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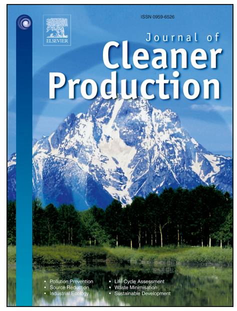

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Greenhouse gas abatement strategies and costs in French dairy production

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Abstract

The French dairy sector—like the rest of the economy—has to address the challenge of mitigating greenhouse gas (GHG) emissions to curb climate change. Deciding the economically optimal mitigation level and mix of abatement strategies requires knowledge on the cost of reducing GHG emissions. Agricultural bio-economic models can help identify which production-system changes are needed to reduce GHG emissions at different levels of incentives at minimal cost. The results reflect the model structure and parameter set, especially for GHG emissions accounting. Here abatement strategies and related costs for several levels of tax on GHG emissions in French dairy production are compared using four bio-economic models: the three supply models AROPAj, ORFEE and FARMDYN and the global partial equilibrium model GLOBIOM. It is found that between 1% and 6% GHG emissions abatement can be achieved at the current price of the EU allowances without substantially reducing milk production or outsourcing input production such as feed or herd renewal. Costs reflect the planning horizon: mitigation is more expensive when past investments are not amortized. Models that account for demand-side factors show a carbon tax has potential negative impacts on consumers through higher milk prices, but could nevertheless partly offset the reduction in income of farmers simulated by farm models. Model results suggest that promising on-farm GHG emissions abatement strategies include measures that let animals reach their full production potential and moderately intensive land management.

Highlights

- GHG abatements simulated by three supply farm models and one partial equilibrium model
- 15% milk price increase and considerable decrease in profits found at 100€/tCO_2eq tax
- 1% to 6% and 4% to 15% abatement found resp.at 20€ and 100€ tax with limited outsourcing
- Up to 70% GHG abatement found at 100€/tCO_2eq tax if the carbon tax is not embodied in trade
- Up to 15% GHG abatement found with productive dairy cows raised on low-input forages

Keywords

Greenhouse gases, bio-economic farm model, partial equilibrium land-use model, abatement cost, livestock

1 Introduction

Anthropogenic activities generate greenhouse gas (GHG) emissions that drive major global climate change. As the impacts of these GHG emissions are not reflected in product prices, they are considered a negative externality. According to Bithas (2011), the internalization of environmental externalities is a necessary condition for sustainability. Economic-environmental instruments such as taxes and subsidies, incentives to invest in greener technologies, or permits are all designed to modify market signals to make polluting goods and technologies less attractive. The EU Emissions Trading System (EU-ETS) caps the total amount of certain GHG that can be emitted by companies covered by the system (European Commission, 2019). These companies receive carbon permits that can be traded. Agriculture is not covered by the EU-ETS, despite the fact that it ranks as third biggest GHG emitter at EU-27 level. The French agricultural sector accounted for about 17% of French GHG emissions in 2016 (EEA, 2018). More than a third of the French agricultural GHG emissions stem from methane, a third of which comes from dairy cattle (EEA, 2018). France is the second largest milk producer in the EU.

Conversely to the sectors currently covered by the EU-ETS where emissions can be relatively simply derived from input use of fossil energy carriers, GHG emissions from agricultural sectors are non-point emissions resulting from many diffuse sources, mostly not CO_2. These emissions are hard to measure on real farms and depend on a complex interplay of location factors such as soil and climate and the chosen production technology. Indicators such as the ones proposed by the IPCC (2006) circumvent these difficulties, but it may not be feasible to use more accurate indicators (Lengers et al., 2013), which explains why European agriculture is not yet integrated in the EU-ETS (Monni et al., 2007). With increasingly ambitious GHG emissions reduction targets but shrinking abatement potentials in non-agricultural sectors, a closer look at the potential GHG emissions savings in agriculture and related costs seems warranted. Whether and how much the dairy sector should contribute towards reduced GHG emissions depends mainly on the economics of dairy GHG emissions abatement costs relative to other sectors. De Cara and Jayet (2011) ran simulations showing that a reduction around 10% of EU agricultural GHG emissions could be obtained with a carbon price at around 35€/tCO_2eq. Pellerin et al. (2017) find that an abatement of at least 10% for the French agriculture could be even cheaper with ⅔ of the mitigation strategies costing less than 25€/tCO_2eq. However, other analyses shows less optimistic results. Mosnier et al. (2017b) ran simulations for typical French dairy farms showing that a tax of 40€/tCO_2eq would only reduce GHG emissions per kg of milk by less than 5%. Lengers et al. (2014) ran simulations showing that to abate 10% of GHG emissions in a typical German dairy farm would require a carbon price if over 100€/tCO_2eq. Vermont and De Cara (2010) showed that marked variability in abatement costs can generally be attributed to methodological differences such as model categories, temporalities, and flexibilities in allocating resources, GHG sources or carbon prices. Povellato et al. (2007) also underlined that any single approach cannot even start covering all the complexity involved.

This paper aims to inform policymakers on GHG emissions abatement strategies and costs in French dairy production and highlight how model and scenario assumptions impact results. The novelty of this study is that different models are used in order to assess the impacts of these strategies 1) both at farm level and market level, 2) for different French geographical contexts and at national level including trade impacts, and 3) on a specific branch of production to emphasize the impacts of model assumptions.

Abatement costs and strategies simulated by four different optimization models are compared. Optimization models are particularly appropriate for this purpose, as they can endogenously simulate the most cost-effective mix of potential abatement measures and re-design production systems. The selected models jointly capture to a large extent the type of models used for this type of analysis: the global partial equilibrium land-use model GLOBIOM (Havlík et al., 2014), the aggregate linear programming model AROPAj (De Cara and Jayet, 2011) describing the behavior of a set of representative farms, and finally two high-technological-detail single-farm models, ORFEE (Mosnier et al., 2017a) as a static model and FARMDYN as a dynamic model (Lengers et al., 2014). These models have already been used elsewhere to assess mitigation potential in dairy production (but not exclusively). Here increasing levels of tax on GHG emissions are simulated in all these models to determine marginal abatement cost (MAC) curves that inform on the costs of an additional unit of emission reduction at the given emission level and pinpoint related cost-effective mitigation strategies.

2 Methodology

Model description

2.1.1 Overview

All four models considered in this study (Table 1) are optimization models based on neo-classical economic theory, where economic agents are supposed to maximize profits (Figure 1).

Table 1. Main model characteristics

	GLOBIOM[a]	AROPAj[b]	ORFEE[c]	FARMDYN[d]
Owner	IIASA	INRA	INRA	University of Bonn
Model type	Partial equilibrium	Supply	Supply	Supply
Scale	Production system	Farm group	Single farm	Single farm
Regional scale	World, for Europe at NUTS-2 level	EU, at NUTS-2 level	Some French regions	Some German regions, here parameterized for the same French case studies as ORFEE

Model type	Linear	Mixed integer linear	Mixed integer linear	Mixed integer linear
Temporal scale	Recursive-dynamic in decadal steps	Static, annual	Static (one year with a monthly level of disaggregation)	Dynamic in annual steps with a monthly level of disaggregation
Production system	Cattle, sheep and goats, swine, poultry, crops, grassland, forestry	Cattle, sheep, goats, swine, poultry, crops and grassland	Cattle, sheep, crops and grassland	Cattle, swine, crops and grassland, biogas
Decision variables	Extent and location of crop area and livestock herd per system, trade and final demand quantities	Herd sizes and feed mix, crop acreages and crop management	Herd sizes and feed mix, crop acreages and crop management, types of machinery and buildings, contract work	Herd sizes and feed mix, crop acreages and crop management, use of on/off farm labour, investments in building and machinery,
Building and machinery cost	Implicit calibrated cost	none	Depends on type of equipment, per unit cost and min. fixed cost per equipment.	Returns to scale depicted by integers, initial endowments lead to sunk costs
Labour (cost)	Implicit calibrated cost	none	Depends on herd sizes crop operations, type of equipment and contract work. Constrained to monthly labour availability	Bi-weekly labour constraints with option to work off-farm (integers, reserve wage); amount of fixed labour to manage farm and branches
Objective function	Sum of producer and consumer surplus	Sum of gross margins	Risk utility function: here, mean-variance of net operating profit	Net present value of profits over simulation horizon, here 20 yr

Notes: more details are available at: [a] *Havlik et al. (2014) and Supplementary Material 1*
[b] *https://www6.versailles-grignon.inra.fr/economie_publique/Media/fichiers/ArticlAROPAj , version V5*
[c] *Mosnier et al. (2017a) and Supplementary Material 2*
[d] *http://www.ilr.uni-bonn.de/em/rsrch/farmdyn/farmdyn_e.htm , version of 2017*

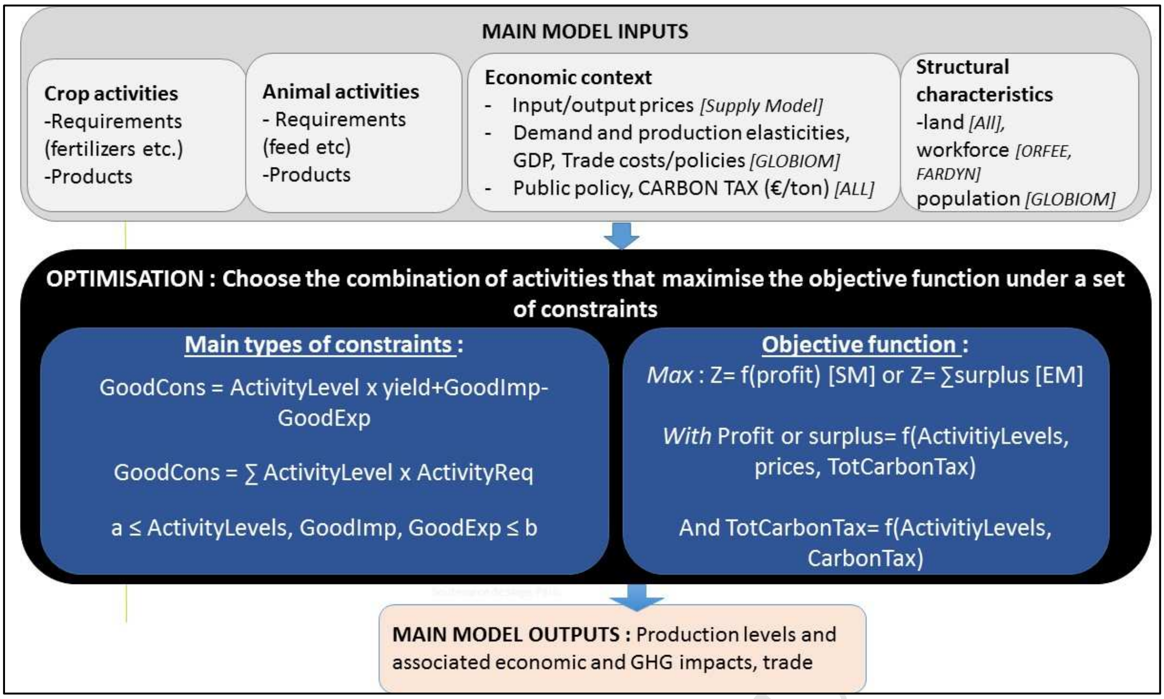


Figure 1: General structure of the optimization models.

Notes: GoodCons, Goodimp, GoodExp: quantity of a given good consumed, imported (purchased), exported (sold); ActivityLevel and ActivityReq: quantity of each crop or animal activity produced and their requirements in goods (or in some goods-related elements); a,b: bounds such as land availability, non-negative variables etc.

SM: Supply model, EM: Equilibrium Model

GLOBIOM-EU (Frank et al., 2015) offers a more detailed representation of the agricultural sector in EU countries. GLOBIOM-EU is a global partial equilibrium model that covers crops, livestock and forestry activities at the sub-national level and markets at each EU country level. AROPAj covers the main EU agricultural production systems aggregating farm types based on the Farm Accounting Data Network (FADN) classification. The FADN collects accountancy data from a representative sample of thousands of agricultural holdings in the European Union by crossing economic and technical orientations of each farm. Decisions in AROPAj and GLOBIOM, are optimized at NUTS 2 level for Europe (Eurostat, 2019). The NUTS classification is a system for dividing up the economic territory of EU in order to produce regional statistics. France is divided into 27 NUTS-2 regions. FARMDYN and ORFEE are single crop–livestock farm models first developed for Germany and France, respectively. In this study, all models focus on French dairy production.

GLOBIOM optimizes production (acreages and herd sizes), trade and consumption decisions to maximize the sum of producer surplus which refers to the benefit for selling the goods and consumer surplus minus trade costs. The consumer surplus is the difference between cost of the goods and the price they were willing to pay for them. It is the only one of the four models to feature endogenous consumption quantities and output prices.

AROPAj, ORFEE and FARMDYN are supply-side models with given exogenous prices. They all simulate decisions of farmers by assuming they optimize a profit function. These decisions encompass crop acreages, herd sizes, feed mix, and fertilizer applications. AROPAj maximizes the weighted sum of gross margin each farm type. Gross margins are defined from outputs multiplied by market prices, variable costs of production and policy support. ORFEE maximizes a risk utility function based on a mean-variance approach in relation to profits under price variability. Profit is calculated as gross margin minus depreciation and financial costs and labour costs. Type of farm machinery and buildings used also serve as decision variables. FARMDYN maximizes the discounted sum of profit over the planning horizon where the timing and cost of investments are taken into account.

The modeling of adaptations over time differs. AROPAj and ORFEE do not simulate farm trajectories but only endpoints. AROPAj assumes that capital is practically fixed, and so the endpoint is thus at short to mid-term. ORFEE can consider either a short-term horizon if capital endowments are constrained to the initial situations or a long-term horizon if capital endowments are freely optimized, assuming that the current equipment will be completely depreciated. GLOBIOM simulates different points between the startpoints and endpoints considering changes in demand, productivities, diets, etc. It is solved with recursive–dynamic decadal steps. FARMDYN depicts the annual evolution between the initial and final states at farm level such that simulation results depend on the time horizon considered and on initial farm endowments.

2.2 Mitigation strategies considered

The different adjustment mechanisms taken into account by each model (Table 2) enable possibilities to reduce GHG emissions by: decreasing herd sizes, improving animal efficiency, improving manure management, modifying crop and forage production to reduce the use of fertilizers, to store more carbon and to provide better diets for animals.

Table 2. Adjustment mechanisms optimized by the model

	GLOBIOM	AROPAj	ORFEE	FARMDYN
Alternative to dairy and forage production	Crops, forest, fallow, other animals	Crops and fallow	Crops (except in permanent grasslands)	Crops (except in permanent grasslands)
Herd size and total milk production	Cow= ± 5% of change by agroecological zone (AEZ)	Cow= up to -15% of initial value	Cow*: Free or = production reference	Free
Milk production/cow	Constant by AEZ- allocation across AEZ is optimized	Fixed	Milk yield: 2 breeds × 3 yield levels	Milk yield: milk potential and below
Reproduction		-Purchase or produce replacement heifers	- 4 calving periods - Age at first calving - Breed	-Culling rate -Age at first calving
Animal feeding		Feed mix optimized in the model		
Crop and forage management	Tillage alternatives, allocation across NUTS-2 and production systems	Type of crop (cereals, forages, fallow), crop yield target	Type of crop (cereals, legumes, forages), crop rotation, 3 yield targets	Tillage alternatives, type of crop (cereals, forages, fallow)
Manure storage	Not considered	Not considered	Fixed	Optimized in the model
Demand	Elasticity = -0.3	Not considered, Fixed price		

**Two alternative scenarios were simulated: "Mountain" and "West" where milk production is free and "Mount.Q" and "West.Q" where milk production is fixed (farm-type reference level).*

2.2.1 Changes in herd sizes, production per animal and animal feeding

GLOBIOM-EU divides cattle farming into dairy cattle, replacement heifers, and other. The balance of the different categories is fixed on statistical data from the year 2000. One type of dairy production is defined per agro-ecological zone, which is defined as an area with similar climatic conditions (Appendix 1). Quantity of meat and milk produced per head and per year and quantity of feed consumed are defined as model inputs based on the RUMINANT model (Herrero et al., 2013). In France, dairy cows productivity ranges between 4064 kg milk/year/cow and 8187 kg milk/year/cow according to agro-ecological zone.

All farm models allow some extent of herd size adjustment. In ORFEE, two alternative scenarios were simulated with and without fixing the herd size. Dairy production can be optimized by modifying breed (Appendix 2), calving period and production objective to produce at below milk potential or delay first calving. In FARMDYN, milk production and replacement rate can be optimized up to the breed potential. The replacement strategies take into account the evolution of milk production according to animal age and year of birth. In AROPAj, it is not possible to modify breed or milk yield for a given farm, but the model can choose between producing or purchasing replacement heifers. In the supply models, the type and quantity of feed used by the different herds are optimized subject to requirement constraints. FARMDYN uses IPCC (2006) equations to define animal requirements based on net energy and crude protein in combination with minimal and maximal dry matter intake. AROPAj and ORFEE use the INRA feeding system (Inra, 2007), which is based on net energy available for milk or meat, digestible protein in the rumen and digestible protein in the intestine in combination with minimal and maximal dry matter intake. The calibration step in AROPAj refines the pre-estimated parameter sets that characterize feed contents and animal requirements.

2.2.2 Changes in land allocation and cropping management

In GLOBIOM-EU, European crop, grassland, forest, and short rotation tree productivity are estimated at NUTS-2 level. Three alternative tillage systems are included: conventional, reduced, and minimum tillage. Crop production is used for animal feed, human food and bioenergy. In AROPAj, crops and fodders, with up to 30 area categories depending on farming system, interact through “rotating” constraints and/or crop-specific thresholds. In ORFEE, crop and grassland production are defined based on expert knowledge and surveys. Emphasis is placed on providing a large variety of grassland management, on integrating effects of crop succession on crop yield and nitrogen requirements, and on proposing two or three levels of yield targets. In FARMDYN, there are five different intensity levels, between 20% and 100% of the normal level, for the amount of N fertilizer applied.

2.3 Estimation of GHG emissions and carbon storage

Methane emissions—the most important GHG in dairy systems—stem from enteric fermentation and excreta of animals. In all four models, methane emissions from enteric fermentation depend on feed intake. In FARMDYN and GLOBIOM, estimations are driven mainly by gross energy intake (Table 3). In ORFEE, the main drivers are quantity and digestibility of organic matter ingested, proportion of concentrate feed, and quantity of dry matter intake per kg liveweight (Sauvant et al., 2011). AROPAj uses an earlier version of the model developed by Sauvant et al. (2011) based on feed digestibility and gross energy. To estimate methane from excreta, all estimations are based on the IPCC (2006) Tier 2 method, which considers type of storage and local climate.

Table 3. Estimations of GHG emissions

	GLOBIOM	AROPAj	ORFEE	FARMDYN
N_2O-soils	Biophysical model	IPCC Tier 1	IPCC Tier 1	IPCC Tier 2
N_2O-manure mgt	IPCC Tier 2	IPCC Tier 2	IPCC Tier 2	IPCC Tier 2
N_2O-indirect	IPCC Tier 1	IPCC Tier 1	IPCC Tier 1 + Velthof and Oenema (1997)	IPCC Tier 1 + Velthof and Oenema (1997)
CH_4-manure mgt	IPCC Tier 2	IPCC Tier 2	IPCC Tier 2	IPCC Tier 2
CH_4-enteric	IPCC Tier 3	(Giger Reverdin et al., 1996)	(Sauvant et al., 2011)	IPCC Tier 3
C soils	Land use change Carbon in crop soils (EPIC)	None	Land use change and carbon storage in grassland	None
GHG emissions related to purchased inputs	None	None	Dia'terre (Ademe)	None

In all four models, N_2O emissions from manure management systems are proportional to the quantity of nitrogen excreted by animals and are differentiated according to storage type as per Tier 2 method (IPCC, 2006). Direct emissions of N_2O from managed soils are computed according to IPCC

Tier 1 (2006). They take into account manure spreading, inorganic N fertilization, and N deposited by grazing. Indirect N_2O emissions from atmospheric deposition of N volatilized from managed soil and leaching (NO_3^-) are taken into account in farm models.

Regarding carbon storage, in GLOBIOM, EPIC (2019) was used to simulate a carbon response function for each crop rotation, management system, simulation unit, and initial stock of carbon. It provides estimates for soil organic carbon in croplands and from land use change from natural land to cropland. In ORFEE, carbon sequestration in grassland and land use change from grassland to annual crops is accounted based on Soussana et al., (2010). Indirect CO_2e emissions of purchased inputs such as feeds and litter produced off-farm, non-organic fertilizers and purchased animals and direct emissions from the burning of fuels are estimated using life cycle assessment values from Dia'terre® (ADEME, 2010) version 4.5.

Emissions are aggregated into a single indicator of global warming potential (GWP) expressed in equivalent CO_2 (CO_2eq) using the 2007 IPCC GWP of each gas (GWP N_2O = 298, GWP CH_4 = 25) calculated at farm level. In GLOBIOM, only the emissions associated with the cropping area required to produce the feed for dairy cows and replacement heifers are included here in GHG estimate.

2.4 Carbon tax scenarios

There are three potential alternatives for simulating mitigation strategies in bio-economic models. Either a carbon tax can be introduced, or the optimization process can look for the optimal strategy under a target of climate change abatement. Both yield the same result at the points where the tax rate is equal to the dual value of the emission ceiling and thus deliver the same MAC curves. The third option is to only consider GHG estimates in model outputs. In this case, alternative production systems are either tested by fixing some decisions exogenously or else taken from the implementation of scenarios not directly involving GHG emissions. In this study, mitigation potential was simulated for three carbon tax levels: €20/tCO_2eq, €50/tCO_2eq and €100/tCO_2eq that were implemented as additional production costs or subsidies in the case of carbon storage (Table 4).

Table 4. Sources of GHG emissions taxed.

	GLOBIOM	AROPAj	ORFEE	FARMDYN
Sources of GHG emissions taxed	CH_4, N_2O, CO_2 *(LUC and crops)*	CH_4, N_2O	CH_4, N_2O, CO_2 *(inputs + grassland soils)*	CH_4, N_2O

LUC: land-use change

In GLOBIOM, taxes are in US dollars (2017 exchange rate €1 = $1.17). Taxes are applied at farm level, except in GLOBIOM in which the tax is implemented at EU level for the whole land-based system. The scenarios are compared with the business-as-usual (BAU) scenario which simulates how production systems would evolve under the same assumptions regarding the economic context, adjustment possibilities, etc. but without carbon taxation. Two contrasting types of farm are chosen for each supply model: one with high milk yield per cow and with a significant proportion of arable land in the western part of France ('West'), and one with lower milk yield per cow and little arable land in the Auvergne upland area of central France ('Mountain'). In AROPAj, these two farms are picked from among the farm groups specialized in dairy production based on the FADN. In ORFEE and FARMDYN, farms are parameterized based on the INOSYS farm types 'PL2B' in Western France and 'C17' in Auvergne (Idele, 2019).

3 Results

3.1 Optimal mitigation strategies simulated

For all the models, a reduction in animal numbers is simulated with higher CO_2eq tax levels (Table 5).

Table 5. Production-system adjustments with carbon tax level (change in % of BAU situation)

		GLOBIOM	AROPAj		ORFEE				FARMDYN	
	Carbon tax(€/t)	France	Mnt.	West	Mnt.	Mnt.Q	West	West.Q	Mnt.	West
Number of dairy cows *(head)*	***BAU***	***3.8 M***	***69*** [a]	***59*** [b]	***63***	***56***	***74***	***54***	***60***	***50***
	20	-1.3%	0%	0%	-7%	0%	-15%	0%	0%	0%
	50	-1.9%	0%	0%	-27%	0%	-51%	0%	0%	0%
	100	-3.5%	0%	0%	-30%	0%	-59%	0%	0%	0%
Pregnant heifers *(head)*	***BAU***	***2.5 M*** [c]	**19**	**10**	***15***	***13***	***27***	***19***	***7***	***9***
	20	-0.5%	-100%	-100%	-7%	0%	-15%	0%	2%	-9%
	50	-2.0%	-100%	-100%	-27%	0%	-51%	0%	-4%	-17%
	100	-3.6%	-100%	-100%	-30%	0%	-59%	0%	-7%	-26%
Milk yield *(t/dairy cow)*	***BAU***	***6.5***	***5.8***	***7.1***	***5.8***	***5.8***	***7.9***	***7.9***	***5.8***	***8.3***
	20	-0.1%	/	/	0%	0%	0%	0%	0%	0%
	50	-0.5%	/	/	0%	0%	0%	0%	0%	0%
	100	-0.9%	/	/	0%	0%	0%	0%	0%	0%
Spring calving (number of cows)[d]	***BAU***	**na**	**na**	**na**	**31**	**24**	**0**	**0**	**na**	**na**
	20	/	/	/	0%	0%	0%	0%	/	/
	50	/	/	/	56%	32%	0%	0%	/	/
	100	/	/	/	103%	32%	0%	0%	/	/
Mineral N application (Kg/ ha)	***BAU***	**na**	**na**	**na**	**20**	**13**	**37**	**43**	**23**	**77**
	20	-2%	0%	3%	-38%	-15%	12%	-25%	-4%	-1%
	50	-4%	-11%	3%	-69%	-14%	22%	-23%	-6%	-22%
	100	-6%	-60%	-21%	-68%	-46%	-4%	-23%	-24%	-43%
Productive grasslands for dairy production (ha)	***BAU***	**1668550**	**96**	**59**	**90**	**90**	**26**	**27**	**83**	**36**
	20	0.4%	-30%	0%	/	/	11%	6%	-1%	5%
	50	1.3%	-30%	0%	/	/	22%	26%	-10%	1%
	100	1.6%	-32%	0%	/	/	27%	32%	-17%	-6%
Consumption of concentrate feed (grain, meal etc. in t)	***BAU***	**na**	**na**	**na**	**76**	**61**	**134**	**72**	**33**	**31**
	20	/	na	na	-16%	0%	-30%	10%	0.5%	2%
	50	/	na	na	-42%	-8%	-61%	-3%	1.2%	3%
	100	/	na	na	-50%	-8%	-70%	-3%	2%	4%

*Note: / adjustment not possible, na: not available; [a] +1 suckler cow + 1 goat + 2 swine; [b] +4 suckler cows; [c] all heifers, [d] proportion of calvings between March and May; * change in ha (baseline = 0); Q: simulations with fixed milk production*

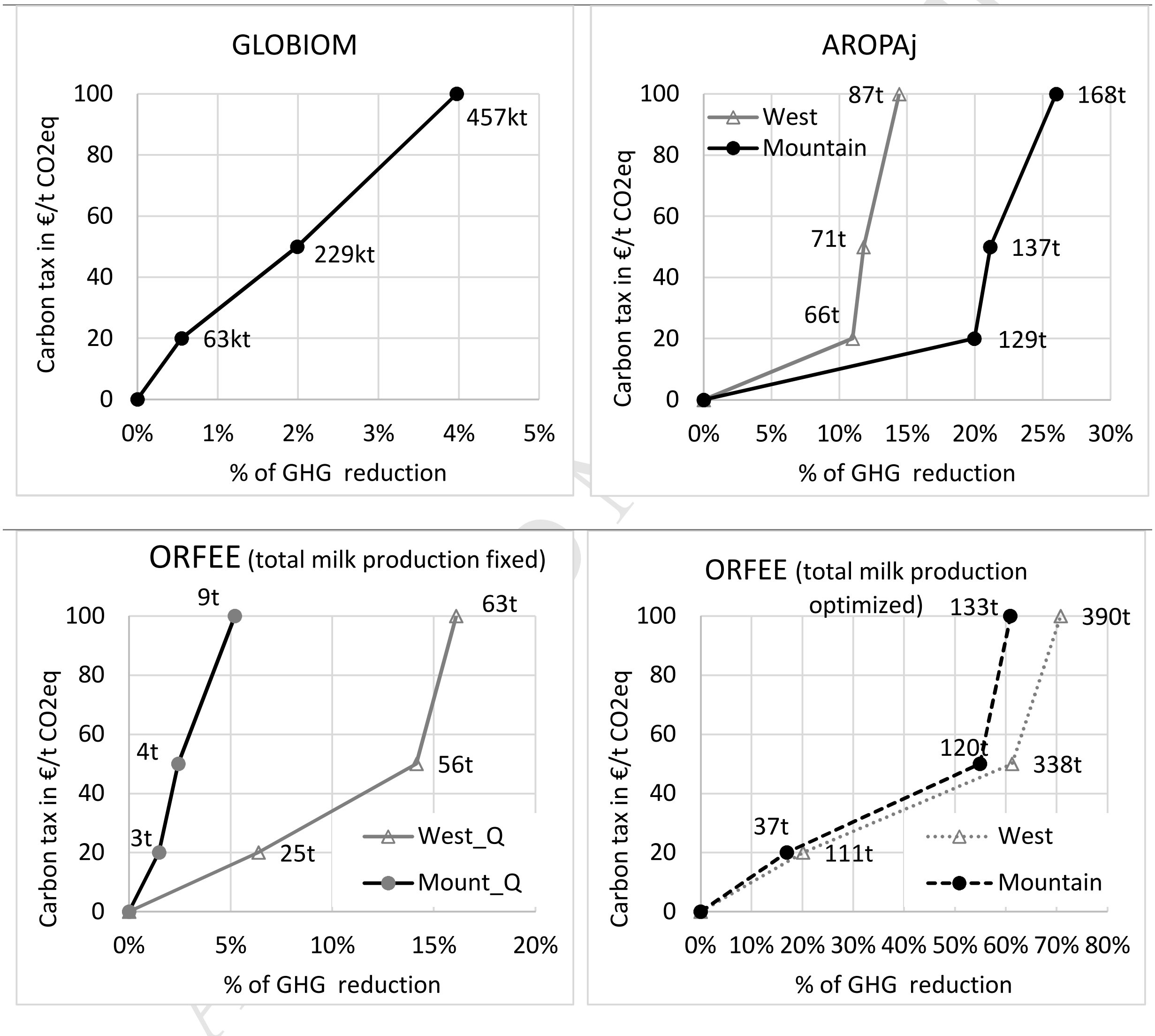
This is the most radical solution to reduce not only all emissions directly related to enteric fermentation and manure management but also emissions related to forage and crop production due to lower feed requirements. All animal numbers are reduced in some models including dairy cows at the expense of beef and milk production. This is the case for GLOBIOM with up to -3.5% of dairy cows for a 100 \$/tCO_2eq tax. For the same carbon tax level, ORFEE finds a stronger reduction of herd sizes of up to -60% whereas the other supply models find that dairy cow inventory is maintained. This higher reduction is linked to the fact that dairy cow marginal profit is much lower in ORFEE, which considers that labour, machinery and housing costs are approximately proportional to the number of dairy cows and thus consequently more sensitive to a carbon tax. Numbers of replacement heifers are reduced in AROPAj and FARMDYN. In FARMDYN, the rearing period is accelerated to let heifers enter the herd earlier in order to reduce the number of unproductive animals. In ORFEE, the youngest age possible at first calving is already reached in the BAU situation. For AROPAj, the rearing of replacement heifers is largely externalized, even at low levels of tax. The number of replacement heifers is divided by 5. This option was initially introduced with the aim of representing practice in some farms rather than reducing GHG emissions. In the 'West' farm under AROPAj, two out of the four suckler cows are eliminated to reduce emissions. Average milk yield is reduced up to 0.9% in GLOBIOM as dairy cows are reallocated to less productive areas. This corroborates the ORFEE results that show a stronger reduction of dairy cow numbers in the western part of France where more alternatives to ruminant production are available. Milk yields are not modified in the other models and are at their maximum values. Note that they were at their maximum potential before the implementation of the tax. In ORFEE, spring calving increases to i) increase fresh grass intakes that emit less methane during digestion than rough forages, and ii) reduces feed purchases which are associated with indirect CO_2 emissions (LCA).

To reduce fertilization-related nitrous oxide emissions, models can opt for technologies or crops requiring less nitrogen, or they can replace on-farm feed production by purchased feed. These two factors explain why the conversion of grassland into fallow, the reduction of wheat, and the marked increase in feed purchases are chosen by AROPAj. In FARMDYN, a reduction in fertilizer use related to the reduction in crop yield is also observed, the partial substitution of pasture by harvested grassland (silage), and the increase in fallow land. In ORFEE, corn is replaced by alfalfa and permanent grassland. ORFEE accounts for CO_2 emissions of purchased inputs and for carbon storage in grassland, which explains the expansion of grassland, particularly permanent grassland, which is assumed to store more carbon. This reduction is made at the expense of corn silage and is associated with maintained or increased levels of alfalfa and protein crops. The proportion of grazed-only pasture also increases, since fresh grass has better nutritional value than conserved grass. In GLOBIOM, the increase in carbon storage is explained by reduced tillage on croplands and by an increase in grassland caused by an increased proportion of grass in animal diet.

3.2 Marginal abatement costs and GHG emissions

GHG emissions are reduced in all the models in response to a carbon tax, but the MAC curves have different shapes according to the model (Figure 2). In GLOBIOM, the abatement rate is almost constant at 0.04% of abatement per additional euro of tax per tCO_2eq. Emissions are reduced linearly with herd reduction. In AROPAj, the externalization of feed and replacement heifer production leads to higher emission reduction at already-low tax levels. In ORFEE, the highest abatement rate corresponds to the greatest herd size reduction. It reaches up to 70% for a 100 € CO_2eq tax. The abatement rate is far smaller when milk production is maintained: between 2 and 7% for 20 € CO_2eq tax and between 5 and 16% for 20 € CO_2eq tax. This is closer to the range simulated by GLOBIOM: 0.5% and 4% respectively. for a 20€ and 100€ CO_2eq tax and FARMDYN: between 1 and 2% and between 8% and 14% respectively. for a 20€ and 100€ CO_2eq tax. In FARMDYN, the 'Mountain' MAC curve is not linear and its inflexion point corresponds to the reduction of age at first calving.

The reduction of GHG emissions per kg of milk produced depends on mitigation options used, emission sources or sink considered, and GHG accounting frame (Figure 3). In the BAU scenario, methane emissions are lowest in GLOBIOM with 0.45 kg CO_2eq/kg milk and highest in AROPAj with between 0.91 and 1.12 kg CO_2eq/kg milk, with FARMDYN (between 0.44 and 0.60) and ORFEE (between 0.62 and 0.73) giving intermediate values. These differences are explained by the methane estimation method (CITEPA, 2019) and the amount of feed consumed per animal, which is smaller in GLOBIOM than ORFEE (Appendices 1 and 2). The rough division of all GHG emitted by the quantity of milk produced can also explain why AROPAj, which also considers some other ruminants on both farms, gives higher methane values. The reduction of methane emissions in response to a 100 € tax depends first on the reduction of unproductive animals e.g. heifers and, in AROPAj, other ruminants per productive cow and second on changes in animal diets. These gains reach up to 25% of BAU-scenario methane estimate in AROPAj and 15% in FARMDYN, but no more than 5% in ORFEE which only modifies diets. In GLOBIOM, methane emissions only increase by 0.5% with the reduction of average milk yield.



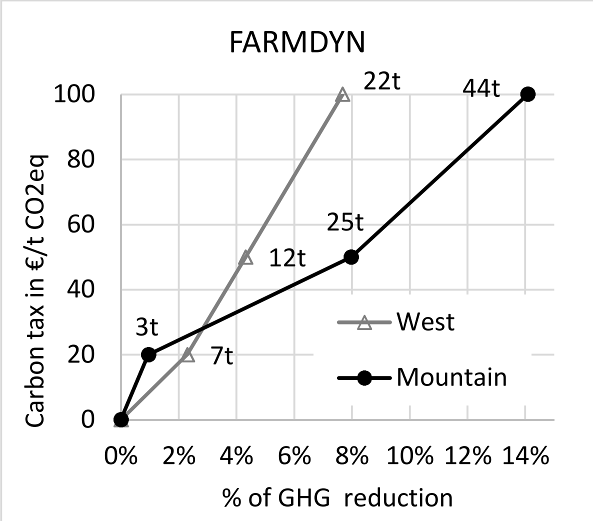


Figure 2. Marginal abatement cost curves: GHG reduction according to carbon tax level (in % and in quantity of GHG emissions in business-as-usual scenarios).

Regarding nitrous oxide emissions, differences in the BAU scenarios are explained by different levels of fertilization, types of manure and proportions of cash crops produced. In the 100€ tax scenario, the proportion of N_2O per kg of milk is reduced up to 20% in AROPAj, up to 13% in FARMDYN, and up to 9% in ORFEE due to fertilization reduction. In ORFEE 'West' farm, parallel to the reduction of herd size, the increase in cash-crop area leads to a higher amount of mineral fertilizer applied at farm level and per kg of milk produced. ORFEE accounts for CO_2 emissions linked to the purchase of inputs, which are almost as high as nitrous oxide emissions and account for 20% of total emissions. The simulated mitigation strategies can reduce these emissions by up to 37% if herd size is reduced but by just 8% if herd size is maintained. Carbon sequestration in grassland accounts for a significant proportion of the GHG emission balance in ORFEE. Quantity of carbon sequestered per kg of milk increases if herd size decreases and/or if some forage crops are substituted for grasslands. Land use change and carbon sequestration in croplands represent a fairly small proportion of GHG emissions related to the French dairy sector in GLOBIOM (7%).

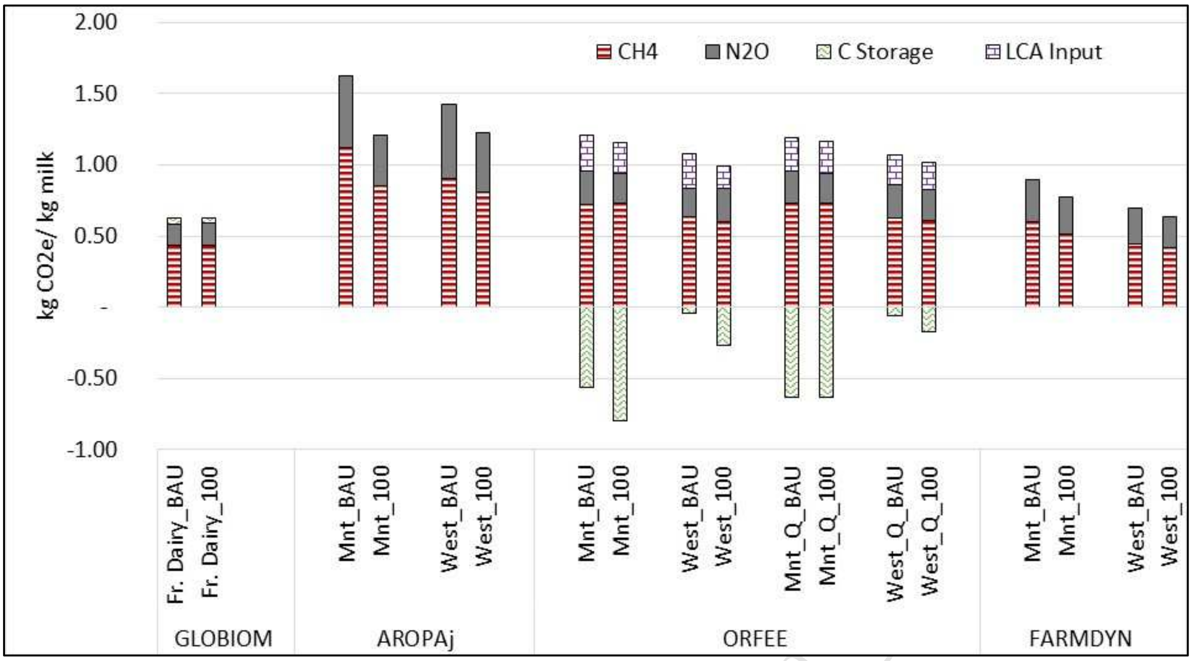


Figure 3. GHG emissions per kg of milk for BAU and 100€ CO_2 eq **tax scenarios.**

3.3 Impacts on the milk market

In GLOBIOM, the tax reduces both production and consumption in France by about 4.5 % for a 100 € carbon tax (Figure 4), which means the tax has little effect on trade. Dairy production in the other EU countries is defined in the same way as in France and has similar marginal abatement costs, and is consequently impacted at similar levels of magnitude. Furthermore, in the calibration year (2000), France only imported milk from Eastern Europe and only in relatively little quantities. GLOBIOM features some barriers to trade, making it possible, but costly, to create new trade flows, which might explain the limited changes in imports. The decrease of supply caused by the tax drives milk prices up (Figure 5). For a tax of 100 \$/tCO_2eq, the increase in milk price is around 40 \$/t milk which is equivalent to a 15% increase of the baseline price. Since GLOBIOM estimates average emissions at 0.63 tCO_2eq/t milk, almost ⅔ of the tax is transferred to an increase in milk price, which is consequently quite high. This is explained by a relatively low elasticity of demand (0.3) and limited possibilities to adjust production technology and trade.

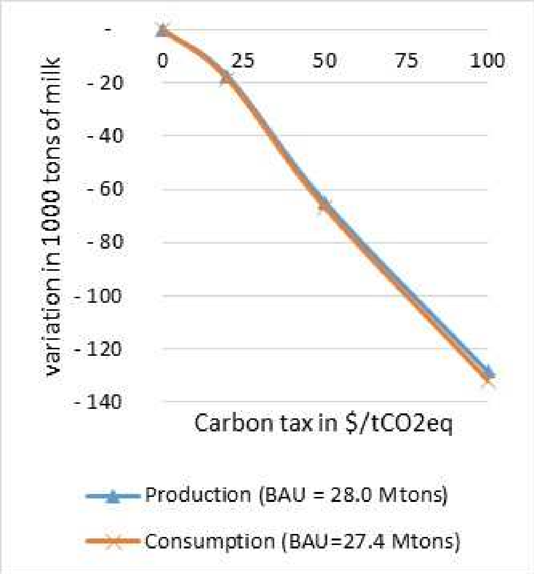


Figure 4. Evolution of milk production and consumption in France in GLOBIOM

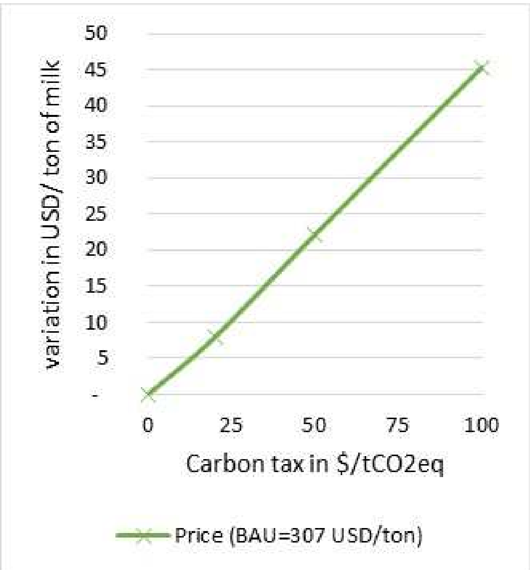


Figure 5. Evolution of milk price in France in GLOBIOM

3.4 Impacts on farm profit

Profit loss at farm level results to a large extent from the implementation of the tax by itself and to a small extent from adaptations of the production system that either drive additional costs and/or reduce receipts due to reduced production (Table 6). This means that there is little room for farmers to avoid the tax other than by drastically reducing herd sizes. It is clear that with a 100 €/tCO_2eq tax, there will be little money left to pay farmers for their work. However, as shown in Figure 4, profit loss can be partly offset by macro-economic adjustments of prices.

Table 6: Total GHG emissions and economic indicator values for BAU and 100€ carbon tax scenarios

	GHG emissions *(tCO2eq)* in BAU	Economic indicator (k€/yr) [a]	
		BAU	*Reduction*
AROPAj – Mountain	647	181	52 *(Tax= 47.9 k€)*
AROPAj – West	601	160	53 *(Tax=51.5 k€)*
ORFEE Mount.	218	43	22 *(Tax=8.5 k€)*
ORFEE Mount.Q [b]	169	39	16 *(Tax=16.0 k€)*
ORFEE West	551	55	48 *(Tax=16.1 k€)*
ORFEE West.Q [b]	393	44	35 *(Tax=32.9 k€)*
FARMDYN Mount.	312	46	28 *(Tax=26.8 k€)*
FARMDYN West	286	65	35 *(Tax=26.4 k€)*

Note: [a] Gross margin in AROPAj, operating profit for ORFEE and FARMDYN (=gross margin – structural costs – depreciation and financial costs); Objective function differs from this indicator of profit, so that profit loss in the 100€ tax scenario is sometimes higher than a 100€ tax applied to GHG emissions in the BAU scenario. [b].Q: simulations with fixed quantity of milk sold.

4 Discussion

Vermont and De Cara (2010) conclude their review on marginal abatement costs in agriculture by stating that "studies that account for market feedbacks of mitigation policies through partial or general equilibrium effects report a higher abatement rate for a given emission price". Here the opposite is found. This suggests that differences in abatement levels at a given tax rate depend more on assumptions regarding costs and flexibility to modify the production system than on type of model. High flexibility results from having broad options for adapting the system to carbon taxes at low cost. Kuik et al. (2009) distinguish "where", "when" and "what" flexibilities. Models assuming a high "where" flexibility, meaning that inputs or outputs can be produced outside the system to avoid the tax, achieve the highest abatement rates, up to -70% in ORFEE scenarios when milk production is allowed to decrease, up to -25% in AROPAj due to the externalization of heifer and feed production, for a moderate carbon tax. If a tax is implemented within a delimited system, one strategy to reduce GHG emissions is to partially or totally externalize the production process into a non-tax part. Although leakage occurs when one region has a less stringent environmental policy than another

(Frank et al., 2015), some simulated leakages such as feed production in supply models would not occur at large scale in the real world without increasing their price, either directly due to the tax or indirectly through market adjustments. The implementation of LCA data in ORFEE partly overcomes leakage by considering emissions from the purchased inputs. This option has a strong impact on model results, as a reversal is observed: a reduction of the purchased inputs and animal stocking rate in line with previous farm level analysis (Adler et al., 2015). LCA is a valuable approach when the primary objective is to identity a strategy to reduce GHG emissions at farm level while avoiding pollution leakage. Nonetheless, it remains economically biased, because the increase in input price will not be equal to the tax applied, since (i) marginal and average emission factors are not equal, and (ii) prices depend on both supply and demand. In addition, it does not prevent externalization of the whole production process by lowering production levels.

In GLOBIOM, emission leakage associated with the externalization of inputs and outputs is accounted for in the optimization program through the global and sectoral approach. Similar to Neufeldt and Schäfer (2008), production is reduced. The simulated reduction of milk output directly impacts consumption. It does avoid leakage, but it also leaves questions hanging over the impact of this change on human diet and health (Hasegawa et al., 2018). This reduction of milk consumption –which here is relatively small- may increase the demand for other products that may leave a larger carbon footprint if mitigation policies are applied only unilaterally on specific products, sectors or regions. GLOBIOM also simulates a sharp increase in milk prices. That price increase could be fed back into the farm-scale models where, at a given tax rate, simulations would lead to a lower reduction of herd size and lower economic losses, which implies higher MAC but without changing the cost-efficiency ranking of the simulated strategies.

The “when” flexibility can be related to the transition or adjustment costs included in the model. Once buildings and machinery have been purchased, they can be considered as sunk costs. Capital is near-fixed in FARMDYN scenarios because the dynamics of investments are included and fixed in AROPAj. These models generate a herd structure that is less sensitive to a carbon tax than ORFEE scenarios which, here, considered capital and labour as fully variable based on annualized costs. This hints at differences in short and long-run abatement costs at business and consequently also sectoral level.

The “what” flexibility should be replaced by “how” in the context of this study, since it was set out to pinpoint what abatement options will be used within the dairy cattle system. The range of options considered in the different models has significant impacts on the MAC curves. Apart from strategies resulting in a reduction of crop and animal production per unit of land, milk yields tend to increase with the tax, if not already at maximum potential in the baseline. This corroborates previous findings (Monteny et al., 2006) that improving animal efficiency through faster growth or higher milk yields will reduce methane production per unit of product. However, GLOBIOM simulations led to a reduction in the proportion of the most productive cows. This is explained by a geographical reallocation of production and by the incentive to store carbon in soils. The incentive to store carbon in soils and the lack of dairy production alternatives also explains why, first, increasing the proportion of grassland emerges as an efficient strategy in ORFEE, and second, why dairy production is more strongly reduced in areas suitable for cash crops. There are also studies which assume, unlike the optimization models used here, where farmers are assumed to always operate on the efficient frontier, there are also other studies that assume that pressure to abate emissions can shift inefficient farmers towards the technical and economic efficiency frontier. In GLEAM (Global Livestock Environmental Assessment Model) for instance, around 33% of emissions are mitigated while maintaining constant output, based on the assumption that producers in a given system were to apply the practices of the 10th percentile of producers with the lowest emissions intensities (FAO, 2019). Pellerin et al. (2017) also estimate that lengthening the grazing period or increasing the proportion of legumes on the grasslands could reduce both emissions and production costs. Further promising strategies were not introduced in the models studied, and might have further increased the abatement rates. They include the improvement of grassland and grazing managements to store more carbon or limit nitrous oxide emissions (Luo et al., 2010), limit fertilizer and fuel consumption, grazed intercropping to reduce tillage, fertilization and conserved forage consumption, and unsaturated fats and additives in animal diets.

5 Conclusion

This analysis compares mitigation strategies and abatement costs in dairy production across four economic models to shed light on abatement potential and costs and the related uncertainties.

Model results suggest that up to 15% of GHG abatement could be achieved with the following strategies: (1) let animals reach their full milk yield and calving potential, (2) feed them with low-input forages such as grassland, legume crops and (3) reallocate dairy production to areas less favourable to cash crops. It was also found that little GHG abatement (between 1% and 6%) can be achieved at the price of 20€/tCO2e, a price close to the current price of EU allowances which fluctuates around 25 €/t CO2eq, without substantially reducing milk production or outsourcing input production for feed and herd renewal. This abatement range between 4% and 15% for a 100€ tax. It can be concluded that dairy production is not a sector where integration into the EU-Emission Trading System is advantageous. Streamlining climate change policies with other common agricultural policies, such as green direct payment, agri-environment climate measures or nitrate directive seems more efficient.

This study finds advantages of co-using different economic models for systematic comparison, to gain insight into different drivers of adjustment, and cover a wider range of mitigation strategies. Both supply models and partial equilibrium model highlight key aspects for policymaking. On one hand, a considerable decrease in profit is simulated for high tax level, highlighting the risk that some farmers might be pushed out of production. On the other hand, the results from the partial equilibrium model show that the decrease of milk production increase milk price and thus food security concerns in a situation where the trade balance is preserved. In further studies, better connections could be made between models: partial equilibrium models could focus on better representing the most important mitigation strategies highlighted by the supply models, while supply models could use the prices simulated by the partial equilibrium models. This would limit the simulation of high reduction of agricultural production and GHG emissions if the carbon tax is not embodied in trade

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Appendix 1. Characteristics of animal production by agro-ecological zone in France for GLOBIOM 2030–business-as-usual

		Medium Arid	**Medium Hum.**	**Medium Temp.**	**Other**
Production (kg/cow/year)	Milk	5411	6808	8187	4064
	Beef	82	107	104	84
Dairy cow	Total intake (tDM/year/cow)	*4.35*	*5.53*	*6.80*	*4.48*
	Grass intake (% DM)	*71%*	*54%*	*44%*	*71%*
Replacement	Total intake (tDM/year/cow)	2.4	2.1	2.4	2.1
	Grass intake (% DM)	87%	85%	74%	85%
	Number of female replacements / cow	0.58	0.71	0.67	0.57
GHG	CH_4 / in kg CO_2eq/kg milk	0.46	0.42	0.39	0.59
	Proportion of dairy cows in 2000	9.6%	32.5%	31.6%	26.0%
	Proportion of dairy cows in BAU	6.6%	25.6%	41.6%	26.2%
	Proportion of dairy cows in 100USD carbon tax	6.8%	26.8%	39.2%	27.2%

Note: The characteristics of the production systems are the same in business-as-usual as in 2000

Appendix 2. Characteristics of animal production by production system for ORFEE 2030– business-as-usual (scenarios with fixed total milk production)

		Mountain.Q	**West. Q**
Production (kg /cow/year)	Milk	5755	7928
	Beef	140	275
Dairy cow	Total intake (tDM /year/cow)	5.6	6.3
	Grass intake (% DM)	85	34
Replacement	Total intake (tDM /year/heifer)	2.4	2.4
	Grass intake (% DM)	94	73
	Number of female replacements / cow	0.66	0.81

GHG	CH_4 / in kg CO_2eq/kg milk	0.73	0.66