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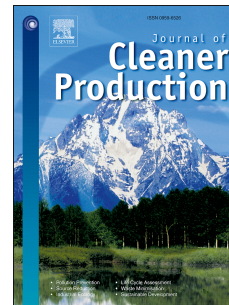
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Greenhouse gas abatement strategies and costs in French dairy production

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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.

29 **Highlights**

- 30 • GHG abatements simulated by three supply farm models and one partial equilibrium model
- 31 • 15% milk price increase and considerable decrease in profits found at 100€/tCO₂eq tax
- 32 • 1% to 6% and 4% to 15% abatement found resp.at 20€and 100€ tax with limited outsourcing
- 33 • Up to 70% GHG abatement found at 100€/tCO₂eq tax if the carbon tax is not embodied in
- 34 trade
- 35 • Up to 15% GHG abatement found with productive dairy cows raised on low-input forages

37 **Keywords**

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

40 **1 Introduction**

41 Anthropogenic activities generate greenhouse gas (GHG) emissions that drive major global climate
42 change. As the impacts of these GHG emissions are not reflected in product prices, they are
43 considered a negative externality. According to Bithas (2011), the internalization of environmental
44 externalities is a necessary condition for sustainability. Economic-environmental instruments such as
45 taxes and subsidies, incentives to invest in greener technologies, or permits are all designed to modify
46 market signals to make polluting goods and technologies less attractive. The EU Emissions Trading
47 System (EU-ETS) caps the total amount of certain GHG that can be emitted by companies covered by
48 the system (European Commission, 2019). These companies receive carbon permits that can be traded.
49 Agriculture is not covered by the EU-ETS, despite the fact that it ranks as third biggest GHG emitter
50 at EU-27 level. The French agricultural sector accounted for about 17% of French GHG emissions in
51 2016 (EEA, 2018). More than a third of the French agricultural GHG emissions stem from methane, a
52 third of which comes from dairy cattle (EEA, 2018). France is the second largest milk producer in the
53 EU.

54 Conversely to the sectors currently covered by the EU-ETS where emissions can be relatively simply
55 derived from input use of fossil energy carriers, GHG emissions from agricultural sectors are non-
56 point emissions resulting from many diffuse sources, mostly not CO₂. These emissions are hard to
57 measure on real farms and depend on a complex interplay of location factors such as soil and climate
58 and the chosen production technology. Indicators such as the ones proposed by the IPCC (2006)
59 circumvent these difficulties, but it may not be feasible to use more accurate indicators (Lengers et al.,
60 2013), which explains why European agriculture is not yet integrated in the EU-ETS (Monni et al.,
61 2007). With increasingly ambitious GHG emissions reduction targets but shrinking abatement
62 potentials in non-agricultural sectors, a closer look at the potential GHG emissions savings in
63 agriculture and related costs seems warranted. Whether and how much the dairy sector should
64 contribute towards reduced GHG emissions depends mainly on the economics of dairy GHG
65 emissions abatement costs relative to other sectors. De Cara and Jayet (2011) ran simulations showing
66 that a reduction around 10% of EU agricultural GHG emissions could be obtained with a carbon price
67 at around 35€/tCO₂eq. Pellerin et al. (2017) find that an abatement of at least 10% for the French
68 agriculture could be even cheaper with 2/3 of the mitigation strategies costing less than 25€/tCO₂eq.
69 However, other analyses shows less optimistic results. Mosnier et al. (2017b) ran simulations for
70 typical French dairy farms showing that a tax of 40€/tCO₂eq would only reduce GHG emissions per
71 kg of milk by less than 5%. Lengers et al. (2014) ran simulations showing that to abate 10% of GHG
72 emissions in a typical German dairy farm would require a carbon price if over 100€/tCO₂eq. Vermont
73 and De Cara (2010) showed that marked variability in abatement costs can generally be attributed to
74 methodological differences such as model categories, temporalities, and flexibilities in allocating
75 resources, GHG sources or carbon prices. Povellato et al. (2007) also underlined that any single
76 approach cannot even start covering all the complexity involved.

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

81 including trade impacts, and 3) on a specific branch of production to emphasize the impacts of model
82 assumptions.

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

95 2 Methodology

96 Model description

97 2.1.1 Overview

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

100 **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

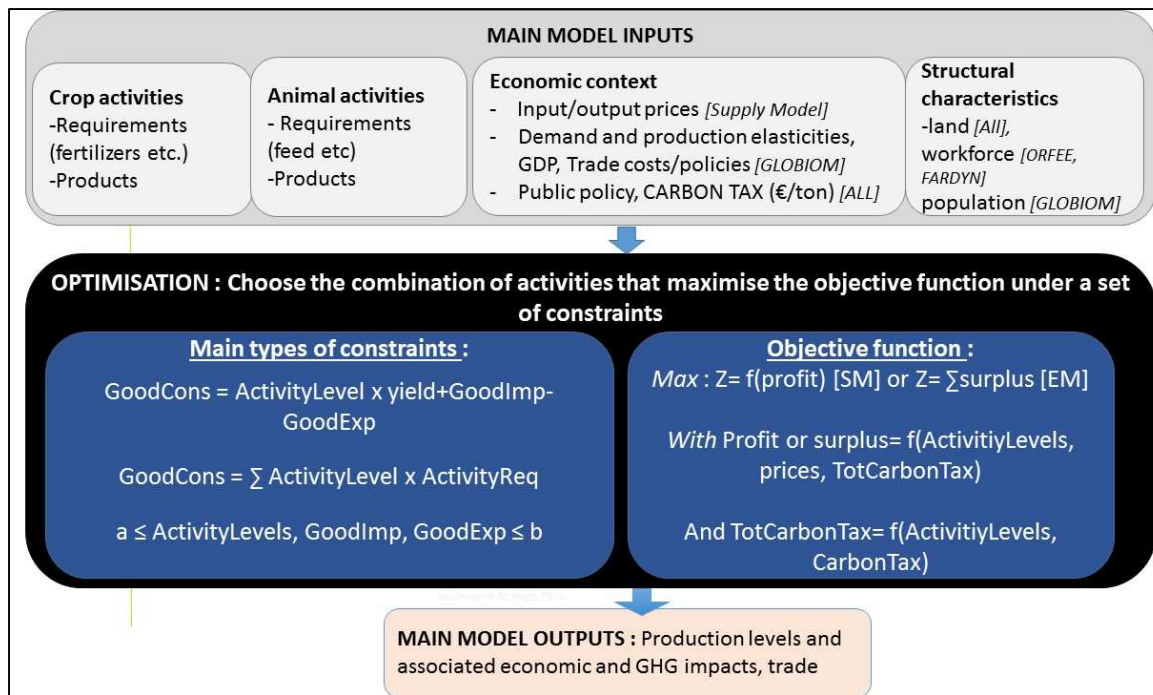
101 *Notes: more details are available at:* ^a *Havlik et al. (2014) and Supplementary Material 1*

102 ^b https://www6.versailles-qriqnon.inra.fr/economie_publique/Media/fichiers/ArticIAROPAj, version V5

103 ^c *Mosnier et al. (2017a) and Supplementary Material 2*

104 ^d http://www.ilr.uni-bonn.de/em/rsrch/farmdyn/farmdyn_e.htm, version of 2017

105



106

107 **Figure 1: General structure of the optimization models.**

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

112

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

124 GLOBIOM optimizes production (acreages and herd sizes), trade and consumption decisions to

125 maximize the sum of producer surplus which refers to the benefit for selling the goods and consumer

126 surplus minus trade costs. The consumer surplus is the difference between cost of the goods and the
127 price they were willing to pay for them. It is the only one of the four models to feature endogenous
128 consumption quantities and output prices.

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

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

147

148
 149 2.2 Mitigation strategies considered
 150 The different adjustment mechanisms taken into account by each model (Table 2) enable possibilities
 151 to reduce GHG emissions by: decreasing herd sizes, improving animal efficiency, improving manure
 152 management, modifying crop and forage production to reduce the use of fertilizers, to store more
 153 carbon and to provide better diets for animals.

154 **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	<u>Cow</u> = ± 5% of change by agroecological zone (AEZ)	<u>Cow</u> = up to -15% of initial value	<u>Cow</u> *: Free or = production reference	Free
Milk production/cow	Constant by	Fixed	<u>Milk yield</u> : 2 breeds × 3 yield levels	<u>Milk yield</u> : milk potential and below
Reproduction	AEZ-allocation across AEZ is optimized	-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	

155 **Two alternative scenarios were simulated: "Mountain" and "West" where milk production is free and*
 156 *"Mount.Q" and "West.Q" where milk production is fixed (farm-type reference level).*
 157

158 2.2.1 Changes in herd sizes, production per animal and animal feeding

159 GLOBIOM-EU divides cattle farming into dairy cattle, replacement heifers, and other. The balance of
 160 the different categories is fixed on statistical data from the year 2000. One type of dairy production is

161 defined per agro-ecological zone, which is defined as an area with similar climatic conditions
162 (Appendix 1). Quantity of meat and milk produced per head and per year and quantity of feed
163 consumed are defined as model inputs based on the RUMINANT model (Herrero et al., 2013). In
164 France, dairy cows productivity ranges between 4064 kg milk/year/cow and 8187 kg milk/year/cow
165 according to agro-ecological zone.

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

180 2.2.2 Changes in land allocation and cropping management

181 In GLOBIOM-EU, European crop, grassland, forest, and short rotation tree productivity are estimated
182 at NUTS-2 level. Three alternative tillage systems are included: conventional, reduced, and minimum
183 tillage. Crop production is used for animal feed, human food and bioenergy. In AROPAj, crops and
184 fodders, with up to 30 area categories depending on farming system, interact through “rotating”
185 constraints and/or crop-specific thresholds. In ORFEE, crop and grassland production are defined
186 based on expert knowledge and surveys. Emphasis is placed on providing a large variety of grassland

187 management, on integrating effects of crop succession on crop yield and nitrogen requirements, and on
 188 proposing two or three levels of yield targets. In FARMDYN, there are five different intensity levels,
 189 between 20% and 100% of the normal level, for the amount of N fertilizer applied.

190 2.3 Estimation of GHG emissions and carbon storage

191 Methane emissions—the most important GHG in dairy systems—stem from enteric fermentation
 192 and excreta of animals. In all four models, methane emissions from enteric fermentation depend on
 193 feed intake. In FARMDYN and GLOBIOM, estimations are driven mainly by gross energy intake
 194 (Table 3). In ORFEE, the main drivers are quantity and digestibility of organic matter ingested,
 195 proportion of concentrate feed, and quantity of dry matter intake per kg liveweight (Sauvant et al.,
 196 2011). AROPAj uses an earlier version of the model developed by Sauvant et al. (2011) based on feed
 197 digestibility and gross energy. To estimate methane from excreta, all estimations are based on the
 198 IPCC (2006) Tier 2 method, which considers type of storage and local climate.

199 **Table 3. Estimations of GHG emissions**

	GLOBIOM	AROPAj	ORFEE	FARMDYN
N₂O-soils	Biophysical model	IPCC Tier 1	IPCC Tier 1	IPCC Tier 2
N₂O-manure mgt	IPCC Tier 2	IPCC Tier 2	IPCC Tier 2	IPCC Tier 2
N₂O-indirect	IPCC Tier 1	IPCC Tier 1	IPCC Tier 1 + Velthof and Oenema (1997)	IPCC Tier 1 + Velthof and Oenema (1997)
CH₄-manure mgt	IPCC Tier 2	IPCC Tier 2	IPCC Tier 2	IPCC Tier 2
CH₄-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

200

201 In all four models, N₂O emissions from manure management systems are proportional to the
 202 quantity of nitrogen excreted by animals and are differentiated according to storage type as per Tier 2
 203 method (IPCC, 2006). Direct emissions of N₂O from managed soils are computed according to IPCC

204 Tier 1 (2006). They take into account manure spreading, inorganic N fertilization, and N deposited by
205 grazing. Indirect N₂O emissions from atmospheric deposition of N volatilized from managed soil and
206 leaching (NO₃⁻) are taken into account in farm models.

207 Regarding carbon storage, in GLOBIOM, EPIC (2019) was used to simulate a carbon response
208 function for each crop rotation, management system, simulation unit, and initial stock of carbon. It
209 provides estimates for soil organic carbon in croplands and from land use change from natural land to
210 cropland. In ORFEE, carbon sequestration in grassland and land use change from grassland to annual
211 crops is accounted based on Soussana et al., (2010). Indirect CO₂e emissions of purchased inputs such
212 as feeds and litter produced off-farm, non-organic fertilizers and purchased animals and direct
213 emissions from the burning of fuels are estimated using life cycle assessment values from Dia'terre®
214 (ADEME, 2010) version 4.5.

215 Emissions are aggregated into a single indicator of global warming potential (GWP) expressed in
216 equivalent CO₂ (CO₂eq) using the 2007 IPCC GWP of each gas (GWP N₂O = 298, GWP CH₄ = 25)
217 calculated at farm level. In GLOBIOM, only the emissions associated with the cropping area required
218 to produce the feed for dairy cows and replacement heifers are included here in GHG estimate.

219

220 2.4 Carbon tax scenarios

221 There are three potential alternatives for simulating mitigation strategies in bio-economic models.

222 Either a carbon tax can be introduced, or the optimization process can look for the optimal strategy

223 under a target of climate change abatement. Both yield the same result at the points where the tax rate

224 is equal to the dual value of the emission ceiling and thus deliver the same MAC curves. The third

225 option is to only consider GHG estimates in model outputs. In this case, alternative production

226 systems are either tested by fixing some decisions exogenously or else taken from the implementation

227 of scenarios not directly involving GHG emissions. In this study, mitigation potential was simulated

228 for three carbon tax levels: €20/tCO₂eq, €50/tCO₂eq and €100/tCO₂eq that were implemented as

229 additional production costs or subsidies in the case of carbon storage (Table 4).

230 **Table 4. Sources of GHG emissions taxed.**

	GLOBIOM	AROPAj	ORFEE	FARMDYN
Sources of GHG emissions taxed	CH ₄ , N ₂ O, CO ₂ (<i>LUC and crops</i>)	CH ₄ , N ₂ O	CH ₄ , N ₂ O, CO ₂ (<i>inputs + grassland soils</i>)	CH ₄ , N ₂ O

231 *LUC: land-use change*

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

243 **3 Results**244 **3.1 Optimal mitigation strategies simulated**245 For all the models, a reduction in animal numbers is simulated with higher CO₂eq tax levels (Table 5).

246

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

	Carbon tax(€/t)	GLOBIOM	AROPAj		ORFEE			FARMDYN		
		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%	-	-	-7%	0%	-15%	0%	2%	-9%
	50	-2.0%	-	-	-27%	0%	-51%	0%	-4%	-17%
	100	-3.6%	-	-	-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%

248 *Note: / adjustment not possible, na: not available; ^a+1 suckler cow + 1 goat + 2 swine; ^b+4 suckler cows; ^c all*
249 *heifers, ^d proportion of calvings between March and May; * change in ha (baseline = 0); Q: simulations with*
250 *fixed milk production*
251

252 This is the most radical solution to reduce not only all emissions directly related to enteric
253 fermentation and manure management but also emissions related to forage and crop production due to
254 lower feed requirements. All animal numbers are reduced in some models including dairy cows at the

255 expense of beef and milk production. This is the case for GLOBIOM with up to -3.5% of dairy cows
256 for a 100 \$/tCO₂eq tax. For the same carbon tax level, ORFEE finds a stronger reduction of herd sizes
257 of up to -60% whereas the other supply models find that dairy cow inventory is maintained. This
258 higher reduction is linked to the fact that dairy cow marginal profit is much lower in ORFEE, which
259 considers that labour, machinery and housing costs are approximately proportional to the number of
260 dairy cows and thus consequently more sensitive to a carbon tax. Numbers of replacement heifers are
261 reduced in AROPAj and FARMDYN. In FARMDYN, the rearing period is accelerated to let heifers
262 enter the herd earlier in order to reduce the number of unproductive animals. In ORFEE, the youngest
263 age possible at first calving is already reached in the BAU situation. For AROPAj, the rearing of
264 replacement heifers is largely externalized, even at low levels of tax. The number of replacement
265 heifers is divided by 5. This option was initially introduced with the aim of representing practice in
266 some farms rather than reducing GHG emissions. In the 'West' farm under AROPAj, two out of the
267 four suckler cows are eliminated to reduce emissions. Average milk yield is reduced up to 0.9% in
268 GLOBIOM as dairy cows are reallocated to less productive areas. This corroborates the ORFEE
269 results that show a stronger reduction of dairy cow numbers in the western part of France where more
270 alternatives to ruminant production are available. Milk yields are not modified in the other models and
271 are at their maximum values. Note that they were at their maximum potential before the
272 implementation of the tax. In ORFEE, spring calving increases to i) increase fresh grass intakes that
273 emit less methane during digestion than rough forages, and ii) reduces feed purchases which are
274 associated with indirect CO₂ emissions (LCA).

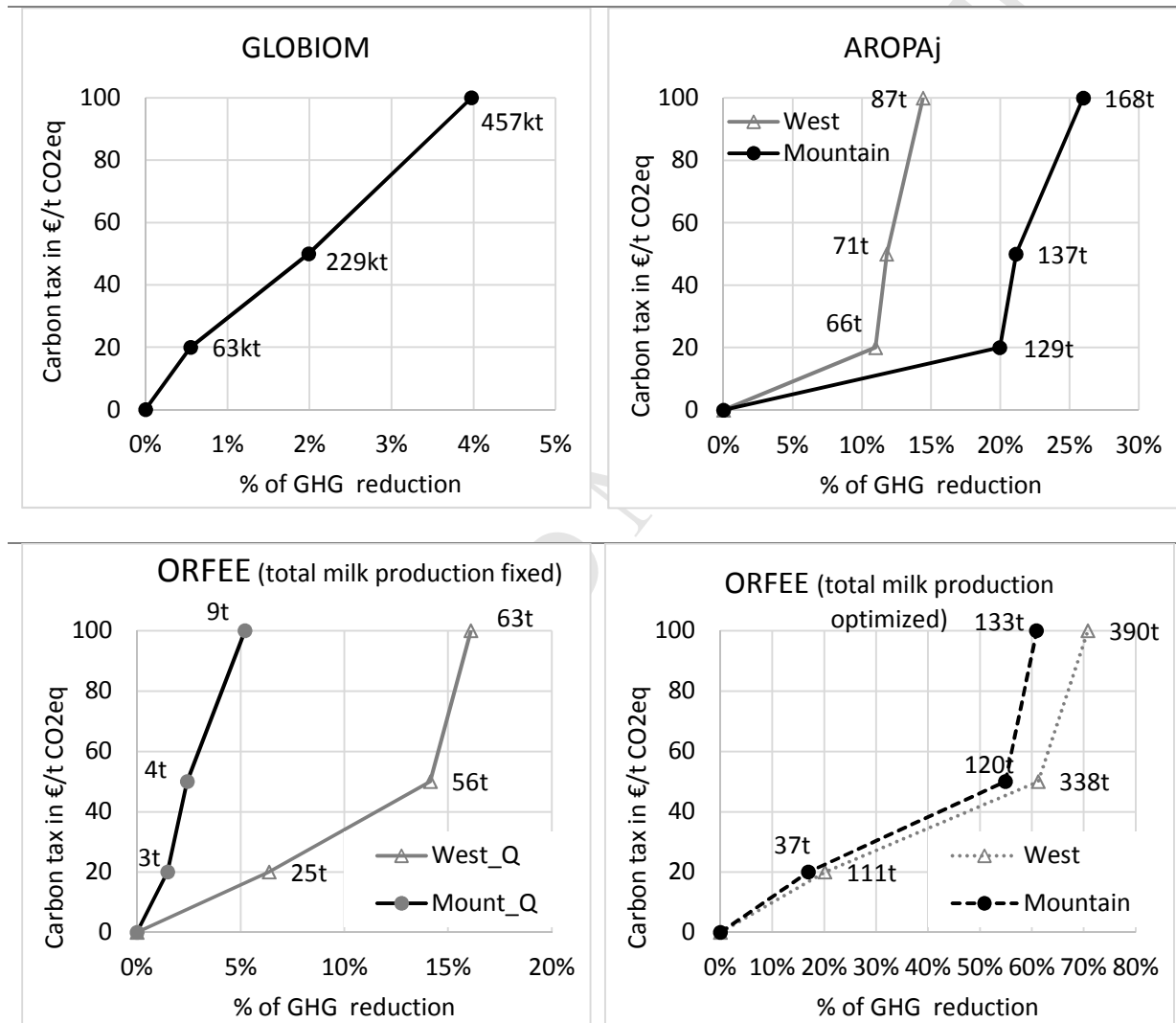
275 To reduce fertilization-related nitrous oxide emissions, models can opt for technologies or crops
276 requiring less nitrogen, or they can replace on-farm feed production by purchased feed. These two
277 factors explain why the conversion of grassland into fallow, the reduction of wheat, and the marked
278 increase in feed purchases are chosen by AROPAj. In FARMDYN, a reduction in fertilizer use related
279 to the reduction in crop yield is also observed, the partial substitution of pasture by harvested
280 grassland (silage), and the increase in fallow land. In ORFEE, corn is replaced by alfalfa and
281 permanent grassland. ORFEE accounts for CO₂ emissions of purchased inputs and for carbon storage

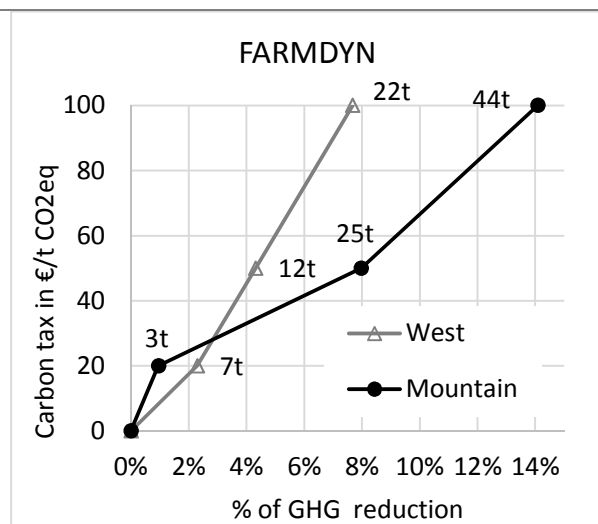
282 in grassland, which explains the expansion of grassland, particularly permanent grassland, which is
283 assumed to store more carbon. This reduction is made at the expense of corn silage and is associated
284 with maintained or increased levels of alfalfa and protein crops. The proportion of grazed-only pasture
285 also increases, since fresh grass has better nutritional value than conserved grass. In GLOBIOM, the
286 increase in carbon storage is explained by reduced tillage on croplands and by an increase in grassland
287 caused by an increased proportion of grass in animal diet.

288 289 3.2 Marginal abatement costs and GHG emissions

290 GHG emissions are reduced in all the models in response to a carbon tax, but the MAC curves have
291 different shapes according to the model (Figure 2). In GLOBIOM, the abatement rate is almost
292 constant at 0.04% of abatement per additional euro of tax per tCO₂eq. Emissions are reduced linearly
293 with herd reduction. In AROPAj, the externalization of feed and replacement heifer production leads
294 to higher emission reduction at already-low tax levels. In ORFEE, the highest abatement rate
295 corresponds to the greatest herd size reduction. It reaches up to 70% for a 100 € CO₂eq tax. The
296 abatement rate is far smaller when milk production is maintained: between 2 and 7% for 20 € CO₂eq
297 tax and between 5 and 16% for 20 € CO₂eq tax. This is closer to the range simulated by GLOBIOM:
298 0.5% and 4% respectively. for a 20€ and 100€ CO₂eq tax and FARMDYN: between 1 and 2% and
299 between 8% and 14% respectively. for a 20€ and 100€ CO₂eq tax. In FARMDYN, the 'Mountain'
300 MAC curve is not linear and its inflexion point corresponds to the reduction of age at first calving.
301 The reduction of GHG emissions per kg of milk produced depends on mitigation options used,
302 emission sources or sink considered, and GHG accounting frame (Figure 3). In the BAU scenario,
303 methane emissions are lowest in GLOBIOM with 0.45 kg CO₂eq/kg milk and highest in AROPAj
304 with between 0.91 and 1.12 kg CO₂eq/kg milk, with FARMDYN (between 0.44 and 0.60) and ORFEE
305 (between 0.62 and 0.73) giving intermediate values. These differences are explained by the methane
306 estimation method (CITEPA, 2019) and the amount of feed consumed per animal, which is smaller in
307 GLOBIOM than ORFEE (Appendices 1 and 2). The rough division of all GHG emitted by the
308 quantity of milk produced can also explain why AROPAj, which also considers some other ruminants

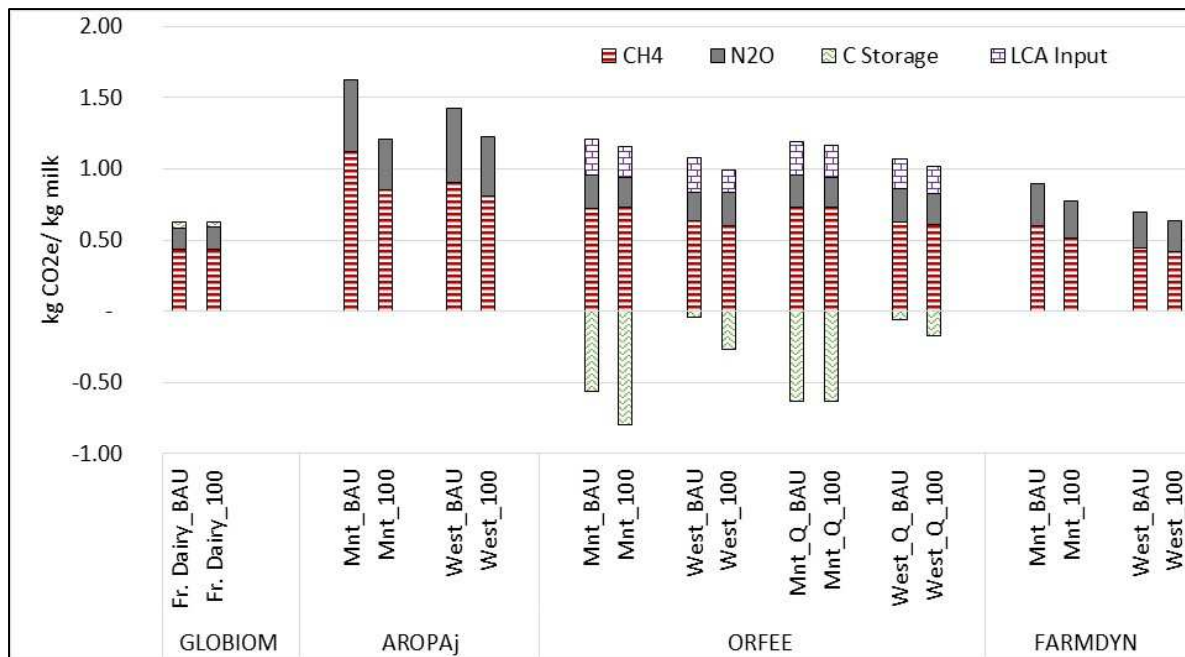
309 on both farms, gives higher methane values. The reduction of methane emissions in response to a 100
 310 € tax depends first on the reduction of unproductive animals e.g. heifers and, in AROPAj, other
 311 ruminants per productive cow and second on changes in animal diets. These gains reach up to 25% of
 312 BAU-scenario methane estimate in AROPAj and 15% in FARMDYN, but no more than 5% in
 313 ORFEE which only modifies diets. In GLOBIOM, methane emissions only increase by 0.5% with the
 314 reduction of average milk yield.





315 **Figure 2. Marginal abatement cost curves: GHG reduction according to carbon tax level (in %**
 316 **and in quantity of GHG emissions in business-as-usual scenarios).**
 317

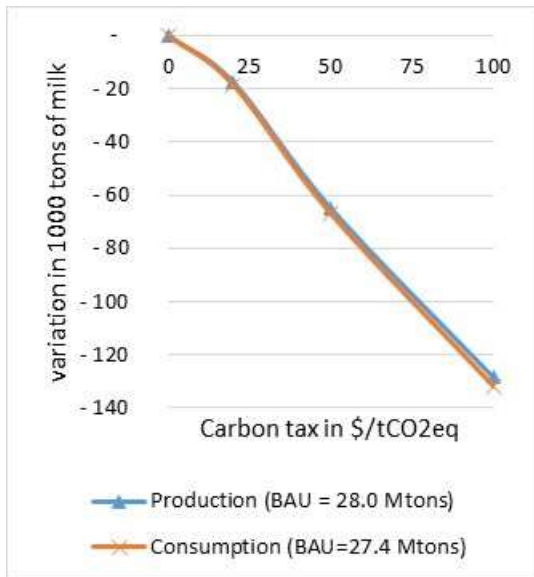
318 Regarding nitrous oxide emissions, differences in the BAU scenarios are explained by different levels
 319 of fertilization, types of manure and proportions of cash crops produced. In the 100€ tax scenario, the
 320 proportion of N₂O per kg of milk is reduced up to 20% in AROPAj, up to 13% in FARMDYN, and up
 321 to 9% in ORFEE due to fertilization reduction. In ORFEE ‘West’ farm, parallel to the reduction of
 322 herd size, the increase in cash-crop area leads to a higher amount of mineral fertilizer applied at farm
 323 level and per kg of milk produced. ORFEE accounts for CO₂ emissions linked to the purchase of
 324 inputs, which are almost as high as nitrous oxide emissions and account for 20% of total emissions.
 325 The simulated mitigation strategies can reduce these emissions by up to 37% if herd size is reduced
 326 but by just 8% if herd size is maintained. Carbon sequestration in grassland accounts for a significant
 327 proportion of the GHG emission balance in ORFEE. Quantity of carbon sequestered per kg of milk
 328 increases if herd size decreases and/or if some forage crops are substituted for grasslands. Land use
 329 change and carbon sequestration in croplands represent a fairly small proportion of GHG emissions
 330 related to the French dairy sector in GLOBIOM (7%).



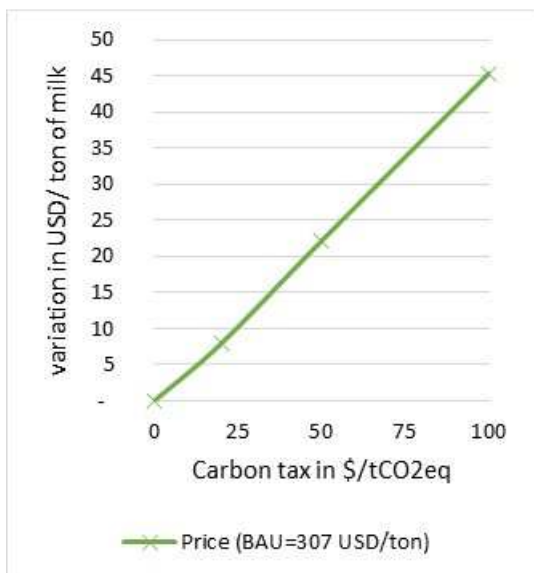
331

332 **Figure 3. GHG emissions per kg of milk for BAU and 100€CO₂ eq tax scenarios.**333 **3.3 Impacts on the milk market**

334 In GLOBIOM, the tax reduces both production and consumption in France by about 4.5 % for a 100 €
 335 carbon tax (Figure 4), which means the tax has little effect on trade. Dairy production in the other EU
 336 countries is defined in the same way as in France and has similar marginal abatement costs, and is
 337 consequently impacted at similar levels of magnitude. Furthermore, in the calibration year (2000),
 338 France only imported milk from Eastern Europe and only in relatively little quantities. GLOBIOM
 339 features some barriers to trade, making it possible, but costly, to create new trade flows, which might
 340 explain the limited changes in imports. The decrease of supply caused by the tax drives milk prices up
 341 (Figure 5). For a tax of 100 \$/tCO₂eq, the increase in milk price is around 40 \$/t milk which is
 342 equivalent to a 15% increase of the baseline price. Since GLOBIOM estimates average emissions at
 343 0.63 tCO₂eq/t milk, almost 2/3 of the tax is transferred to an increase in milk price, which is
 344 consequently quite high. This is explained by a relatively low elasticity of demand (0.3) and limited
 345 possibilities to adjust production technology and trade.



346

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

348

349 **Figure 5. Evolution of milk price in France in GLOBIOM**

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351

352 **3.4 Impacts on farm profit**

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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 €/tCO₂eq tax, there will

357 be little money left to pay farmers for their work. However, as shown in Figure 4, profit loss can be
 358 partly offset by macro-economic adjustments of prices.

359 **Table 6: Total GHG emissions and economic indicator values for BAU and 100€ carbon tax**
 360 **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€)

361 *Note: ^a Gross margin in AROPAj, operating profit for ORFEE and FARMDYN (=gross margin – structural costs –*
 362 *depreciation and financial costs); Objective function differs from this indicator of profit, so that profit loss in the*
 363 *100€ tax scenario is sometimes higher than a 100€ tax applied to GHG emissions in the BAU scenario. ^b.Q:*
 364 *simulations with fixed quantity of milk sold.*

365 **4 Discussion**

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

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

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

401 The “when” flexibility can be related to the transition or adjustment costs included in the model. Once
402 buildings and machinery have been purchased, they can be considered as sunk costs. Capital is near-
403 fixed in FARMDYN scenarios because the dynamics of investments are included and fixed in
404 AROPAj. These models generate a herd structure that is less sensitive to a carbon tax than ORFEE
405 scenarios which, here, considered capital and labour as fully variable based on annualized costs. This

406 hints at differences in short and long-run abatement costs at business and consequently also sectoral
407 level.

408 The “what” flexibility should be replaced by “how” in the context of this study, since it was set out to
409 pinpoint what abatement options will be used within the dairy cattle system. The range of options
410 considered in the different models has significant impacts on the MAC curves. Apart from strategies
411 resulting in a reduction of crop and animal production per unit of land, milk yields tend to increase
412 with the tax, if not already at maximum potential in the baseline. This corroborates previous findings
413 (Monteny et al., 2006) that improving animal efficiency through faster growth or higher milk yields
414 will reduce methane production per unit of product. However, GLOBIOM simulations led to a
415 reduction in the proportion of the most productive cows. This is explained by a geographical
416 reallocation of production and by the incentive to store carbon in soils. The incentive to store carbon in
417 soils and the lack of dairy production alternatives also explains why, first, increasing the proportion of
418 grassland emerges as an efficient strategy in ORFEE, and second, why dairy production is more
419 strongly reduced in areas suitable for cash crops. There are also studies which assume, unlike the
420 optimization models used here, where farmers are assumed to always operate on the efficient frontier,
421 there are also other studies that assume that pressure to abate emissions can shift inefficient farmers
422 towards the technical and economic efficiency frontier. In GLEAM (Global Livestock Environmental
423 Assessment Model) for instance, around 33% of emissions are mitigated while maintaining constant
424 output, based on the assumption that producers in a given system were to apply the practices of the
425 10th percentile of producers with the lowest emissions intensities (FAO, 2019). Pellerin et al. (2017)
426 also estimate that lengthening the grazing period or increasing the proportion of legumes on the
427 grasslands could reduce both emissions and production costs. Further promising strategies were not
428 introduced in the models studied, and might have further increased the abatement rates. They include
429 the improvement of grassland and grazing managements to store more carbon or limit nitrous oxide
430 emissions (Luo et al., 2010), limit fertilizer and fuel consumption, grazed intercropping to reduce
431 tillage, fertilization and conserved forage consumption, and unsaturated fats and additives in animal
432 diets.

433 5 Conclusion

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

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

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

458

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560 **Appendix 1. Characteristics of animal production by agro-ecological zone in France for**
 561 **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 ₂ eq/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%

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

563 **Appendix 2. Characteristics of animal production by production system for**
 564 **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

565	GHG	CH ₄ / in kg CO ₂ eq/kg milk	0.73	0.66
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