Meat Consumption and Trade in China. *Sustainable Production and Consumption*, 42(2023), 281-291, https://doi.org/10.1016/j.spc.2023.09.021.

Weitzman M. L. (1974). Prices vs. Quantities. *Review of Economic Studies*. October, 41(4), 477-491.