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Economic, social and environmental effects of reducing dairy methane emissions through market-based policies: An application of the Livestock Policy Simulation Model☆

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Abstract

Several technological approaches to mitigate methane dairy emissions are available; however, assuming that technological change alone generates the necessary incentives to accelerate emissions reduction is risky. Without adequate market signals, producers might choose not to use the technologies available or to the

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desired extent. Addressing this economic problem requires altering producers' and consumers' behaviour by introducing incentives or constraints. Employing the livestock policy simulation model, we examine the effects of reducing methane emissions in the dairy sector under different market-based policy instruments. We used the primary dairy sector in Uruguay as a case study. The results show that a policy mix combining a set of market-based instruments can be more effective than a single policy instrument alone.

1. Introduction

At the 26th Conference of Parties (COP 26), 105 nations signed the Global Methane Pledge and agreed to reduce methane emissions by 30%, from 2020 levels, by 2030 (Arora & Mishra, 2021). Methane (CH_4) is a potent greenhouse gas (GHG) responsible for around 30% of the rise in global average temperature since the industrial revolution (IEA, 2022); on a 100-year horizon, CH_4 has 25-times the global warming potential of carbon dioxide (CO_2) (Foster et al., 2007). Emissions from livestock enteric fermentation, particularly cattle, account for roughly 32% of global CH_4 anthropogenic emissions (UNEP & CCAC, 2021). Thus, abating enteric CH_4 emissions from the dairy sector have been considered an effective strategy for reducing climate change induced by short-lived climate pollutants (Liu et al., 2021).

In Uruguay, a signatory country of the Global Methane Pledge, dairy production systems are predominantly grass-based, with only 8% of the milk produced under confinement (FFDSAL, 2021). The country has around 2.161 dairy farms operating on 429.462 ha. The level of productivity per animal ranges between 9.8 and 21.4 litres, with an average of 18.5 litres per day, and the carrying capacity ranges between 0.71 and 1.28 animals per hectare, with an average of 0.99 (Baraldo et al., 2022). According to Uruguay's latest cattle footprint report (Baraldo et al., 2022), CH_4 emissions from the primary dairy sector accounts for 805.4 GHG CO_2 equivalent, while the level of emission intensity per kg of fat-protein-corrected milk is 0.497. On average, this level of CH_4 emission is slightly higher than Europe (0.4), similar to North America (0.5) and lower than Oceania (0.6), Latin America (0.7), Asia and Pacific (0.7) and Africa (1.6) (Key & Tallard, 2012).

Several enteric CH_4 mitigation solutions are technically available, including increased animal productivity, selection of low-methane-producing animals, diet reformulation, pasture and forage crops management, action on rumen fermentation, immunisation against methanogens and defaunation of the rumen (Beauchemin et al., 2022). However, without strong market signals, farms—especially smaller ones—could risk making sub-optimal decisions in adopting emissions reduction technologies (Edenhofer et al., 2013). This problem is traditionally addressed by introducing market-based instruments (MBIs) with the capacity to force producers internalise environmental externalities into their cost function, enhance the adoption of new technologies or reorient consumers' choices towards low-emissions alternatives (Tol, 2019). Indeed, many economies are debating the benefits of using MBIs, and some countries have already decided to use taxes, quotas or subsidies to shape emissions (Moran & Edgar, 2022).

Previous studies have analysed the effectiveness of MBIs on shaping economic, social and environmental output (De Cara et al., 2005; Pérez Domínguez, 2006; Dumortier et al., 2010; Walter, 2020). Using the CAPRI model, Kempen et al. (2011) showed that abolishing the milk quota regime in the European Union would increase production by 4.4%, reduce income by 1.6% and increase methane emissions by 1.4%. Key and Tallard (2012) used the AGLINK-COSIMO model to show that a CH_4 tax on milk could shift the composition and location of goods consumed and produced. Golub et al. (2013), using the GTAP-AEZ-GHG model, showed that combining an emissions tax with a carbon sequestration incentive would lead to higher emissions abatement. Slade (2018) modelled the effects of using different MBIs, finding that, among different options, a producer tax would generate the highest emission reduction at the lowest social cost.

Employing the livestock policy simulation model (LPSM) from the Food and Agriculture Organization of the United Nations (FAO), we examine the effects of reducing CH_4 dairy emissions under different MBIs policy scenarios. LPSM is a recursive dynamic open computable general equilibrium (CGE) model designed for country-level ex-ante policy analysis. Using the primary dairy sector in Uruguay as a case study, we compare the economic, social and environmental effects of increasing the sector's total factor productivity (TFP) by employing an investment alone, combining an investment with an emissions quota, or coupling an investment with an emissions tax. The results show that no one-size-fits-all solutions exist, and a policy mix that combines a set of market-based policy instruments can be more effective than using a single policy instrument alone.

This paper makes three contributions to understanding the broader economic effects of using MBIs to shape the dairy output. First, while many dairy policy changes have been analysed using partial equilibrium models, few focus on general equilibrium frameworks. Second, although some focus on assessing the single effect of a tax or quota on dairy emissions, none has compared the economic, social and environmental effects of combining these MBIs to reduce dairy emissions. Third, we illustrate and quantify the potential trade-offs derived from increasing dairy productivity to achieve sustainable development objectives.

2. Methodological framework

LPSM is a recursive (solved sequentially and repeatedly, one period at a time), dynamic (the economy's progression is modelled over time) and open (allowing for trade across borders) CGE model. These characteristics allow the model to simulate the direct and indirect effects of policy changes or economic shocks on the different productive sectors, focussing on dairy. This section provides a discursive illustration of the main features of LPSM (Fig. 1). Appendix A presents a detailed mathematical statement of the model.

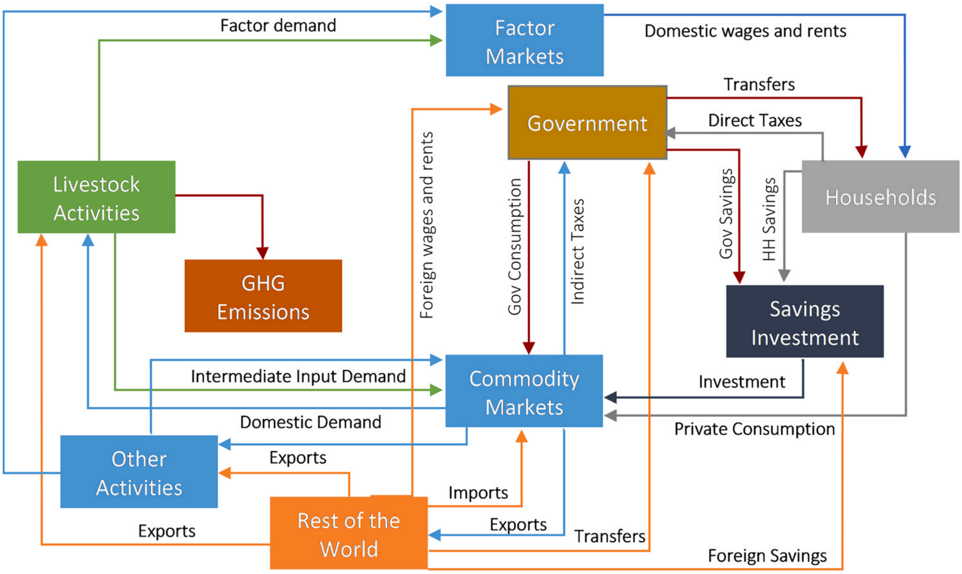

Fig 1. Livestock Policy Simulation Model Structure.

LPSM is a multi-purpose model that can analyse policies in various areas, including growth, employment generation, poverty and inequality, while capturing the effects of external shocks. The starting point for the LPSM specification is Cicowiez and Acosta (2023), which draws on GEM-Core (Cicowiez & Lofgren, 2017), Lofgren et al., (2013, 2002). LPSM has been extended and adapted to the livestock sector's peculiarities, benefitting from the literature on agricultural CGE and household modelling. Among others, see Keeney and Hertel (2005), Gelan and Muriithi (2012), Oladosu and Msangi (2013) and Taylor and Adelman (2003).

Fig. 1 presents an overview of LPSM, showing the payment flows in any single year of the simulation period. Productive sectors are represented by profit-maximising activities that operate in competitive markets, both for factors and commodities. For each simulation period, income flows circularly within and between the economy and the rest of the world. The arrows show the direction of payments (excluding transfers) made in exchange for something else that flows in the opposite direction, for example, the provision of a good or service for consumption in the current period. The primary building blocks are livestock activities (the entities that carry out livestock production), non-livestock activities, commodities (goods and services produced by activities and provided via imports), factors of production and institutions (households, enterprises, the government and the rest of the world). LPSM provides a relatively detailed treatment of the financing of private investment (compared to most other CGE models). The private (non-government) capital account is presented in its own box.

Appendix B presents the production function for livestock activities in the LPSM. The livestock production structure characterises the substitution possibilities between range-fed and ranch-fed production; thus, LPSM defines an extended value-added decomposed into a labour-capital and land-feed composite for the livestock sector. The capital-labour composite is decomposed into capital and labour components, and the land-feed composite is decomposed into a feed composite and land. The feed aggregate is further decomposed into different components, such as wheat, oilseeds and other grains (depending on data availability). For non-agricultural sectors, the figure is simplified by not allowing for substitution between intermediate inputs and factors. For crops, LPSM allows for substitution between fertilisers and land. Activities can produce one or more commodities; furthermore, each commodity can be produced by one or more activities. The total production of each good or service can be sold domestically or exported to the rest of the world.

The model identifies the following institutional sectors: households, enterprises, government and the rest of the world. Households obtain their income from two sources: factor income from their factor endowments and transfers from other institutions. Households spend their income to buy goods and services, save, pay direct taxes and transfer part of their income to other institutions. The government receives tax revenue, consumes/provides goods and services, transfers to households and (dis)saves. The rest of the world demands exports, supplies imports and provides transfers/grants to domestic institutions. The model assumes that the economy is modelled as a small country and takes the world prices of its exports and imports as given. Furthermore, the model identifies eight types of taxes: income, activities, consumption, value-added, export, import, factor income and factor use by activities. In addition, trade and transport margins are explicitly modelled, assuming that the services required to move a commodity from the producer to the consumer are a fixed share of the marketed commodity.

For international trade, LPSM follows the usual treatment in CGE modelling and assumes that goods and services are differentiated according to their country of origin (Armington, 1969); thus, two-way trade can be considered (i.e., the same commodity is imported and exported simultaneously). The combination of domestic and imported products is conducted at the border; for a given commodity, the domestic/imported composition of consumption is the same regardless of the product destination (e.g., intermediate consumption versus final consumption). Imperfect substitution between imports and domestic purchases is implemented through a constant elasticity of substitution function. On the production side, there is a symmetrical assumption that exports and sales to the domestic market are imperfect substitutes; a constant elasticity of transformation function is used to model the imperfect transformability between exports and domestic sales.

We assume that unemployment is modelled through a wage curve, which establishes a negative relationship between the level of wages and the unemployment rate (Blanchflower & Oswald, 2005). In a given simulation, labour can be perfectly or imperfectly mobile among sectors. In contrast, once installed, capital cannot move across sectors. LPSM can also track the evolution of greenhouse gas (GHG) emissions from different domestic uses: intermediate consumption by production activities (e.g., of energy commodities), final consumption by households and factor employment by production activities (e.g., cattle). Specifically, this application projects CH_4 emissions from enteric fermentation linked to dairy cattle stocks.

As mentioned, LPSM is recursive and dynamic; that is, it assumes that agents are myopic. Economic agents, such as firms and households, expect future prices to be the same as current prices. The economy grows due to the accumulation of capital, growth in the labour force, growth in the supply of natural resources, and increases in factor productivity. At the beginning of each period, sectoral capital stocks are updated based on investments from the previous period. In turn, the endowments of the other factors grow exogenously. The model differentiates between private and public investments and capital stocks in each period.

Table 1
The economic structure of the Uruguayan dairy sector.

Commodity	Sector Structure %						Sector Factor Intensity %			Sector Demand Structure %					
	VA	EMP	EXP	EXP-O	IMP	IMP-D	Labour	Capital	Land	Intermed Use	Private Cons	Gov Cons	GFCF	Inventory Change	Exports
Other agriculture	4.29	4.57	11.44	35.60	3.28	12.58	22.32	36.65	41.03	36.77	26.55	0.00	1.42	5.23	30.02
Milk	0.50	0.66	0.00	0.00	0.00	0.00	31.53	32.31	36.16	98.65	1.35	0.00	0.00	0.00	0.00
Cattle	2.29	3.45	1.43	9.82	0.02	0.19	34.91	30.71	34.38	83.47	0.00	0.00	9.05	-2.01	9.49
Forestry	0.49	0.53	0.11	2.58	0.08	1.39	31.05	61.51	7.44	81.51	16.90	0.00	0.00	-0.96	2.55
Mining	0.20	0.12	0.08	3.81	4.97	72.95	40.41	49.26	10.33	99.99	0.00	0.00	0.00	-1.06	1.06
Bovine meat	1.19	0.78	10.10	57.14	0.37	4.50	35.91	64.09	0.00	10.03	36.12	0.00	0.00	0.00	53.85
Other food	3.80	3.55	10.16	26.98	8.22	20.07	41.01	58.99	0.00	23.57	56.96	0.00	0.00	0.44	19.03
Dairy	0.62	0.44	3.40	43.96	0.34	6.51	54.45	45.55	0.00	11.59	51.45	0.00	0.00	-2.82	39.78
Leather	0.31	0.41	2.47	49.07	1.89	39.95	73.87	26.13	0.00	27.61	38.40	0.00	0.88	0.00	33.11
Other manufacturing	7.33	7.29	29.42	40.97	59.47	54.68	43.20	56.80	0.00	42.63	28.28	0.00	8.57	0.11	20.40
Agrochemicals	0.06	0.03	0.41	27.03	2.31	67.23	66.51	33.49	0.00	87.30	3.05	0.00	0.00	-1.01	10.66
Elect, gas, water	3.16	1.05	0.78	4.08	0.00	0.00	32.60	67.40	0.00	56.03	38.65	1.55	0.00	0.00	3.77
Construction	5.59	7.55	0.00	0.00	0.56	1.31	78.76	21.24	0.00	14.42	0.00	0.00	85.58	0.00	0.00
Trade	9.40	14.39	0.21	0.36	0.00	0.00	60.73	39.27	0.00	98.63	0.83	0.00	0.19	0.00	0.36
Transport	6.28	5.67	4.67	12.24	3.73	10.87	49.79	50.21	0.00	71.36	17.66	0.08	0.35	0.00	10.55
Hotels and rest	2.49	3.40	6.55	35.23	0.37	3.28	55.13	44.87	0.00	5.36	62.96	0.00	0.00	0.00	31.69
Other services	52.01	46.11	18.78	6.47	14.37	5.47	56.93	43.07	0.00	34.26	35.09	20.73	4.02	0.00	5.90
Total	100.00	100.00	100.00	14.94	100.00	15.45	53.31	43.94	2.75	41.59	29.46	7.68	8.18	0.22	12.87

VA: Sectoral share in value-added (GDP contribution); EMP: Employment Share; EXP: Export share; EXP-O: domestic sectoral supplies between exports and domestic sales; IMP: import share; IMP-D: domestic sectoral demand between imports and domestic sales output; Capital: capital factor intensity; Land: land factor *intensity; Intermed: intermediate sectoral demand; Priv Cons: private consumption sector demand; Gov Cons: government consumption sector demand; Inventory: inventory changes; Exports: Export sector demand.*

3. Model data

The accounting structure of the LPSM is derived from a social accounting matrix (SAM). Most features of a SAM for LPSM are familiar to those used for other models (Round, 2003; Pyatt and Round, 1985); however, a SAM for LPSM has some unconventional features related to (a) the livestock and crop sectors, (b) the rural economy (e.g., household production for household consumption) and (b) the explicit treatment of selected financial flows.

This study calibrated LPSM using a modified version of the SAM for Uruguay in 2016 (Cicowiez et al., 2021). The SAM accounts, which determine the disaggregation of the model, split the economy into 38 activities, 43 commodities and 7 factors of production; however, all figures and tables in the main text aggregate SAM data to 17 activities and commodities to save space, focussing on livestock and three factors.

In addition to a SAM, LPSM requires a set of elasticities for production, consumption, trade and base-year estimates for sectoral employment levels and unemployment rates. Furthermore, given that LPSM is a dynamic model, we must project the modelled economy under the assumption of a 'business as usual' or base scenario. The base scenario is a reference for comparing the counterfactual simulation scenarios, in which one or more shocks are introduced and compared to the baseline (or reference) scenario. For the base, we require base-year capital stocks, a baseline projection for population and labour force growth and a baseline projection for gross domestic product (GDP) growth.

The required (exogenous) elasticities apply to the production, trade, consumption and labour markets. In sum, the values for elasticities are as follows. (a) The elasticities of substitution among factors are in the 0.2–0.95 range and are lower for natural resource activities, such as agriculture (0.25) and mining (0.2) (Aguiar et al., 2019). (b) The wage curve unemployment elasticity is –0.1 (Blanchflower & Oswald, 2005). (c) The expenditure elasticities are in the 0.62–5.4 range (Muhammad et al., 2011). (d) Trade-related elasticities are in the 0.9–2 range for the substitution between imports and domestic purchases and the transformation between exports and domestic sales (Saudolet and de Janvry, 1995). The parameters associated with the amount of CH_4 emissions were obtained from FAO (2022); this application only considers CH_4 dairy emissions from enteric fermentation.

Table 1 summarises the main descriptive statistics calculated from the SAM, providing an overview of the functioning and contribution of the dairy sector to the economy. The contribution to value-added of the agrifood sector is 13.2%, illustrating the country's reliance on the sector. Of agrifood's total value-added, dairy and milk contribute 8.5% (1.1% of GDP), with the remainder attributable to crops and other livestock; thus, the dairy sector is a small but significant component of the total agricultural value-added. Factor intensity reflects the relative importance of each production factor within a sector.

All production factors are represented: labour, capital, land and other natural resources. In terms of factor intensity within agriculture, dairy is the activity that uses the highest share of labour. In relative terms, dairy operates at a higher labour intensity than bovine meat (54.4% vs 34.9%) and a lower capital intensity (45.5% vs 64.0%). Regarding land rents, dairy production has relatively more rents (36.1%) than beef production (34.3%). In contrast, regarding the demand structure, almost all the raw milk is used as an intermediate input to other sectors (98.6%). The private domestic consumption of dairy products (56.9%) is slightly higher than bovine meat (36.1%). Agriculture's highest exports are bovine meat (10.1%), followed by dairy (3.4%); the exported sectoral output shares are 57.1% and 44.0% for bovine meat and dairy, respectively.

4. Simulation results

We build four scenarios to assess the outcome effect of combining different types of policy instruments. The base scenario (BASE) simulates a business-as-usual projection of the economy without any policy changes. The first scenario (INV) analyses the effect of a government investment oriented to increase TFP in dairy production systems by 10%. The second scenario (INV+EQ) assesses the combined effect of an investment with an emissions quota, and the third scenario (INV+ET) investigates the effect of an investment with an emissions tax.

The base scenario is designed to provide a business-as-usual projection into the future. This scenario assumes that (a) the GDP growth rate is exogenous, drawing on recent IMF data (IMF, 2021), (b) all international (export and import) prices are constant in real terms, and (c) GDP shares for most institutional payments, including all receipt and spending items in the government budget, are constant (based on the SAM data). In addition, for the total population and population in the labour force age (15–64), we impose projections from the 2019 World Population Prospects of the United Nations Population Division (UN, 2019). Fig. 2 summarises results from the base scenario covering GDP, exports, imports, absorption, private consumption and private investment.

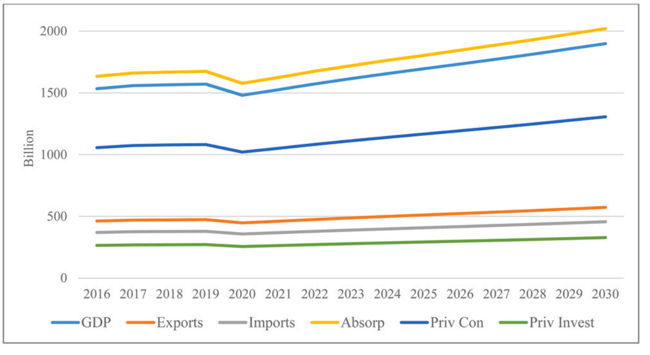

Fig. 2. Selected economic indicators for the base scenario (billion 2016 UYU pesos).

As intended, to facilitate comparisons to non-base scenarios, the picture is one of stable growth; the main deviation from this is related to COVID-19 (Acosta et al., 2021). Specifically, after a substantial decline in 2020, GDP growth is simulated at an annual rate slightly below 2.5% up to 2030. The macroeconomic aggregates covered grow at annual rates of 2.4–2.5%. Moreover, given that private consumption growth exceeds population growth—which for 2022–2030 is projected at 0.3%—aggregate household welfare is increasing. In per-capita terms, household consumption grows at 2.2% per year, which decreases the poverty rate from 10.2% in 2021 to 6.1% in 2030. Finally, the growth rates are 2.0–3.0% at the sectoral level. For agriculture, growth is lower due to the slow growth of land supplies and low-income elasticities of demand. Due to their input–output relationship, the growth rates for milk and dairy are both 2.4%.

Fig. 3 shows the changes in the GDP trend compared to the baseline under the three alternative scenarios. Overall, the impact is always positive: by 2030, the level of GDP will be 0.12%, 0.16% and 0.11% higher under INV, INV+EQ and INV+ET, respectively. It is interesting to note the difference between the short, medium and long-term effects. While INV has the highest effect in the short term, it yields the lowest returns in the long term. Indeed, if the

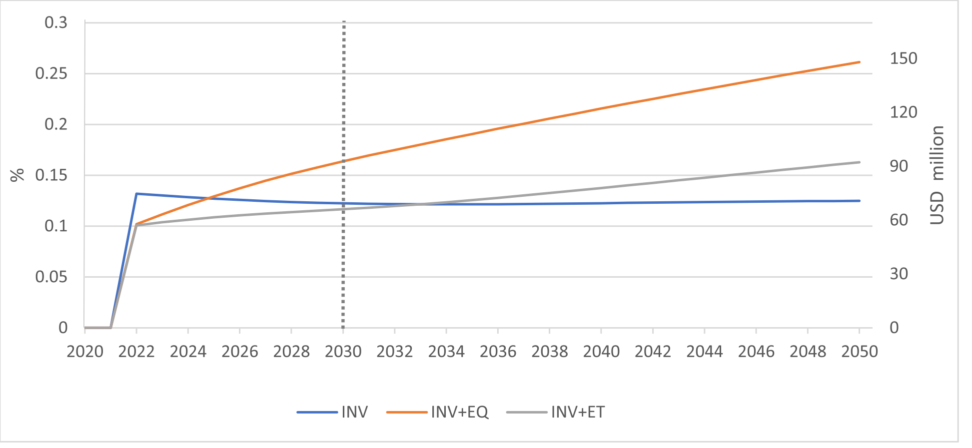

Fig. 3. Gross domestic product (deviation from the baseline simulation by 2030).

simulation is expanded to 2050, INV+EQ yields the highest return (USD 149 million), followed by INV+ET (USD 93 million) and INV (USD 71 million). This result is explained by the fact that, in the INV+EQ scenario, the quota rents assumed to be received by the private sector increase enterprises' savings. Over time, these savings increase investment, capital stock and GDP. In turn, the tax collection in the INV+ET scenario is recycled as a decrease in the income tax rate, benefitting both households and enterprises; therefore, the impact on private savings is less intense.

Fig. 4 displays the effect on other macroeconomic indicators and sectoral output. Regarding private investment, the most significant gains are under INV+EQ, as enterprises benefit directly from the quota rents. Exports, imports and wages increase relatively faster under INV. The largest decrease in unemployment is achieved under INV. As observed, enhancing the production system's output level increases the system's demand and supply, and downstream and upstream, activities along the dairy supply chain. For example, in the case of dairy cattle, a 10%

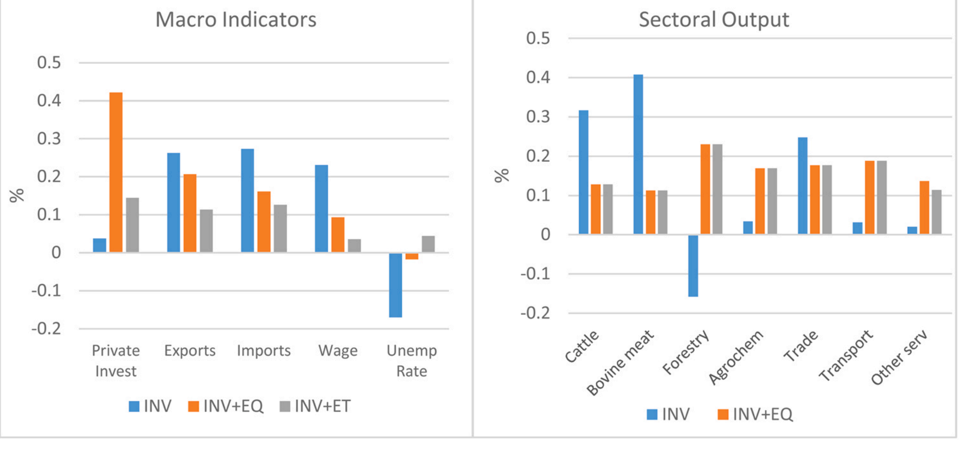

Fig. 4. Macroeconomic indicators and sectoral output (deviation from the baseline simulation by 2030).

TFP change (by 2030) in investment alone increases cattle supply by 0.3% and meat output by 0.4%. In addition, increased production generates additional demand for products such as agrochemicals, transport and trade services, which stimulates further growth in other manufacturing and service sectors; however, there are also potential adverse effects. For example, under the investment alone scenario (INV), forestry has a negative effect due to a change in land used; nevertheless, this effect is controlled under the other scenarios.

Table 2 presents the effects on employment, indicating that the effect on employment differs among policy scenarios and economic activities. A productivity increase has a negative employment effect on milk production under all scenarios, as the increase in the supply of the sector's goods and services decreases their real price. In contrast, the increase in demand brought about by the rise in household incomes and investment demand is generally lower than the increase in supply. For instance, in the investment alone scenario, the domestic milk and dairy supply price declines by about 10.6% and 4.2% (not shown in the table). Simultaneously, the reduction in the use of factors of production in dairy frees up these resources to be used by other economic sectors.

Table 2.
Employment (% deviation from the baseline simulation by 2030).

	Inv	Inv + EQ	Inv + ET
Soy	-0.25	0.12	0.06
Wheat	-0.55	0.23	0.12
Barley	-0.24	0.09	0.07
Cattle	-0.94	0.18	0.11
Milk	-3.36	-15.98	-15.93
Dairy products	12.88	-0.12	-0.05
Agrochemicals	0.05	0.16	0.09
Electricity, gas and water	0.19	0.09	0.18
Trade	0.36	0.17	0.15
Transport	0.04	0.19	0.18

The decrease in employment is explained by the increased TFP, given that demand for milk is not horizontal; in other words, results would differ under a higher degree of export orientation for the milk sector. Thus, the result illustrates the importance of accounting for demand constraints and relative price changes. As observed, the negative effect on employment in milk production is particularly high under the INV+EQ and INV+ET scenarios. This result is unsurprising, as an increase in TFP will release labour from primary production activities; thus, if the quantity supply is restricted using either a quota or a tax, the effect of reducing the use factors of production (labour) is higher. Conversely, the situation differs for those forward-linked activities under INV, where the additional output creates incentives for employment generation. This result is particularly evident for dairy processing, where employment increases by 12.8%, somewhat compensating for the negative effect on primary production.

Fig. 5 depicts the effects on household consumption and poverty rate. Compared to the baseline simulation, increasing the sector productivity leads by 2030 to an increase in household per-capita consumption of 0.15%, reflecting the effect that an income increase, particularly among the poorest, has on demand. The scenario that yields the most significant increase in consumption is INV, where the positive effect is driven by the rise in output and income from the TFP increase. The poverty rate is reduced on average by around 0.42% under the three

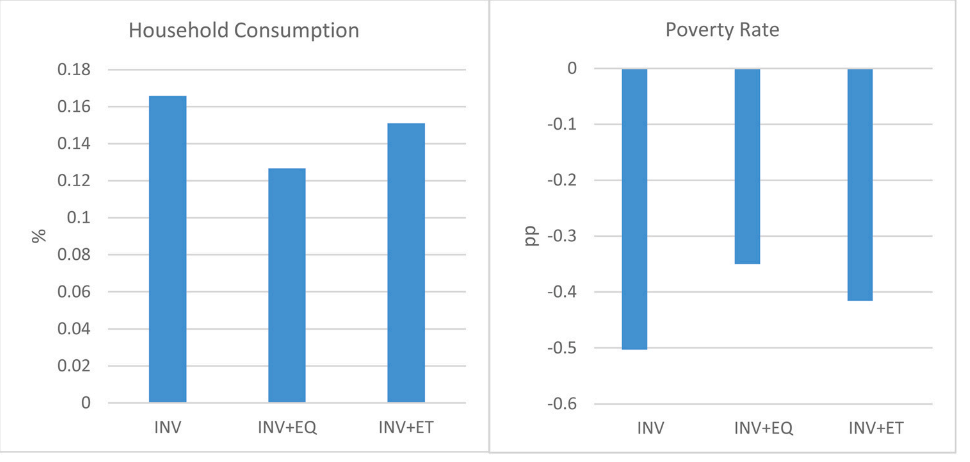

Fig. 5. Household consumption and poverty rate (deviation from the base simulation by 2030).

scenarios, following the household per-capita consumption results; however, reductions differ slightly depending on the combination of policy instruments. As observed, the scenario with the highest effect on poverty reduction is INV (0.50%), followed by INV+ET (0.41%) and INV +EQ (0.34%).

Fig. 6 presents the effect on methane emissions from enteric fermentation, showing an increase in the total CH_4 enteric emissions under all policy scenarios. INV is the scenario with the highest increase in CH_4 emissions, with a change of 1.5% from the base scenario; this is followed by INV+EQ quota with a 0.1% increase and INV+ET with a 0.05% increase. This result is explained by the rebound effect that an investment alone has on productivity, and the effect that an emissions tax and emissions quota have on shaping producers' supply response.

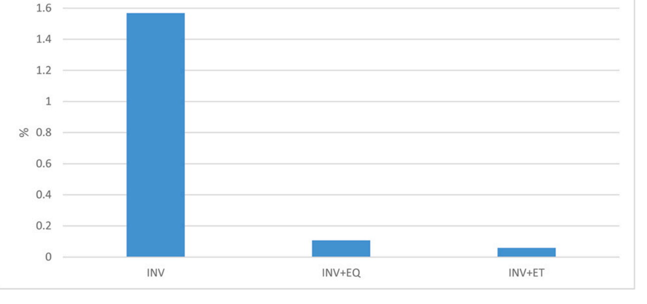

Fig. 6. Methane emissions from enteric fermentation (% level deviation from the base in 2030).

5. Sensitivity analysis

As in other simulation models, LPSM results depend on the values of the employed behavioural and economic parameters, such as price and income elasticities; therefore, analysing the sensitivity of results to selected parameter values is often informative. This section systematically tests the sensitivity of our results to all elasticities simultaneously. We analyse the sensitivity concerning all model elasticities of simulated results for two significant indicators: private consumption and investment and dairy output. To do so, we implement a variant of the method proposed by Harrison and Vinod (1992).

We assume that each model elasticity is uniformly distributed around the central value used to obtain the results presented in the main text. The range of variation allowed for each elasticity is + /– 75%; i.e., we consider a relatively wide range of variation for each model elasticity. The model is solved iteratively with different sets of elasticities, and the resulting distribution of results is used to build confidence intervals for selected model results. The steps for the systematic sensitivity analysis are as follows.

i. The distribution (i.e., lower and upper bound) is computed for each model parameter to be modified: elasticities of substitution between the primary factor of production, trade-related elasticities, price elasticities for household demands and wage curve elasticity.
ii. The model is solved repeatedly with a different set of elasticities following a Monte Carlo-type procedure. First, the value for all the model elasticities is randomly selected. Second, the model is calibrated using the selected elasticities, and third, the same counterfactual scenarios as previously described are conducted.

These steps are repeated 1000 times, with sampling with a replacement for the value assigned to the elasticities. Table 3 shows the percentage changes in private consumption and investment, respectively; the results were estimated (i) under the central elasticities and (ii) as the average of the 1000 observations generated by the sensitivity analysis. The upper and lower bounds under the normality assumption were also computed for the second case.

Table 3
Systematic sensitivity analysis: 95% confidence interval under normality assumption for consumption and private investment in 2030 (% change from the base).

	Consumption			Private Investment		
Item	INV	INV+EQ	INV+ET	INV	INV+EQ	INV+ET
Central elast	0.166	0.151	0.127	0.037	0.145	0.422
Mean	0.168	0.146	0.128	0.045	0.145	0.411
Standard dev	0.018	0.015	0.011	0.042	0.036	0.038
Lower bound	0.134	0.12	0.106	-0.037	0.075	0.336
Upper bound	0.203	0.18	0.150	0.127	0.215	0.486

Fig. 7 show non-parametric density function estimates for the percentage change in private consumption and investment in 2030, respectively. In all cases but one, both the sign of the results and their relative magnitudes are not altered when we allow the elasticities to differ by + /– 75% of the value used for the estimates presented in the paper's main text. In the INV scenario, we found that private investment might decrease under a particular set of elasticities; specifically, private investments might decrease when production and trade elasticities for the livestock sector are close to zero (i.e., it is more difficult for the livestock sector to adjust its production and trade). However, such a result would be based on implausibly low production and trade elasticities.

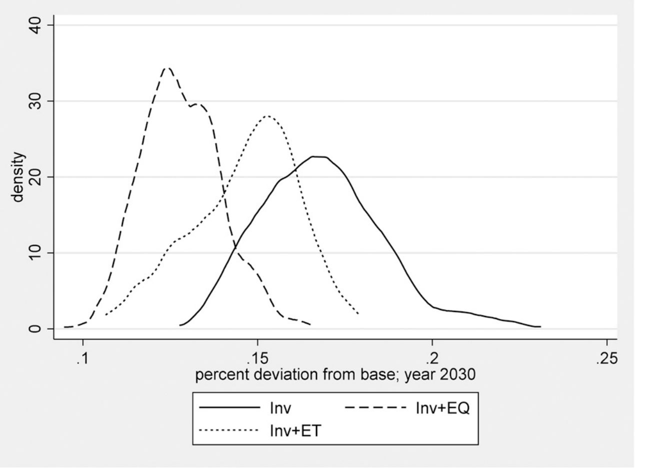

Fig. 7. Sensitivity analysis results: Non-parametric estimate of the density function for the percentage change in real private consumption in 2030.

Fig. 8 show that the results reported in the main text are within the confidence intervals depicted in Table 3. For example, if TFP increases with an emissions tax (scenario INV+ET), consumption will almost certainly increase between 0.11% and 0.17%. In other words, the results in Tables 3 and 4 show that the model is robust regarding the elasticity parameters, as the deviation from the results in the main text is relatively small for the selected indicators.

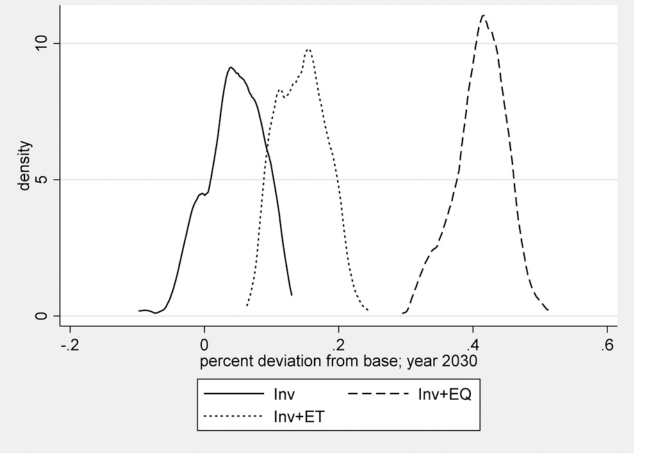

Fig. 8. Sensitivity analysis results; non-parametric estimate of the density function for the percentage change in real private investment in 2030.

6. Discussion

This section synthesises and discusses the main transmission channels under the INV, INV +ET and INV+EQ scenarios. As observed, the transmission channel can differ based on the scenario and the sign of the effects.

Under the INV scenario (Fig. 9), the productivity increase boosts dairy production, reducing prices and releasing factors of production for use in other sectors. Given the lack of reliable data, we are not interested in explicitly modelling the source of TFP increase; thus, we implicitly assume a spending reallocation exists in the system, allowing financing of a public investment that increases TFP. Notwithstanding its origin, an increase in TFP has a clear effect in this model. It traduces into an increased output, coupled with a consequent decrease in prices and a reduction in the amount of labour and capital used in that sector, and a release of factors for use in other sectors. The increase in the supply of dairy output decreases its real price since demand increases are generally less than the increase in supply. The overall effect on wages, employment and household welfare is positive, which increases private investments and, consequently, total GDP.

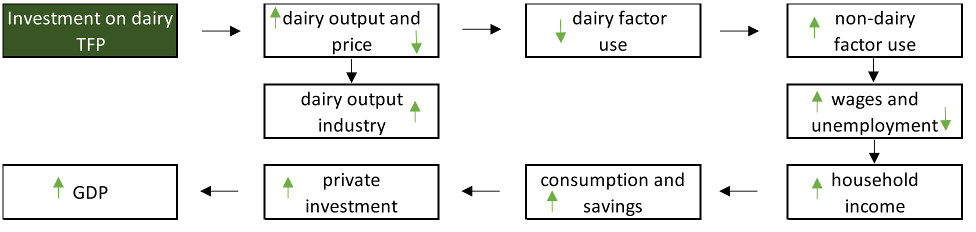

Fig. 9. Main transmission channels for the INV scenario.

In the INV+EQ scenario (Fig. 10), the investment is combined with a quota on emissions from dairy production. The effect of the quota is two-fold. On the one hand, the quota decreases the output of the dairy primary sector and increases demand and prices; on the other hand, the generated quota rents increase enterprises' income and savings. Consequently, there is a positive impact on private investment and growth and a reduction in emissions.

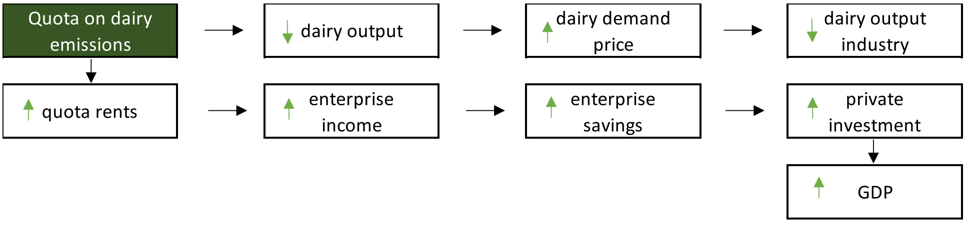

Fig. 10. Main transmission channels for the scenario INV+EQ.

Finally, under the INV+ET scenario (Fig. 11), the investment is combined with an emissions tax. The additional tax revenue reduces the direct (income) tax rate. We assume that the tax collection goes to the government under the supposition that government receipts and spending remain constant. The tax has the same effect as a quota on total output and prices, respectively decreasing and increasing; however, the additional tax revenue is used to reduce the direct

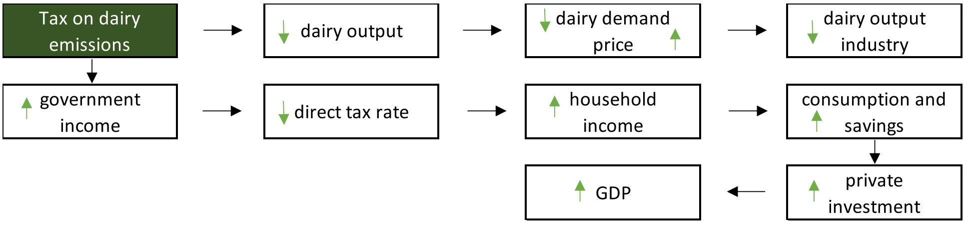

Fig. 11. Main transmission channels for the scenario INV+ET.

(income) tax rate, which, by increasing households' disposable income, positively affects consumption, savings and private investments, generating an increase in total GDP.

7. Conclusion

We employ the LPSM and use Uruguay's dairy sector as a case study to compare the effect of reducing methane emissions in the dairy sector using different market-based instruments. We build different scenarios to assess the broader economic, social and environmental effects of combining different MBIs, namely, an investment alone (INV), an investment with an emissions quota (INV+EQ) and an investment with an emissions tax (INV+ET).

The results show positive and negative spillovers under the different policy scenarios. For example, INV leads to higher employment generation, household consumption and poverty reduction, but it is also the scenario that generates higher total methane emissions. INV+EQ can partially help control the increase in emissions, contributing to GDP gains and private investment; however, it significantly reduces employment in the primary dairy sector. Finally, INV+ET leads to the highest control in the rise in GHG emissions but at the cost of lower performance in the other macroeconomic indicators, compared to the second scenario. The sensitivity analysis shows that the results reported are within the confidence intervals built, highlighting the robustness of the elasticity parameters.

These results have important policy implications showing that there is no one-size-fits-all solution, and welfare outcomes differ depending on the type of policy instruments employed. A policy mix, which includes a set of market-based policy instruments, can be more effective than using a single policy instrument alone. The analysis also illustrates the capacity of LPSM to integrate economic, social and environmental dimensions while quantifying spillover and trade-offs.

Code availability

The codes that supportthe findings of this study code can be downloaded from https://github.com/mcicowiez/LPSM/raw/main/GEM-LPSM-in-GAMS.zip.

Data Availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request.

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