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Research article

Curbing methane emissions from Italian cattle farms. An agroeconomic modelling simulation of alternative policy tools

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ABSTRACT

Methane (CH_4) emissions from cattle farms have been prioritised on the EU agenda, as shown by recent legislative initiatives. This study employs a supply-side agroeconomic model that mimics the behaviour of heterogeneous individual farms to simulate the application of alternative economic policy instruments to curb CH_4 emissions from Italian cattle farms, as identified by the 2020 Farm Accountancy Data Network survey. Simulations consider increasing levels of a tax on each tonne of CH_4 emitted or of a subsidy paid for each tonne of CH_4 curbed with respect to the baseline. Individual marginal abatement costs are also derived. Besides, to consider possible technological options to curb emissions, a mitigation strategy is simulated, with different levels of costs and benefits to appraise the potential impacts on the sector.

Relevant reductions in operating income are foreseen, the most substantial in farm types and size classes characterised by lower levels of carbon productivity. The introduction of the mitigation strategy shows that the outcome in terms of mitigation potential, without undermining production level, highly depends on the implementation costs, but can also vary widely due to heterogeneous farms' economic performances. Policy implications are also derived.

1. Introduction

The United Nations 2030 Agenda established in 2015 17 Sustainable Development Goals (SDGs), five of which directly dealing with environmental issues and one (SDG 13) specifically focused on climate action. This SDG claims for joint international actions against climate change to be embodied into national development strategies, for limiting global warming far below the threshold of 2 °C, thus avoiding its most severe consequences. Sustainable natural resource management is pivotal to this aim and to prevent environmental deterioration, encompassing all production sectors of the economy (including, among the others, the agricultural sector). All countries, both industrialized (Wu et al., 2022; Salvia et al., 2021) and the emerging industrialized ones (Onifade et al., 2021; Gyamfi et al., 2021; Bekun et al., 2021) are called to contribute to this goal. At the EU level, the European Climate Law,[1] adopted in June 2021, wrote into regulation the goal set out in the Green Deal for the European Union (EU) to achieve economic climate neutrality by 2050 (European Commission, 2019). The EU's agriculture and forestry sectors will play a crucial role in achieving this ambitious goal – they are the only sectors where carbon can be naturally stored in soil and biomass, helping offset GHG emissions that cannot be decreased (European Commission, 2021). However, carbon sinks deriving from soils and biomasses will be insufficient to meet the neutrality target. The agricultural sector should thus also reduce its so-called non-CO_2 GHG emissions (namely, methane–CH_4–and nitrous oxide-N_2O). Non-CO_2 GHGs from EU agriculture are covered by the EU Effort Sharing Regulation, which provides for national annual emissions targets that reference the emissions of different sectors (including agriculture, transport and residential). At the EU level, if the additional measures currently planned are implemented, there is an expectation of a modest 8% decline in these emissions by 2030 (compared with 2005 levels), highlighting the need for further reductions.[2]

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[1] Regulation (Eu) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law').

[2] https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-agriculture?activeAccordion=ecdb3bcf-bbe9-4978-b5cf-0b136399d9f8 (accessed on November 1st, 2023).

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Recently, political attention has been particularly focused on the reduction of CH_4 emissions, with the EU communicating a strategy to reduce these (European Commission, 2020a). The EU Committee on Environment, Public Health, and Food Safety has also developed procedures that are focused on CH_4 emissions. Moreover, in October 2021, the Parliament issued a resolution emphasising the significance of their monitoring, calling for the creation of a legal framework with reduction targets. This political focus on CH_4 is certainly warranted; in terms of total emissions, after CO_2, CH_4 is the second greatest source of GHG and is more powerful than CO_2 in terms of its Global Warming Potential (GWP), 25 times that of CO_2. Although it stays in the atmosphere for a shorter period,[3] it has a substantial impact on the climate (IPCC, 2014), aiding in the creation of tropospheric ozone, a powerful local air pollutant that has considerable health consequences (European Commission, 2020a). Hence, reducing CH_4 emissions helps to slow climate change and improve air quality.

Along this line, in April 2022, the Commission proposed extending the Industrial Emissions Directive (IED; 2010/75/EU) to CH_4 emissions from big livestock farms, for the first-time adding cattle farms to the pig and poultry farms already subject to the (old) directive (European Commission, 2022). According to the proposal, the IED's extended coverage to include the largest 10% of cattle farms will lead to a yearly reduction of at least 184 kt of CH_4; these farms represent 41% of the sector's emissions. The measures should be targeted to installations of 150 livestock units (LSU) or more (whether of cattle, pigs or poultry alone, or any mix of these livestock categories).

The CH_4 reductions are expected to result from the introduction of so-called best available techniques (BAT) that establish proportionate requirements for different farming systems (intensive, extensive, organic).[4] BAT relate to such factors as nutritional management, feed preparation, housing conditions, manure collection, storage, processing and land spreading, and storage of dead animals (European Commission, 2017). Complying with BAT involves realising investments and/or increasing production costs (OECD, 2017; Loyon et al., 2016); this is why their adoption by farmers would hardly be spontaneous and thus needed to be prescribed.

At the time of writing in late 2023, the proposal is being evaluated in a trialogue procedure, which it is hoped will result in a political agreement before the end of the year. Whatever the political agreement on the inclusion of big cattle farms in the IED directive, it is now clear that particular attention is being paid (in politics and society more broadly) to the GHG emissions of the beef and dairy sector, which account for over 67% of agricultural GHG emissions globally (Laborde et al., 2021). It is thus likely that the proposal to target emissions from big cattle farms will be on the political agenda again in the future, and it is highly relevant to provide *ex ante* simulations of the likely impacts on the bovine livestock sector of policy targeting its GHG emissions.

Studies simulating GHG reductions in the European agricultural sector have become increasingly important, mainly to allow *ex ante* impact assessments to support agricultural policy reform (Frank et al., 2019). Some of these studies analyse the role of existing policies, namely the Common Agricultural Policy (CAP) and its evolution over time, in modulating the GHG emissions of the agricultural sector, or simulate eventual CAP reforms that could target the reduction of emissions. Other studies, instead, appraise the impact of hypothetical policy directly targeting agricultural GHG emissions.

As regards the first stream of the literature, using an econometric approach, Balogh (2023) investigates the influence of CAP subsidies on emissions, concluding that CAP direct payments under Pillar 1 encourage GHG emissions; by contrast, enforcing rural development measures contributes to reducing these. Along the same lines, Coderoni and Esposti (2018) find that the decoupling of the Pillar 1 payments is associated with a reduction in GHG emissions from Italian farms over the period 2003–2007. Jansson et al. (2021) simulate the removal of voluntary coupled aid to ruminants, showing that this could reduce agricultural GHG emissions in the EU by 0.5%. However, three-quarters of this reduction would be offset by emissions leakage in other parts of the world.

Himics et al. (2020) instead, quantify the impact of diverting financial resources from Pillar 1 of the CAP from direct income support to subsidies for reducing GHG emissions, keeping the total CAP budget unchanged. The authors show that the introduction of these subsidies in place of direct payments would lead to a 21% reduction in emissions by 2030, but a relevant part of the emissions saving would, once again, be offset by carbon leakage elsewhere. They conclude that increases in the price of agricultural products and farm revenues as a result of the subsidy (although only in substitution of pre-existing direct aid) would compensate for income loss only at the aggregate level, with relevant redistributive effects among EU regions.

Among studies simulating policy targeting GHG emissions it prevails the application of a carbon tax or the imposition of a cap on GHG emission, whether at national or EU level (Fellmann et al., 2018; Himics et al., 2018; Pérez Domínguez et al., 2012, Pérez-Domínguez et al., 2016; Van Doorslaer et al., 2015). In particular, Fellmann et al. (2018) and Van Doorslaer et al. (2015) simulate the impacts of achieving a targeted 28% emissions reduction at EU level by 2030 (with respect to 2005 levels) through the voluntary adoption (subsidised or not) of mitigation options.[5] These studies show that regardless of the instrument used to reduce GHG emissions, there will be a reduction of EU internal production that will impact different crop and livestock activities differently.

More recent studies highlight the importance of accounting for heterogeneity among farms (or regions) in terms of characteristics and performance when simulating GHG mitigation policies (Fellmann et al., 2021; Huber et al., 2023) as farms' responses to these policies largely depend on their structural and productive characteristics. When there is a high level of heterogeneity in the socioeconomic and biophysical characteristics of farms, the relevance of average values diminishes (Baldoni et al., 2023); adoption costs may be significantly different for a significant number of farms (Moran et al., 2013), thus overestimating the real mitigation potential (Kesicki and Ekins, 2012; Moran et al., 2011).

Against this background, this study offers the first *ex ante* impact assessment of the introduction of alternative policy tools to curb CH_4 emissions for the Italian bovine livestock sector. Simulations take the form of a tax paid on each unit of residual emissions or a subsidy to reward the reduction of emissions with respect to the baseline case; both measures are simulated for increasing intensities. We assess the impacts on farm operating income (OI), number of livestock units (LSU) reared

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[3] The issue that CH_4 is a short-lived GHG, unlike CO_2, has relevant implications for the calculation of its contribution to global warming, as it does not accumulate in the atmosphere and its climate impact is initially very high, but rapidly declines after 20 years. This behaviour is not captured by traditional GWP 100, thus alternative metrics have been proposed (Cain et al., 2019) and some stakeholders have also called for the need of a separate regime for short and long-lived GHG.

[4] As regards the definition of these farming systems, the proposal is very generic, indicating only that: "*operating rules for livestock farms will take into consideration not only the nature, type, size and density but also the complexity of these installations and the range of environmental impacts they may have, together with economical aspects. This will allow establishing proportionate requirements for different farming practices (intensive, extensive, organic), including by taking into account the specificities of pasture based cattle rearing systems, where animals are only seasonally reared in indoor installations, while minimising burdens for the sector and the competent authorities*" (European Commission, 2022).

[5] The technological mitigation options considered were: farm-scale anaerobic digestion, community anaerobic digestion, nitrification inhibitors, improved timing of fertilization, precision farming and changes in the composition of animals' feed.

and level of emissions. These impacts are identified and discussed with reference to the different cattle specialisations and LSU-size classes.

One of the novelties of the proposed approach is the use of a microeconomic supply model ('AGRIcultural TerritoriAL tIme econoMic' or AGRITALIM) that represents professionally managed Italian agricultural farms. This allows for the simulation of farm-management decisions on animal husbandry and land cultivation, depicting the complex biophysical and economic processes involved in the production of multiple outputs, for example, the joint production of milk and meat under different herd dynamics. Herd management is linked to a CH_4-estimation method that allows the representation of more intensive or extensive livestock systems. This detailed representation of farm characteristics allows us to consider farm heterogeneity for a large number of farms (1,550) that, ideally, could be overlapped to cover a large range of farm structures and management, including across the EU. This micro-level simulation model to derive marginal abatement cost (MAC) estimations is thus a bottom-up approach.

Moreover, we improve the model with the addition of a binary choice regarding the adoption of one exemplary mitigation measure (the use of linseed-based feed additives to reduce emissions from enteric fermentation of dairy cows). Supplementing ruminant diets with lipids (for instance, from linseed), in given proportions, is in fact a measure introduced to limit CH_4 emissions that has been investigated for several years (Beauchemin et al., 2008; Martin et al., 2008). This measure is introduced by simulating different implementation costs and GHG reduction shares. With this improvement, the possible impact on production activities and GHG emissions of the mitigation measure can be assessed. In addition, the economic determinants of farmer's choices are highlighted, given the simulated economic policy instruments available to curb emissions. Unlike previous micro-level studies, we simulate the introduction of the tax or subsidy without imposing any reduction target, in the absence of a clear GHG reduction target for the livestock sector (Talenti, 2023). The decision to opt for the mitigation measure (or not) then becomes one of actual economic convenience for the farms in terms of profit maximisation. Of course, these profit-maximising choices can be very different at the micro level, as different farms will respond differently to economic incentives according to their characteristics. As a result, the use of a micro-economic model is fundamental to the assessment.

The remainder of the article proceeds as follows. In Section 2, we present the materials and methods used to carry out the simulation exercise. In Section 3, we set out the results, and in Section 4, we discuss our findings and put forward policy implications; Section 5 concludes.

2. Materials and methods

2.1. Sample description

The analysis in this study is based on the 2020 Italian dataset of the Farm Accountancy Data Network (FADN), a harmonised source of micro-data at the EU level. The main regional farm types in the FADN are considered and randomly sampled to provide representative data along three dimensions: geography, economic size, and farm specialisation (Arzeni et al., 2021).

Table 1 sets out some of the baseline characteristics recorded by the FADN with respect to cattle farms. These are distinguished by farm type (dairy, beef and mixed) and LSU-size class (less than 150 LSU, 150–350 LSU and more than 350 LSU). Variables reported include the number of farms in the sample, OI, number of LSU and amount of CH_4 emissions, expressed as tons of CO_{2eq}.[6] In addition to these data, indicators are provided to better describe the baseline characteristics of the different farm types and LSU-size classes. These are emission intensity (EI; expressed as CO_{2eq} emissions divided by the number of LSU), profitability per LSU (OI divided by the number of LSU) and carbon productivity (CP; indicating the amount of OI generated by one tonne of CO_{2eq} emissions). Table A1 of Appendix 2 details the distribution of farms and CH_4 emissions among Italy's geographical regions.

Regarding farm types, around 60% of farms specialise in rearing dairy cattle and are mainly distributed in Northern Italy. These farms, accounting for 76% of OI, 69% of LSU and 76% of emissions in the sample, are characterised by the highest EI (due to enteric fermentations for milk production) and by the highest profitability per LSU. About 30% of the sample farms specialise in rearing beef cattle and represent 19% of OI, 25% of LSU and 18% of emissions; the greater number of these farms is fairly equally distributed between Northern and Southern-Insular Italy. These farms have the lowest EI and the highest CP of farms in the sample. Mixed cattle farms, almost entirely located in Northern and Southern-Insular Italy, represent 10% of the farms in the sample and account for 5% of OI and 6% of LSU and emissions. These farms are characterised by an intermediate EI, profitability per LSU that is nearly identical to beef cattle farms and the lowest CP in the sample. The territorial distribution of emissions from the different farm types follows the distribution of these farms, with over 60% of emissions produced in Northern Italy, followed by Southern and Insular Italy (accounting for just under 30% of emissions produced).

Distinguishing by LSU size, the LSU<150 includes 85% of sample farms. About half of these farms are distributed in Northern Italy, with just under 30% in Southern and Insular Italy and accounting for 37% of OI, 43% of LSU and 42% of emissions. Farms in this class are characterised by the lowest profitability per LSU and CP. The intermediate class includes 10% of sample farms, representing about 25% of OI, LSU and emissions. These farms are characterised by the highest EI and intermediate profitability per LSU and CP. Finally, farms in the upper class represent only 4% of the sample but account for 38% of OI, 33% of LSU and 31% of emissions. This class is characterised by the lowest EI and by the highest profitability per LSU and CP.

2.2. Model description

The analysis is carried out using the AGRITALIM agroeconomic supply model, which represents the entire 2020 FADN sample of Italian farms distinguishing among geographical areas, altimetric levels and farm types (Cortignani et al., 2022; Dell'Unto et al., 2023). From a temporal point of view, the model considers both short and medium-long term aspects. The short-term nature is identified by the fact that farms cannot change their production orientation, sell or buy land, improve their skills or professional knowledge, etc. However, the model has some dynamic elements, as it can consider structural changes (e.g., number of animals and related areas) by way of the annualization of the investments made (depreciation rates). In addition, the model was recently integrated with the estimation of GHG emissions (Cortignani and Coderoni, 2022) following an approach that adapts Intergovernmental Panel on Climate Change (IPCC) methodology (IPCC, 2006) at the farm level (Coderoni and Vanino, 2022; Baldoni et al., 2017, 2018). The mathematical representation of the AGRITALIM model is presented in Appendix 1, along with specifications for its calibration.

As regards CH_4 emissions estimation, the IPCC approach is used – it is an established international standard and is already widely used in the literature as a farm-level indicator of GHG emissions (Coderoni and Vanino, 2022; Dabkiene, 2017; Dabkienė et al., 2020; Coderoni and Esposti, 2018; Baldoni et al., 2017, 2018). The system boundaries for the calculations are set at the farm gate to account for emissions over which the farmer has direct control.[7]

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[6] Hereinafter, mentioning CO_{2eq} emissions we will refer to the emissions of CH_4 expressed in CO_{2eq} (see next sub-section for details on the methodology for emissions estimation).

[7] Thus, emissions from input production are not included in the calculations, as well as emissions from the consumption of food.

Table 1

Characteristics of specialised cattle farms in FADN sample.

	Farms	OI	LSU	CH4 emissions	EI	Profitability per LSU	CP
	N.	EUR,000	N.	Tonne CO_2eq.	Tonne CO_2 eq./LSU	EUR,000/LSU	EUR,000/tonne CO_2 eq.
	Farm type						
Dairy cattle	931	76,868	99,782	321,580	3.22	0.77	0.24
Beef cattle	466	19,436	35,849	74,740	2.08	0.54	0.26
Mixed dairy & beef	153	4,947	9,282	24,924	2.69	0.53	0.20
	LSU size						
<150	1,324	37,288	61,802	178,862	2.89	0.60	0.21
150–350	160	25,483	35,981	110,862	3.08	0.71	0.23
>350	66	38,480	47,130	131,520	2.79	0.82	0.29
Total	1,550	101,250	144,913	421,244	2.91	0.70	0.24

Source: own elaboration

The general IPCC approach to computing emissions relies on a linear relationship between the emissions factors (EF) and the activity data (AD). In this study, AD are cattle numbers, and there are two EF types. The first is a farm-specific EF, defined as a so-called Tier 2 IPCC approach, that is used for CH_4 emissions calculated from enteric fermentations. This EF is farm-specific as it is estimated by using the quantity of milk produced per cow at the farm level. This approach is a refinement of the methodology proposed in other studies (Coderoni and Vanino, 2022; Baldoni et al., 2017, 2018; Dabkienė et al., 2020) and allows the amount of CH_4 emissions produced to be differentiated according to the level of management intensity of each farm (e.g., milk produced, calving interval choice, herd management, etc.). Although this refinement of the methodology is applied to only one emissions source, it is still very relevant as enteric fermentations represent 83% of bovine and 69% of agricultural CH_4 emissions at the national level in 2021 (ISPRA, 2023).

The CH_4 emissions from manure management are instead calculated using a Tier-1 approach because data availability in FADN would not allow a finer representation. In this case, EF are country-specific and are derived using data from the Italian national accounting system (ISPRA, 2016, 2021). Finally, emissions are expressed in total CO_{2eq} by multiplying CH_4 emissions for their GWP (i.e., 25) in accordance with the IPCC Fourth Assessment Report.

2.3. Definition of simulated scenarios

a) Tax and subsidy

The simulated scenarios consider the application of two alternative policy instruments: (1) an environmental (or carbon) tax paid for each unit (tonne) of CH_4 emitted (expressed in CO_{2eq}), or (2) an environmental subsidy to reward each unit reduction (tonne) of CH_4 reduced (expressed in CO_{2eq}) with respect to the situation observed in the baseline. From a mathematical point of view, the two types of instruments are represented by the following models:

(1) Tax on emitted CO_{2eq}

$$max_X = \boldsymbol{C}\ \boldsymbol{X} - \boldsymbol{L}\ \boldsymbol{Emis}\ \boldsymbol{X}$$

$$s.to\ \boldsymbol{A}\ \boldsymbol{X} \le \boldsymbol{B}\ [\lambda]$$

$$\boldsymbol{L} = \boldsymbol{C}\ \boldsymbol{X} - \boldsymbol{L}\ \boldsymbol{Emis}\ \boldsymbol{X} + \lambda\ (\boldsymbol{B} - \boldsymbol{AX})$$

$$\frac{\delta \boldsymbol{L}}{\delta \boldsymbol{X}} = \boldsymbol{C} - \boldsymbol{L}\ \boldsymbol{Emis} - \ \lambda\ \boldsymbol{A}$$

(2) Subsidy on reduced CO_{2eq}

$$max_X = \boldsymbol{C}\ \boldsymbol{X} + \boldsymbol{L}\ (\boldsymbol{EmisB} - \boldsymbol{Emis}\ \boldsymbol{X})$$

$$s.to\ \boldsymbol{A}\ \boldsymbol{X} \le \boldsymbol{B}\ [\lambda]$$

$$\boldsymbol{L} = \boldsymbol{C}\ \boldsymbol{X} + \boldsymbol{L}\ (\boldsymbol{EmisB} - \boldsymbol{Emis}\ \boldsymbol{X}) + \lambda\ (\boldsymbol{B} - \boldsymbol{AX})$$

$$\frac{\delta \boldsymbol{L}}{\delta \boldsymbol{X}} = \boldsymbol{C} - \boldsymbol{L}\ \boldsymbol{Emis} - \ \lambda\ \boldsymbol{A},$$

where ***C*** is the unitary income of ***X*** production activity, and ***L*** is the level of taxation or subsidy applied to each unit (tonne) of emissions (***Emis***) or reduction of emissions with respect to the ***EmisB*** baseline. The model is subject to various constraints where ***A*** is the technical coefficient matrix, and ***B*** represents the resources available.

Passing through the representation of a Lagrangian function, the first-order conditions (Kuhn–Tucker conditions) with respect to the ***X*** variables show the same equations for the two types of instruments used. This means that the simulation results for the same level of ***L*** are the same in terms of ***X*** production choices (in our case, variables relating to the number of animal heads) and then for the impacts on quantities of GHG emissions.

Specifically, three levels of ***L*** were considered, equal to EUR25/tonne, EUR50/tonne and EUR100/tonne, respectively, for a total of six scenarios (three for the tax and three for the subsidy).[8] This definition makes it possible to compare the results of the imposition of the tax or the establishment of a subsidy of the same level ***L***, and, more generally, to evaluate the sustainability of the various levels and their feasibility for the two instruments. Table 2 schematises the scenarios considered as regards the policy modelled.

Table 2

Characteristics of the simulated scenarios about tax and subsidy.

Short name	Tax	Subsidy
L25	EUR25/tonne	EUR25/tonne
L50	EUR50/tonne	EUR50/tonne
L100	EUR100/tonne	EUR100/tonne

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[8] In the absence of an operating carbon tax on agricultural emissions, or an official carbon market for agricultural sinks, these price levels were chosen by looking at the historical prices experienced by the EU Emission Trading System. As the model was calibrated on 2020 FADN, we looked at the ETS prices from January 2020 (when the price of a permit was EUR25/tonne) to the maximum level experienced (February 2023, when was EUR100/tonne). An average value of EUR50/tonne was also considered (Source: https://ember-climate.org/data/data-tools/carbon-price-viewer/). This price range is in line with what done in other studies (Fellmann et al., 2021; Pérez-Domínguez et al., 2020).

b) Mitigation strategy

Additional simulated scenarios concern the application of a mitigation strategy allowing a reduction in CH_4 emissions per cow. These simulations do not intend to delve into the potential of the numerous and varied mitigation strategies that exist, widely discussed in the literature (Van Doorslaer et al., 2015; Pérez-Domínguez et al., 2016, 2020; Huber et al., 2023). The objective here is to highlight, from a theoretical point of view, the decision-making process underlying farmers' choice in a system where the unit economic value of CO_{2eq} ($\boldsymbol{L}$) determines the reduction of LSU number, stressing relevant technical and economic aspects.

Among the various possible mitigation strategies, this study took into consideration the use of feed additives capable of reducing enteric fermentations in dairy cows, already considered by Pérez Domínguez et al. (2016, 2020). This specific mitigation measure has been considered particularly relevant for three main reasons. First, it reduces emissions from the most important source of CH_4 within the analysed farms. Secondly, there are already many scientific studies describing the costs and benefits of this measure (Artavia et al., 2018; Pérez-Domínguez et al., 2016, 2020). Thirdly, from a modelling perspective, it is an interesting solution to reproduce as the use of feed additives is not a win-win measure[9]; it has benefits and costs for the farm, allowing the simulation of different implementation scenarios. In fact, the mitigation strategy analysed directly involves productive animals in terms of benefits (lower emissions that translate into lower levels of taxation or higher subsidies) and costs (of feed additives). Therefore, the choice of the strategy is determined through parameters that can potentially be controlled and verified by farmers. It is thus useful to represent the decision-making behind the choices that farmers are expected to make. We better represent this decision-making process by including a binary choice in the AGRITALIM model with the following general structure:

(3) Binary model

$$max_X = \boldsymbol{C}\,\boldsymbol{X} - \boldsymbol{L}\,(\boldsymbol{Emis} - \ \boldsymbol{EmisR}\,\boldsymbol{BIN})\,\boldsymbol{X} - (\boldsymbol{SC}\,\boldsymbol{BIN})\,\boldsymbol{X}$$

$$s.to\ \boldsymbol{A}\,\boldsymbol{X} \leq \boldsymbol{B}\,[\lambda]$$

where, with respect to the elements of the model already described previously, $\boldsymbol{BIN}$ is the binary variable (0; 1), $\boldsymbol{EmisR}$ is the reduction of emissions per head ($\boldsymbol{EmisR} = \boldsymbol{Emis} * \%\,\boldsymbol{rid}$), $\boldsymbol{SC}$ is the cost to farms of feed additives per head.

The two possible choices can be expressed as follows for the purposes of comparison:

(4) Without mitigation strategy (BIN = 0)

$$max_X = \boldsymbol{C}\,\boldsymbol{X} - \boldsymbol{L}\,\boldsymbol{Emis}\,\boldsymbol{X}$$

$$s.to\ \boldsymbol{A}\,\boldsymbol{X} \leq \boldsymbol{B}\,[\lambda]$$

$$\boldsymbol{L} = \boldsymbol{C}\,\boldsymbol{X} - \boldsymbol{L}\,\boldsymbol{Emis}\,\boldsymbol{X} + \lambda\,(\boldsymbol{B} - \boldsymbol{AX})$$

$$\frac{\delta \boldsymbol{L}}{\delta \boldsymbol{X}} = \boldsymbol{C} - \boldsymbol{L}\,\boldsymbol{Emis} - \ \lambda\,\boldsymbol{A}$$

(5) With mitigation strategy (BIN = 1)

$$max_X = \boldsymbol{C}\,\boldsymbol{X} - \boldsymbol{L}\,(\boldsymbol{Emis} - \ \boldsymbol{EmisR})\,\boldsymbol{X} - \boldsymbol{SC}\,\boldsymbol{X}$$

$$s.to\ \boldsymbol{A}\,\boldsymbol{X} \leq \boldsymbol{B}\,[\lambda]$$

$$\boldsymbol{L} = \boldsymbol{C}\,\boldsymbol{X} - \boldsymbol{L}\,(\boldsymbol{Emis} - \ \boldsymbol{EmisR})\,\boldsymbol{X} - \boldsymbol{SC}\,\boldsymbol{X} + \lambda\,(\boldsymbol{B} - \boldsymbol{AX})$$

$$\frac{\delta \boldsymbol{L}}{\delta \boldsymbol{X}} = \boldsymbol{C} - \boldsymbol{L}\,(\boldsymbol{Emis} - \ \boldsymbol{EmisR}) - \boldsymbol{SC} - \ \lambda\,\boldsymbol{A}$$

Taking into consideration the first-order conditions with respect to the $\boldsymbol{X}$ variable of Models (4) and (5) and comparing these, the choice of whether to apply the strategy is determined by the following conditions, which the farmer uses to compare the costs and benefits of the mitigation strategy:

- $\boldsymbol{L\,EmisR} > \boldsymbol{SC}\quad \textbf{\textit{application of mitigation strategy}};\boldsymbol{BIN} = \mathbf{1}$
- $\boldsymbol{L\,EmisR} < \boldsymbol{SC}\quad \textbf{\textit{non} - \textit{application of mitigation strategy}};\boldsymbol{BIN} = \mathbf{0}$

In particular, in a system with a unit economic value of CO_{2eq} emissions, the benefit corresponds to the value of the reduced emissions, evaluated through $\boldsymbol{L}$. On the other side is the $\boldsymbol{SC}$ cost of applying the strategy (in this case, the cost of feed additives per head).

Given that $\boldsymbol{EmisR} = \boldsymbol{Emis} * \%\,\boldsymbol{rid}$, the elements that determine the choice are the percentage of emissions reduction ($\%\,\boldsymbol{rid}$), the $\boldsymbol{L}$ level and the $\boldsymbol{SC}$ cost. Specifically, the following values were simulated: i) three levels of $\boldsymbol{L}$ (25, 50, 100); ii) three levels of $\%\,\boldsymbol{rid}$ (−10%, −20%, −30%)[10]; and iii) a loop of 20 iterations, with an increase of EUR5/cow each (from EUR5/cow to EUR100/cow) regarding the $\boldsymbol{SC}$ costs of feed additives incurred by the farms; this takes account of Artavia et al.'s (2018) simulation of the mitigation effort's accounting cost of EUR71.88/cow.

Additionally, a simulation was performed with an emissions cap to achieve the same reduction in emissions as those simulated under L100. Table 3 outlines the simulations performed by applying the mitigation "feed additives" mitigation strategy.

The simulations, for each level L, were conducted by exogenously introducing the parameters into the model and performing a sensitivity analysis. This is because the objective of the simulation is to identify the mechanisms underlying farmers' choice of mitigation strategy in a system where the per unit economic value of CO_{2eq} ($\boldsymbol{L}$) determines the reduction of LSU.

The additional simulation with the emissions cap was then hypothesised to compare the two approaches and highlight some relevant differences between them (i.e., the unit economic value of CO_{2eq} emissions *vs* the emissions cap).

3. Results

Table 4 reports the impacts on the number of LSU reared and the quantity of CO_{2eq} emitted under the considered scenarios of tax and subsidy. Impacts are shown distinguishing among farm types and LSU-size classes for the general cases of L = 25, 50 and 100, regardless of the policy type (tax or subsidy); impacts on LSU and GHG emissions are

Table 3
Simulations performed applying the 'feed additives' mitigation strategy.

Instruments for emissions reduction	Potential for emissions reduction (*%rid*)	Costs of feed additives (*SC* in EUR/head)
L25 L50 L100 Emissions cap	−10%, −20%, −30%	from 5 to 100 (+*5 each loop*)

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[9] Win-win mitigation measures are those that reduce greenhouse gas emissions and save costs (Moran et al., 2013).

[10] Emissions reduction from feed additives can vary according to the different additive chosen. Recent technological developments show very high mitigation potential (up to 30%; https://www.darigold.com/6-feed-additives-reduce-cows-methane-emissions/).

Table 4
Impacts on reared LSU (Δ% over baseline) and CO_{2eq} emissions (Δ% over baseline and *absolute variation in tonnes*) under the considered tax and subsidy scenarios.

	LSU			CH_4 emissions in CO_{2eq}					
	L25	L50	L100	L25		L50		L100	
	Farm type								
Dairy cattle	−8.3	−14.6	−26.3	−8.4	*−27,065*	−14.8	*−47,466*	−26.2	*−84,196*
Beef cattle	−11.3	−21.5	−36.8	−11.2	*−8394*	−22.2	*−16,580*	−37.4	*−27,939*
Mixed dairy & beef	−9.9	−17.3	−33.1	−10.2	*−2538*	−18.1	*−4500*	−33.6	*−8370*
	LSU size								
<150	−9.6	−16.3	−28.9	−9.8	*−17,556*	−16.6	*−29,726*	−29.0	*−51,889*
150 - 350	−8.6	−15.8	−27.4	−8.5	*−9441*	−15.7	*−17,446*	−27.1	*−30,062*
>350	−9.0	−17.4	−31.3	−8.4	*−10,999*	−16.3	*−21,374*	−29.3	*−38,554*
Total	−9.1	−16.5	−29.3	−9.0	*−37,997*	−16.3	*−68,546*	−28.6	*−120,505*
Source: own elaboration									

the same for the same L levels under both policies.

The impacts on the number of LSU are closely correlated with the impacts on emissions in the absence of options for farms to reduce emissions per LSU while keeping the animals on the farm (e.g., changes in feed rations, administration of feed additives, vaccination against methanogenic bacteria, and modification of manure management). Such options are not considered at this stage of the analysis; thus, the only way farms can reduce emissions from livestock is to reduce the number of LSU. Therefore, the impacts shown in Table 4 have to be treated as a worst-case or short-term scenario, meaning that it is not possible to change the production technology. In this hypothesis, increasing the level of taxation or subsidisation allows progressive reductions of emissions at the cost of proportional decreases in LSU.

Looking at farm types, the reduction in LSU mainly affects beef cattle farms, which are characterised by the lowest EI and the highest CP at the baseline. LSU reduction is pivotal for these farms to limit OI losses resulting from the application of the tax relative to other farm types. In fact, as evidenced in Table A2 (see Appendix 2), beef cattle farms are the only type of farm that manages to slightly increase profitability per LSU and CP with an increase in the level of tax applied, showing a kind of intensification process. Instead, dairy cattle farms are expected to undergo the smoothest reduction of productive activities (and emissions) due to having the highest profitability per LSU and EI at the baseline. However, this leads profitability per LSU and CP of these farms to deteriorate, increasing the level of tax application (Table A2). The impacts on the number of LSU and emissions of mixed cattle farms are, as expected, somewhere between those of farms specialising in dairy cattle and those specialising in beef cattle.

Considering the different LSU-size classes, the lowest-size class is the only one in which it is possible to achieve a more than proportional reduction of emissions (albeit slight) with respect to the number of LSU. This is probably since this class has the lowest profitability per LSU level in the baseline case, which further decreases with an increase in taxation (Table A2). The reduction of emissions involves, instead, a more than proportional reduction of the number of LSU in the intermediate and upper-size classes. By contrast to the smallest class, the biggest LSU size class undergoes an increase in EI and profitability per LSU, indicating that, to some extent, these farms manage to limit the impacts of the tax.

Table 5 reports the impacts on OI of the tax and subsidy for the reduction of CO_{2eq} emissions, which, of course, are very different depending on the policy tool employed. The last two rows report a measure of the total tax collected and total subsidies granted, first with reference to target farms included in the FADN sample and then extrapolated to the Italian target farms (i.e., cattle farms) based on measures of statistical representativeness provided by the same FADN.

In terms of overall impacts, increasing the level of taxation involves increasing reductions of OI, and the opposite occurs when increasing the level of subsidisation; this is as expected given the nature of the policy tools. The financial amounts reported in the last two rows with respect to taxes collected and subsidies paid tend to increase as the level of their application (and consequent emissions reduction) increases.

Table 5
Impacts on OI (Δ% over baseline) under the considered tax and subsidy scenarios and total tax revenues and subsidies paid (EUR,000).

	Tax			Subsidy		
	L25	L50	L100	L25	L50	L100
	OI: Farm type					
Dairy cattle	−10.0	−19.2	−35.8	0.5	1.7	6.0
Beef cattle	−9.0	−17.0	−30.4	0.6	2.2	8.0
Mixed dairy & beef	−11.9	−22.7	−41.4	0.7	2.5	9.0
	OI: LSU size					
<150	−11.3	−21.7	−40.2	0.7	2.3	7.7
150–350	−10.4	−19.9	−37.0	0.5	1.8	6.5
>350	−8.2	−15.7	−28.8	0.4	1.4	5.3
Total	−9.9	−19.0	−35.1	0.5	1.8	6.5
	Amount of tax and subsidy					
Sample farms	9,581	17,635	30,074	950	3,427	12,050
Total	242,251	437,727	740,822	25,330	97,434	329,501

Source: own elaboration

With reference to the different farm types, tax application is expected to exert the strongest impacts on the OI of mixed cattle farms, which, at the baseline, are characterised by the lowest profitability per LSU and CP, although the reduction in LSU and CO_{2eq} emissions achieved by these farms is intermediate. By contrast, beef cattle specialists somehow managed to limit the negative impacts on OI by taking advantage of the greatest reduction of productive activities to increase their profitability per LSU and their CP, which was already the highest in the baseline case (Table 1). This is also possible because these farms have the lowest EI in the baseline case, which is key to limiting the sensitivity of OI to the application of a tax. Instead, OI impacts are intermediate in dairy cattle farms. In this case, the highest profitability per LSU makes it possible to contain the OI reduction even with the smallest reduction in LSU and CH_4 emissions and given the highest EI.

As regards impacts per LSU-size class, the impacts of tax application smooth as LSU size increases, resulting in the mildest impacts in the upper class. This can be explained by the fact that these farms are characterised by the lowest EI and the highest profitability per LSU and CP at baseline, despite the former increases (Table A2) with the level of tax application (though less than proportionally to profitability per LSU). The negative impacts on OI worsen as profitability per LSU and CP decrease, affecting the smallest size class the most.

As regards the subsidy, impacts on OI are, in general, very low (almost neutral) for the lowest subsidy level (L25) or slightly positive for growing levels of subsidy. It is expected that the farms that are more subsidised will be those in the mixed and small-sized classes. As mentioned, the subsidy designed for the study is an environmental one and is applied to each level of emissions reduction. Thus, the total amount of subsidy is provided on the basis of reduced emissions, while the tax is applied to GHG emitted; this explains the substantial differences in the total amounts of tax collected and subsidies granted at the sample or population level.

As subsidies have relevant impacts on government budgets, a further simulation is performed to assess the absolute values at stake. Table 6 details the CO_{2eq} emissions that would be reduced and the subsidy that should be granted to achieve the respective reduction; the figures reported refer to the universe of cattle farms represented by the FADN sample. For example, with a subsidy of EUR25/tonne, there is a 1 million tonne reduction in CO_{2eq} emissions with an expenditure of EUR25 million. Instead, with a subsidy of EUR100/tonne (a value similar to some agri-environmental payments or eco-schemes), the reduction reaches almost 3 million tonnes $CO_{2eq,}$ and the expenditure is EUR329 million; lower levels of subsidy thus appear to be more cost-effective.

It is worth considering the total subsidies that should be granted under the different scenarios (reported in the last row) must be granted yearly to farms reducing CH_4 emissions. This would result in a public expense of about EUR2.3 billion under the L100 scenario, considering the standard seven years (2023–2029) programming period of the agricultural policy.

With reference to farm types, about 70% of the subsidy should be granted to dairy cattle farms, which are the main farms involved in the mitigation effort, and represent the majority (60%) of cattle farms in the FADN sample. Considering LSU-size classes, farms in the smallest class should receive just over half the total amount of the subsidy despite representing 85% of the farms in the sample. By contrast, farms in the upper class, representing 4% of the sample, should receive about 20% of the subsidy as they are responsible for 31% of emissions.

Finally, Table 7 offers an idea of the unitary costs of reduction, reporting the MAC incurred by farms to reduce emissions under the tax scenarios considered. MACs were calculated by readapting the procedure in Huber et al. (2023) to the simulations performed in the present study. In particular, the absolute reduction of OI under each tax scenario with respect to the baseline OI was divided by the corresponding reduction of CO_{2eq} emissions. Under the tax scenarios considered here, the OI is computed excluding the tax burden, thus reflecting the impact of the reduction in productive activities.

The analysis of MAC values gives a measure of the cost-effectiveness of the contribution to the mitigation effort of the different farm types and LSU-size classes.

Overall, MAC values increase with the level of emissions reductions, indicating that further reductions of productive activities can only be achieved at the expense of increasingly profitable activities. This is in line with the findings of existing studies (Lötjönen and Ollikainen, 2019; Breen and Donellan, 2009), although MAC values obtained here are on a much lower scale than those previously reported (Huber et al., 2023).

Table 6
Emissions reduced, and amount of the subsidy granted.

	CH_4 emissions reduction (,000 tonnes CO_{2eq})			Amount of the subsidy (EUR,000)		
	L25	L50	L100	L25	L50	L100
	Farm type					
Dairy cattle	708	1,273	2,189	17,688	63,651	218,932
Beef cattle	248	569	904	6,199	28,431	90,387
Mixed dairy & beef	58	107	202	1,443	5,352	20,181
	LSU size					
<150	547	965	1,698	13,665	48,239	169,807
150–350	284	529	912	7,108	26,428	91,229
>350	182	455	685	4,556	22,767	68,465
Total	1,013	1,949	3,295	25,330	97,434	329,501

Source: own elaborations

Table 7
MAC of CO_{2eq}emissions (EUR/tonne CO_{2eq}) under the considered tax scenarios (OI without tax).

	L25	L50	L100
	Farm type		
Dairy cattle	11.6	22.5	45.3
Beef cattle	11.4	23.8	44.0
Mixed dairy & beef	11.5	22.9	47.0
	LSU size		
<150	11.0	21.7	44.3
150–350	11.6	23.1	44.6
>350	12.3	24.2	46.7
Total	11.5	22.8	45.2

Source: own elaboration

This is because, at this stage of the analysis, reducing emissions involves cutting the number of LSU in the absence of mitigation options that will maintain the animals on a farm while still reducing their emissions. LSU reduction also involves a proportional reduction of rearing costs (growing of forage crops, purchase of concentrates, labour, etc.), which smooths the negative impact on OI of the reduction in productive activities. The overall impacts on OI of the introduction of a tax are provided in Appendix Table A4, which sets out the estimates of the MAC values calculated with OI that includes the financial burden of the tax.

Finally, Table 8 shows the impacts on LSU numbers and emissions expected when applying the “feed additives” mitigation strategy. The simulations performed first consider the three levels of L (25, 50, 100), representing the per unit economic value of CO_{2eq} emissions. For each level of L, we simulated three levels of emission reductions (−10%, −20%, −30%), and a loop of 20 iterations was performed, with a EUR5 increase at a time in the ***SC*** cost of feed additives incurred by the farms. Table 8 summarises the impacts with reference to a reduction in unit emissions (% rid) equal to 20%, the intermediate potential for emissions reduction among the simulated scenarios. It also highlights relevant SC costs under each L level, beyond which point the strategy is no longer applied by the totality of farms. The results for the simulations of 10% and 30% reductions in unit emissions are available in Appendix Tables A5 and A6, respectively. In addition, Table 8 shows the impacts under an alternative scenario, in which an emissions cap is simulated in

Table 8
Simulation of the strategy application ‘feed additives’ with a reduction in unit emissions (%rid) equal to 20% for each *L* level and increasing feed additives costs (EUR).

	Levels of L	Costs of feed additives	LSU	CO_{2eq}	% of farms that apply the strategy
Without mitigation strategy	25		−8.3	−8.4	
	50		−14.6	−14.8	
	100		−26.3	−26.2	
With mitigation strategy and increasing costs	25	15	−8.0	−21.6	100.0
		35	−8.2	−9.9	6.5
		75	−8.2	−9.9	6.4
		100	−8.2	−9.9	6.4
	50	15	−13.5	−26.3	100.0
		35	−14.3	−27.0	100.0
		75	−14.4	−16.1	7.3
		100	−14.4	−16.1	7.2
	100	15	−23.9	−34.9	100.0
		35	−24.5	−35.5	100.0
		75	−25.8	−36.5	100.0
		100	−25.9	−27.1	8.4
	0[a]	15	−13.8	−26.2	94.5
		35	−15.2	−26.2	81.8
		75	−18.7	−26.2	46.7
		100	−21.1	−26.2	29.8

[a] *An emissions cap equal to 0.738 has been hypothesised.*

Source: own elaboration

place of the two economic policy instruments considered in the main study.

The results are consistent with what is expected given farmers' cost–benefit analyses: the higher the unit economic value of CO_{2eq} emissions, the higher the threshold cost below which the mitigation strategy "feed additives" is adopted by all farms. In fact, under the L100 scenario, all dairy farms choose to administer feed additives up to a cost of EUR75 per cow, which reduces to EUR35 per cow under L50 and to EUR15 per cow under L25. Evidently, in a system in which emissions have a per unit economic value, increasing the unit amount of L triggers a wider adoption of the mitigation strategy by farms. It is worth mentioning here, however, that given the high heterogeneity of farm behaviour regarding GHG emissions and economic performance, there are farms that still find it convenient to opt for the mitigation strategy even if the "average" breakeven point has been reached (e.g. when the cost of the mitigation strategy is EUR100 per cow and the tax is equal to 100, 8.4% of the farms still opt for the strategy).

Of course, adopting the mitigation strategy proves effective in reducing emissions, although this effect is closely linked to the proportion of farms adopting the technology. In particular, for intermediate levels of taxation (L50), if the strategy was adopted by all farms (i.e. if the cost to farms of the application of feed additives did not exceed EUR35 per cow), then reductions of emissions could be even higher than those obtained under L100 without the application of the mitigation strategy. The other important advantage of introducing mitigation strategies is the possibility that GHG can be reduced while preventing strong reductions of productive activities (LSU number). In some cases, in fact, the same mitigation objectives can be reached with much lower LSU reductions (e.g., with L = 50 and cost of feed = EUR15, the same GHG reduction of 26% could be reached with an LSU reduction of just 13%, compared to the no-mitigation scenario with a price of EUR100 and an LSU reduction of 26%).

In other cases, LSU reduction differences are less relevant, for example, in the case of L50 and a cost of feed equal to EUR75, where the reduction of emissions is only slightly higher than in the no-mitigation case (−16% against 15%), while the cut in LSU is almost the same. This is obviously because the percentage of GHG reductions is just a fraction of the total emissions linked to the cows. Therefore, if mitigation targets are relevant and the cost of adoption is too high for farms, the only effective strategy remains reducing the number of cows. Therefore, the costs to farms of implementing mitigation measures become crucial in smoothing the trade-off between mitigation efforts and economic performance.

4. Discussion

The present study describes the potential productive and economic impacts of the application of economic policy instruments to mitigate CH_4 emissions from the Italian bovine sector, by simulating the imposition of taxes on CO_{2eq} emissions or the provision of subsidies for their reduction, with an increasing per unit economic value of emissions. Also, the application of a mitigation strategy to reduce emissions from enteric fermentation is simulated to show the impacts, in the dairy sector alone, of the introduction of technological options to curb emissions.

Simulations are performed using the microeconomic supply model AGRITALIM, implemented to endogenously estimate emissions from CH_4 originated by both enteric fermentation and manure excretion and management. The attention here is on cattle farms that, given the proposal to include the largest of them in the revised IED framework, are at the centre of the political debate on agricultural CH_4 emissions, representing one of the biggest emissions sources in the EU.

The impacts of the tax or subsidy on LSU and GHG emissions are the same, whether the policy applied follows the "polluter pays" or the "provider gets" principle; that is, the tax or the subsidy is consistent with what is expected. The difference among farm types and LSU-size classes in the magnitude of the impacts from the application of taxes and subsidies is in large part explained by considering the baseline average values of three indicators (EI, profitability per LSU and CP), which intrinsically characterise the heterogeneous performance of each group. Stronger productive and economic impacts generally affect farm types and LSU-size classes characterised by lower levels of CP.

CP, which combines the information of EI and profitability per LSU (Coderoni and Vanino, 2022), is pivotal in explaining the economic impacts of tax and subsidy application. In fact, the strongest negative impacts on OI are for the farm type (mixed dairy & beef) and LSU-size class (<150 LSU) with the lowest CP levels. By contrast, this farm type and LSU-size class is this for which the OI most benefits from the subsidy.

Focusing on LSU-size classes, the economic impacts of tax application decrease as LSU size increases, resulting in the lowest impacts in the upper class (which, in fact, is characterised by the highest CP). The policy implication of this result, if read alone, is that the IED directive should correctly target only the biggest farms to reduce any negative impact on the sector. By contrast, the smallest farms seem to incur the lowest MAC. Nonetheless, it is likely that the smallest farms in terms of LSU would find it much more difficult and expensive to apply mitigation options, the practical implementation of which might ultimately not be cost-effective. Again, given the high level of heterogeneity, there should be further in-depth investigation of the issue.

What changes between the imposition of a tax and the provision of a subsidy are, of course, the payoffs of the different agents involved (the farmers and the government that imposes the regulation). In the case of taxes (subsidies), farmers experience a negative (positive) direct impact on their income, which corresponds with an equal and opposite positive (negative) impact on the government's budget.

The effectiveness of compulsory or voluntary policy interventions is a topic that is discussed outside the specific context of agriculture and within the broader literature on environmental protection; for a comprehensive discussion of the issue, see Barreiro Hurle et al. (2023).

Generally, a subsidy leads to a less efficient allocation of resources than a tax system because, with the subsidy, producers do not have to bear the true social cost of their production, which leads to inefficiency (OECD, 2022b). This is indirectly confirmed by the results of this study, which show that the application of a subsidy has the greatest positive impacts on the OI of farms with the lowest productivity of emissions (CP). In contrast, with an appropriately defined environmental tax system, producers must bear the true social costs of production (OECD, 2010). Also, although the subsidy gives the same productive result as the tax in the short run, it fails in the long run because the extra profits in the sector generated by the subsidy could potentially attract new farms. This would contribute to an overall increase in emissions and, moreover, could allow inefficient farms to remain active in the market (OECD, 2019, 2022a).

In addition, the revenue from the environmental tax decreases the need for taxation in other sectors, thus decreasing the distorting effect of the state's tax levy. Nonetheless, this could result in a net transfer of financial resources from agriculture to the other sectors, which, at least in part, contrasts with the aim of CAP support to fill income gaps through non-agricultural sectors.

Revenues from taxation should be instead redistributed, as suggested by Himics et al. (2018) and Parry et al. (2022), to address competitiveness concerns by subsidising farmers to adopt mitigation technologies (Pérez-Domínguez et al., 2016) and to finance sustainable technology R&D programmes (Sarpong et al., 2023). In this regard, a recent study on the agricultural sector of four EU countries (Italy, France, Germany and Spain) shows the validity of the co-benefit of environmental tax in terms of environmental sustainability and value-added to agriculture (Alola et al., 2023).

A policy targeting the most cost-effective mitigation options could simply refer to the MAC values. In fact, as stated by Huber et al. (2023), MAC allows the potential and cost-effectiveness of mitigation measures to be assessed. Cost-effectiveness depends on the farms' structural characteristics and productive orientation, which can be properly represented by the model and provide useful information to policymakers and stakeholders to ensure more effective mitigation policies. In this study, average MAC values are quite similar for lower values of taxation and more differentiated for higher values. A focus on dairy cattle specialisation would seem to be the most promising and cost-effective approach to curbing CH_4 emissions. Absolute values of MAC derived in this study are not directly comparable with those in other studies as they are constructed using the impacts on OI excluding taxation – this allows the indirect impact of carbon pricing on production level to be assessed without considering any direct impact on revenues. Comparisons with other MAC estimates in the literature are not easy to make, as methodological differences and constrains limit comparability with other studies, as stated also by Fellmann et al. (2021). However, a confrontation can be made referring to Table A4, which shows MAC values calculated with OI that include the financial burden of the tax and add to the loss resulting from the reduction of productive activities. These values are substantially in line with those reported by Cecchini et al. (2018) with reference to a sample of dairy cattle farms in Central Italy (on average EUR243.08 t^{-1} CO_{2eq}, ranging from EUR111.55 to EUR337.25 t^{-1} CO^{2eq}).

Although taxes prove to be a relatively more efficient policy tool for environmental protection, when it comes to agriculture's competitiveness, forced adherence to stricter environmental standards imposed unilaterally or without compensation can be detrimental and result in limited acceptance by farmers (Barreiro-Hurle et al., 2023). Moreover, the peculiar characteristics of the agricultural sector in terms of its structure and the intrinsic characteristics of GHG pollution have by now made the application of a tax on agricultural non-CO_2 emissions unfeasible. In fact, the characteristics of the European agricultural sector – with a very large number of small or medium farms (which are on average even smaller in Italy) – and the nature of GHG generation in farming – with its non-point sources of pollution –exponentially increase the transaction costs of a possible tax on CO_2 (Bakam et al., 2012). As a result, this form of taxation is hardly applicable at the farm level, with the subsidy instrument more widely applied in the agricultural sector (e.g., the CAP agri-environmental and climate measures).

The main issue with the subsidy is that its financing requires taxes to be levied in other sectors. These, by their nature, have a (perhaps undesirable) distorting effect. One way to partially overcome this problem is to use the CAP expenditure to subsidise the policy – these funds are already financed within the EU budget and would not require additional taxation. Of course, providing more CAP funds for subsidising CH_4 mitigation in agriculture would require diverting money from other objectives, and this would require a substantial reshaping of the policy. As an idea of the likely extent of funds required, this study offers a quantitative assessment of the public resources needed to finance a subsidy on CH_4 emissions reduced with respect to baseline emissions. We do so by extrapolating the results referring to FADN sample farms to the universe of Italian cattle farms represented by the sample. Our results show that €329.5 million should be granted yearly (EUR2.3 billion in the entire agricultural policy programming cycle) for a mitigation potential of up to 3.3 million tons of CO_{2eq} from CH_4 emissions alone. Although these emissions correspond to 11.2% of total agricultural emissions (ISPRA, 2021), tackling them with such a policy would imply using 15% of the total Italian budget (considering EU funding and national co-financing) for climate change mitigation actions in the cattle sector alone, disregarding all other policy goals.

This approach, although hardly imaginable in the current context, could be evaluated within a more general CAP reframing around environmental objectives. In fact, as stated by Laborde et al. (2021), more recent agricultural subsidies and protectionist trade policy reform have had very little impact on global GHG emissions, while historically, they have incentivised high-emission farming systems. Thus, a profound revision of current agricultural policies is needed to meet ambitious reduction targets, including changing incentive structures to reduce emissions more directly (Springmann and Freund, 2022). The newly established incentive structure could include carbon taxes, financing R&D in technologies that increase productivity and reduce emissions or subsidising the cost of their implementation (Laborde et al., 2021).

Such reframing is surely relevant since CAP Pillar 1 measures contribute, on average, 18.9% to the OI of livestock farms, with a peak of 45–46% for beef cattle and mixed dairy and beef cattle farms. Of course, the revision of the incentive structure should take into proper consideration the overall coherence of the policy framework (Coderoni, 2023). Introducing a tax or a subsidy for the curbing of bovine CH_4 while maintaining coupled support for those productions could be counterproductive. It would be better to reorganise incentive structures around shared sustainability (economic and environmental) objectives.

As regards the possibility of introducing mitigation measures, the results here show that, as expected and consistent with fully rational economic behaviour, technologies for mitigating GHG emissions are adopted by farmers if they improve their competitiveness. In this case, by reducing the incidence of the burden of a hypothetical tax on production costs (Himics et al., 2018) or increasing revenues through the subsidy. Overall, the use of a mitigation strategy (i.e., the feed additives) allows the smoothing of the reduction of economic impacts (Frank et al., 2019; Cole et al., 1997; Smith et al., 2014) in terms of number of LSU; however, if the reduction targets to be met are relevant, impacts on LSU also are relevant, unless the mitigation measures are not applied by all farms.[11] This evidence makes clear the need (independently from the level L simulated) to limit the cost of the application of feed additives to ensure the effectiveness of the mitigation strategy. In this regard, support from agricultural policy might be needed to cover at least part of the application costs incurred by farms (Cortignani and Coderoni, 2022).

Among the major limitations of the study is the lack in the AGRITALIM model of other mitigation options, as an alternative to the reduction of the number of LSU or the introduction of feed additives (although this mitigation measure is considered with different levels of achievable GHG reductions and costs). We have thus not considered any interaction among mitigation measures, except from the one between the two options (as reducing herd size has an effect on the mitigation potential of feed additives). Considering interactions between measures is important because their application in combination can have a different impact than when operating as stand-alone measures (Huber et al., 2023).

Also, the hypothesis here made regarding the choice of mitigation strategies is based just on the perfect rationality of the farmer that seeks to maximize profits, disregarding any other driver for the choice. In fact, the possibility to adopt a mitigation strategy that imposes changes in feeding practices can largely depend also on the specific type of livestock farming, animal breed and farm characteristics. As an example, many Italian livestock farms are under the regulation of production specifications, and the measures and actions implemented should be admitted by the production specifications and not to alter the quality of the products. Besides, farmers' technical background could be also relevant

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[11] As recalled also by the European Court of Auditors, the only way to strongly reduce emissions from livestock is reducing animal food production and consumption across Europe (European Court of Auditors, 2021).

for mitigation uptake and farmers' adoption behaviour in respect of climate change mitigation measures can be more complex that the one here represented (Wang et al., 2023; Kreft et al., 2022).

Another limitation of the AGRITALIM model lies in not considering patterns of global agricultural production and trade, and thus in the impossibility of endogenously predicting international trade dynamics and impacts on the market price of agricultural products. This is a common limitation of microeconomic models that can fully capture farm-level heterogeneity and related performance, but, unlike aggregate models, cannot include trade patterns and price effects. Although the AGRITALIM model cannot capture changes in internal demand[12] and international trade dynamics, the impacts estimated by the model with respect to the reduction of reared LSU, to comply with a unilateral emissions reduction policy (i.e., applied only at the EU level), could reasonably have two interdependent consequences, as the bulk of the literature has already shown. First, there could be an increase in the price of agricultural products (Himics et al., 2018; Stevanovic et al., 2017), also evidenced by Beckman et al. (2022) in the case of the implementation of the farm-to-fork strategy (European Commission, 2020b). Second, there could be an (at least) partial relocation of production in third countries where no emissions mitigation policy is in place, with a consequent effect of emissions leakage due to the increase in imports from outside the EU (Stepanyan et al., 2023; Arvanitopoulos et al., 2021, Fellmann et al., 2018; Himics et al., 2018; Pérez-Domínguez et al., 2016; Van Doorslaer et al., 2015; Pérez Domínguez et al., 2012; Wang et al., 2022). For instance, Himics et al. (2018) predict that 21% of the EU mitigation effort could already have been undermined by the application of an emissions tax of 50 $€t^{-1}$ CO_{2eq} on emissions from EU agricultural activities.[13] The leakage effect might further be accompanied by a substantial loss of competitiveness in the EU agricultural sector if market policy instruments, such as border adjustment measures, are not undertaken (Himics et al., 2018). Of course, the outcome in terms of both emissions and competitiveness of the sector will ultimately depend also on actual modifications of consumption behaviours towards livestock products, which ultimately will shape the future of the food sector (Reisch et al., 2021).

A final limitation of the AGRITALIM model as it currently stands relates to not considering the shortage of cattle manure for fertilisation, consequent to the simulated reduction by cattle farms of their LSU. This could involve an increase in the demand of mineral fertilisers and could make a substantial contribution to N_2O emissions from cropping activities (not considered in this study) while increasing the costs of growing forage crops. However, we did not account for these impacts, given that cutting the number of LSU involves a reduction of feed requirements and, in turn, of the acreage of forage crops, which compensates for the reduction of manure availability.

5. Conclusions

The present study provides the first evidence for Italy of the impact of the introduction of different policies targeting CH_4 emissions from cattle farms. The first set of scenarios, with no mitigation measures in place, is treated as a worst-case scenario to show the impacts of a tax or subsidy on the bovine sector in the short term (with no technological change); in this case, the only viable strategy is to cut LSU numbers, which is inherently tied to the level of GHG emissions (USDA, 2004) and is the most direct (and drastic) mitigation measure.

The introduction of one mitigation measure and the simulations of the different scenario hypotheses with different shares of GHG reductions and mitigation costs are useful for showing that the final outcome, in terms of GHG mitigation potential (without undermining production), highly depends on the costs of the mitigation techniques, (without accounting for differences in farmer behaviours). However, given the high level of heterogeneity in farms' economic performance (and thus in the opportunity costs of mitigating CH_4), the real mitigation potential may be positive (higher than zero) even in the presence of very high implementation costs.

As regards the different policy tools simulated, the imposition of a tax will clearly result in a net transfer of wealth from the agricultural sector to the government unless there are policies in place to reallocate funds to taxed farms (e.g., subsidising the transition of the sector to lower emissions). If this is not the case, absent a change in consumer behaviour with respect to the consumption of livestock products, emissions would be simply leaked to third countries where productive processes can be even more emission intensive (Laborde et al., 2021), undermining EU mitigation efforts at the global level.

In the case of the subsidy, the decrease in operating income due to the reduction of productive activity is somehow offset by the amount received by the farms. However, resources that are necessary to finance such an instrument correspond to a high share of the total budget assigned to Italy, implying a rethinking of the CAP intervention in the sector; this could, however, create problems of political acceptance among other farmers.

The discussed major limitations of the study include: not considering different mitigation measures, additional to LSU reduction and feed additives; not including more realistic modelling of farmers' behaviour with respect to climate change mitigation adoption and excluding trade and consumption patterns.

Despite these limitations, the present study is a first step in analysing the impacts of the reduction of CH_4 emissions from the Italian bovine sector. The next steps include the following: (i) the assessment of the impacts of a possible CAP reform that diverts the financial resources of Pillar 1 from direct support to agricultural incomes to direct support for GHG emissions reduction; (ii) the modelling of a more sophisticated policy tool that couples a tax with a subsidy to simulate the imposition of a tax on farms that do not reduce emissions and the grant of a subsidy to farms that reduce emissions according to a specific reference level; (iii) modelling alternative and combined mitigation options (technologies and productive techniques) to derive farm-level MAC that can be used to more properly assess the mitigation potential of the sector.

Credit author statement

Davide Dell'Unto: Conceptualization, Data curation, Formal analysis, Investigation, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Methodology. Raffaele Cortignani: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. Silvia Coderoni: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Data curation, Methodology, Supervision, Validation

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[12] As regards possible changes in internal demand, is the literature documents both a decrease in the demand for livestock products (although mitigated by low price elasticities) and an increase in market prices (Pérez-Domínguez et al., 2016). In this respect, just as an exercise, simulations have been performed with the AGRITALIM model to consider possible market effect, by introducing different scenarios of price increase for livestock products (namely +5%, +10%, +15% over baseline prices for meat and milk) under the L100 tax scenario. Results show that the target of substantially reducing CH_4 emissions might be progressively hampered at growing levels of exogenously imposed price increase. In fact, the grow-back of profitability of livestock activities is foreseen to slow the reduction of their level, despite the incidence of taxes and subsidies.

[13] In addition, to our knowledge, none of these studies considers the emissions originating from the transportation sector, which would naturally increase for satisfying higher EU import demand. Accounting for these emissions would certainly contribute to further undermine the mitigation efforts made.

CRediT authorship contribution statement

Silvia Coderoni: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Data curation, Methodology, Supervision, Validation. **Davide Dell'Unto:** Conceptualization, Data curation, Formal analysis, Investigation, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Methodology. **Raffaele Cortignani:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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