Greenhouse gas abatement strategies and costs in dairy production – a comparison across bio-economic models

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Abstract

All sectors of the economy are being asked to cut their greenhouse gas (GHG) emissions to curb climate change. Whether the dairy sector should be included in the collective effort, and if so what mitigation strategies should be fostered to reduce GHG emissions, depend mainly on abatement cost. This analysis compares abatement strategies and costs in dairy production across bio-economic models. Increasing taxes on GHG emissions were simulated on French dairy production systems with three supply models (AROPAj, ORFEE and FARMDYN) and one global partial equilibrium model GLOBIOM. We found that the main differences across studies were explained by flexibility assumptions. The highest abatement rates were obtained with the models that allowed the production process to be (partially) externalized outside the system to avoid the tax. Nonetheless very few of these abatement strategies can be generalized at a large scale without inducing important leakage issues or market drawbacks. Models that introduce temporal rigidity (including sunk costs) make milk production less sensitive to carbon tax. Using different bio-economic models opens up a broader range of mitigation strategies. Whether or not soil organic carbon is considered explains marked differences in abatement strategies and emerges as an important issue.

Highlights

- When optimization models let the possibility to externalize input production such as feed or animal replacements without taking into account the GHG emissions related to these inputs, their mitigation strategies and marginal abatement costs don't make sense
- Mitigation strategies that consist in reducing output production should be considered cautiously since this production could be produce abroad or substituted by more polluting products
- Shorter time horizon and higher rigidity relative to the current situation increase marginal abatement costs
- Soil organic carbon is an important issue that is very unequally considered across models

Keywords

Greenhouse gases, bio-economic model, abatement costs, livestock, meta-analysis

1 Introduction

The French agricultural sector was responsible for about 20% of national greenhouse gas (GHG) emissions in 2015 (CITEPA 2017). With its 3.7 million dairy cows in 2015, the dairy sector is an important emitter mainly of methane from enteric fermentation, which represents more than a third of the total GHGs from the agricultural sector (Citepa 2015). Whether the dairy sector should be included in a collective effort to reduce GHG emissions, following the commitment made by France and 187 other countries for the Paris Agreement (COP21, 2015), is mainly an issue of abatement cost relative to other sectors. Here both private and social costs linked to political instruments in dairy farms to foster GHG abatements need to be considered.

Different mitigation options have been identified that reduce emissions from ruminants. The most radical option is to decrease animal production (Garnett 2009), but there are also various strategies to reduce GHG emissions per animal or unit of product (Monteny *et al.* 2006; Dollé *et al.* 2011; Pellerin *et al.* 2017). Important strategies include (i) improving animal efficiency through faster growth, higher milk yields, fewer unproductive animals or low-emissive diets (Martin *et al.* 2009), (ii) significant reduction by improving manure management (type of manure, storage, biogas, etc.) and fertilization (type of fertilizer and crops, soil N process inhibitor) (Monaghan *et al.* 2007; Luo *et al.* 2010), and (iii) storing more carbon within grassland (Soussana *et al.* 2010) or arable lands (Freibauer *et al.* 2004), or by avoiding deforestation (Cohn *et al.* 2014). These strategies are often conflicting. For instance, higher animal productivity requires both higher quantity and quality of feed, which drives up fertilizer and fuel demands (Garnett 2009; Gerber et al. 2011; Mosnier et al. 2017b). Consequently, these options need to be jointly evaluated at the system level to find cost-minimal combinations.

Identifying these most cost-effective strategies involves finding the lowest-cost options among a set of different mitigation measures and policies to reach a target of climate change moderation. Marginal Abatement Cost Curves (MACCs) provide information on costs for an additional unit of emission reduction at given emission level (Huang *et al.* 2016), and represent an important tool to support climate change policy. Several studies have reviewed and compared the abatement costs simulated by different approaches (Povellato *et al.* 2007; Kuik *et al.* 2009; Vermont & De Cara 2010). They showed that there is a marked variability in the estimates of abatement costs that can be attributed largely to methodological differences. These approaches differ in many aspects, such as system boundaries, behavioural assumptions, details of technology, and GHG emission calculation.

The aim is to assess the implications of model and scenario assumptions on mitigation strategies and marginal abatement curves, and to highlight the most cost-effective strategies to mitigate GHG in dairy production.

In this study we compared four different approaches: the global partial equilibrium model GLOBIOM (Havlík *et al.* 2014), the aggregate linear programming model describing the behaviour of a set of representative farms AROPAj (De Cara & Jayet 2011), and finally two single farm models with technological features, ORFEE (Mosnier *et al.* 2017a) as a static, and FARMDYN as a dynamic one (Lengers *et al.* 2014). These models have already been used to assess the mitigation potential of dairy production (but not exclusively) in previous publications. For this study, increasing taxes on GHG emissions are simulated in all models. The differences and similarities between mitigation strategies and marginal abatement costs are discussed in the light of model assumptions.

2 Methodology

2.1 Model description

All the models considered are economic models assuming rational agents considered as a constrained optimization supply problem. In each farm or group, the representative farmer chooses the profit-maximal mix of production activities subject to available production technologies, given endowments and the market and policy environment. ORFEE, FARMDYN and AROPAj are supply-side models where market conditions are reflected by given and fixed prices, whereas GLOBIOM comprises market clearing such that demand and prices are also endogenous.

AROPAj covers the main European production systems and targets the French and European levels, aggregating farm types based on a FADN classification, crossing the farm's economic and technical orientation at NUTS 2 level. ORFEE focuses on French ruminant farms and is currently parameterized for the regions in which ruminant production is of particular importance. FARMDYN simulates arable dairy and pig production systems in Germany. GLOBIOM is a global partial equilibrium model for agri-food and forestry. It covers a wide range of production systems to represent agricultural production and forestry worldwide. While prices for agri-food and forestry products, along with land, are endogenous in GLOBIOM, all other prices including prices for labour and intermediates are exogenous.

All four models are based on mathematical programming and optimization techniques. They use linear functions as much as possible (by using linearization techniques). AROPAj, ORFEE and FARMDYN introduce additional integer variables. They are used to model indivisibilities of investments in FARMDYN and to a lesser extent in ORFEE (only for some machines or equipment), minimum labour requirement when starting an activity (FARMDYN) and conditional subsidies (ORFEE, AROPAj, and FARMDYN). Linear programming will not model decreasing marginal return to inputs directly. Nonetheless, as an activity increases, costlier technology may be required (less fertile soils or less favourable cropping successions, etc.), indirectly inducing decreasing marginal return. Technology can also become cheaper in FARMDYN and ORFEE due to economies of scale through indivisibilities.

These models differ in their representations of how farmers adjust their production systems. ORFEE and AROPAj are static models: they simulate a farm at steady state without explicitly considering the transition period to reach the new optimal equilibrium, but they can limit model flexibility and add sunk costs based on the initial situation. FARMDYN simulates the evolution of the farm between the initial and the final situations, with special emphasis on the evolution of investments and herd size, such that simulation results depend on the time horizon considered and on the initial farm endowments. GLOBIOM uses a recursive dynamic framework with decadal time resolution. It simultaneously considers the evolution of the world population and so the evolution of global demand. These main characteristics are summarized in Table 1.

Table 1. Main model characteristics

	GLOBIOM[a]	***AROPAj***[b]	***ORFEE***[c]	***FARMDYN***[d]
Organization	IIASA	INRA	INRA	University of Bonn
Model type	Sectoral	Supply	Supply	Supply
Scale	Global	EU through aggregation of farm groups	Farm	Farm
Area of application	World	European Union	Some French regions	Some German regions
Solving program	Linear	Mixed integer linear	Mixed integer linear	Mixed integer linear
Evolution over time	Recursive-dynamic	Static	Static	Dynamic
Production system simulated	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
Objective function	Sum of producer and consumer surplus	Weighted sum of gross margins	Function of net profit	Function of Net Present Value of profits

[a] *Havlik et al. (2014)*
[b] *https://www6.versailles-grignon.inra.fr/economie_publique/Media/fichiers/ArticlAROPAj*
[c] *Mosnier et al. (2017a)*
[d] *http://www.ilr.uni-bonn.de/em/rsrch/farmdyn/farmdyn_e.htm*

2.1.1 Cattle, grassland and crop production

All models cover cattle, but with different approaches. GLOBIOM-EU divides bovine production into dairy cattle, replacement cows and other. The balance of the different categories is fixed on 2000 statistical data. Technologies for each bovine type are defined based on the RUMINANT model (Herrero *et al.* 2013), each characterized by a quantity of meat and milk produced per head and per year and by a quantity of feed consumed. Settings for this simulation specify that bovine production at the level of France is a combination of four technologies, with productivity ranging between 4064 kg milk/year/cow and 8187 kg milk/year/cow. Only one of these technologies is possible per spatial unit (Appendix 1). In GLOBIOM-EU, European crop, forest, and short rotation tree productivity are estimated for a 1 × 1 km pixel spatial unit (SimU) and are then aggregated at the NUTS 2 level since production decisions are optimized at this level. Three alternative tillage systems (conventional, reduced, and minimum tillage) are included. Crop production is used for animal feed, human food and bioenergy. In this simulation, only the areas dedicated to dairy cows and replacement heifers were taken into account.

The farm level models and AROPAj split cattle production into more categories to represent the heterogeneity of production systems in greater detail and provide more options to manage cattle production. In ORFEE, dairy production can be optimized by modifying the breeds (appendix 2), calving period and production objective (possibility to produce below milk potential, delay first calving or modify average daily gain). In FARMDYN, milk production (up to milk potential) and the replacement rate can be optimized for the farm type breed. 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 and purchasing replacement heifers.

In farm models, diets are not predefined, but a cost-minimal mix subject to requirement constraints is simulated. 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 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.

In AROPAj, crops, fodders and CAP-specific areas, up to 30 area categories depending on farming systems, interact through "rotating" constraints and/or crop-specific thresholds. In place of input and yield estimates provided by the FADN, when applied, input-yield functions are provided by STICS. 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 for the amount of N fertilizer applied (between 20% and 100% of the normal level).

In GLOBIOM, per-hectare costs are assumed to equal average country productivity per hectare multiplied by product price. For livestock the cost per hectare is mostly feed costs plus calibration costs. In AROPAj, only variable costs are considered: feed, fertilizer, pest control treatment, irrigation, etc. In ORFEE and FARMDYN, the cost of investments in buildings and machinery, together with borrowing costs, is included in addition to variable inputs. In the case of ORFEE, labour costs are added. In FARMDYN, there is a discrete set of stable sizes, size increasing by 15 places; stable cost per cow thus decreases as the stable fills, and then increases again when a stable of greater capacity is required.

2.1.2 Estimation of impacts on climate change

Methane emissions come from enteric fermentation and excreta of animals. In all the models, enteric fermentation depends on animal intake. In FARMDYN and GLOBIOM, estimations are based on IPCC Tier 2/3 and are driven mainly by gross energy intake. In ORFEE, the main drivers are quantity of organic matter ingested and its digestibility, proportion of concentrate feed, and quantity of dry matter intake per kg of live weight (Sauvant *et al.* 2011). AROPAj uses an earlier version of this model 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.

Nitrous oxide emissions are divided into direct emissions from manure management, direct emissions from managed soils, and indirect N_2O emissions. In all the models, N_2O emissions from manure management systems, calculated according to Tier 2 (IPCC, 2006), are proportional to the quantity of nitrogen excreted by animals and differentiated according to storage type. 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. In FARMDYN, the corresponding IPCC (2006) equations are 11.9 and 11.10 with emission factors per ha of land from Velthof and Oenema (1997). N leaching is estimated in ORFEE based on the nitrogen balance with the emission factor taken from (Oenema *et al.* 1997).

In GLOBIOM, EPIC 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 for in ORFEE according to the CA2ER methodology, based on Soussana *et al.* (2010). In ORFEE, indirect CO_2 equivalent emissions of inputs purchased (feeds and litter produced off-farm, non-organic fertilizers, purchased animals) and direct emissions from the burning of fuels are estimated using the Life Cycle assessment values from Dia'terre ® (ADEME, 2010) version 4.51.

Emissions are aggregated into a single indicator of Global Warming Potential expressed in equivalent CO_2 (CO_2e) using the 2007 GWP of each gas (GWP N_2O = 298, GWP CH_4 = 25) calculated at farm level. In GLOBIOM, the emissions associated with the cropping area required to produce dairy cows and replacement females are included.

Table 2. Estimation 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	None	IPCC Tier 1	IPCC Tier 1+ Oenema, 1997	IPCC Tier 1 +Velthof 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
CO_2 inputs	None	None	Dia'terre (Ademe)	None

2.2 Scenario design

In each model, the mitigation potential was simulated for three carbon prices (€20/tCO_2e, €50/tCO_2e and €100/tCO_2e[1]) and compared with the baseline without carbon price (Business As Usual). These taxes were implemented as additional production costs (or subsidies). In the baseline most models performed simulations at a mid-to-long term horizon (2030) except for AROPAj, which performed simulation at a shorter horizon since farm capital is assumed to remain unchanged. GLOBIOM and FARMDYN target the year 2030. Assumptions are presented in Table 3 and based on previous publications (De Cara & Jayet 2011; Lengers *et al.* 2014; Frank *et al.* 2015; Mosnier *et al.* 2017b). Two alternative scenarios were simulated in ORFEE, with and without fixing milk production.

These scenarios were applied at farm level except for GLOBIOM, in which the tax was implemented at the EU level, but with a focus on the French dairy livestock sector. Two contrasting types of farm were 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 ('Mountain'). In AROPAj, these two farms were picked among the

[1] in GLOBIOM, taxes are in US dollars (2017 exchange rate €1 = $1.17).

farm groups (based on FADN) specialized in dairy production: ('PL70' and 'AU50'). In ORFEE and FARMDYN, farms were parameterized based on the INOSYS farm types ('PL2B' and 'C17').

Table 3. Implementation of the scenarios in the different models

	GLOBIOM	**AROPAj**	**ORFEE**	**FARMDYN**
Carbon tax	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
Adaptation time	2030	Short to mid-term adaptation	2030	2030
FLEXIBILITY (optimized by the model)				
Alternative to dairy and grassland	Crops, forest, fallow, other animals	Crops and fallow	Crops (except in uplands)	Crops (except in uplands)
Herd size and total milk production	Cow= +/-5% of change	Cow= +/- 15% of initial value Milk ≤ current production	Cow: Free *Milk = free or = production reference	Free
Milk production / cow	4 types of cows		Milk yield: 2 breeds × 3 yield levels	Milk yield:
Reproduction	4 types of cows	-Externalize or produce replacement heifers	- 4 calving periods - Age at 1st calving > min - Breed	-Culling rate -Age at 1st calving
Animal feeding	4 types of cows	Feed mix (type and quantity of feed free but constraints on its nutritional value)		
COSTS				
Building and machinery cost	implicit	none	Approx. proportional to production	High non-linearity and sunk costs
Labour cost	implicit	none	proportional to production	none

*Notes: LUC Land Use Change; *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).*

3 Results

- The BAU situation

The results in Table 5 show that in GLOBIOM, the dairy cow inventory in BAU-2030 (3.8 million head) and average milk yield (6.6 t / cow) is close to the levels measured in France in 2013 and used to estimate the French GHG inventory (3.7 million head and 6.6 t of milk produced per cow), (Citepa 2015). In BAU-2030, 42% of cows produce 8.2 t milk/cows, 26% produce 6.8 t milk/cows, 27% produce 4.1 t milk/cows" and the remaining 5.4 t milk/cows. Milk yields simulated in the supply models fall within this range. Regarding dairy cow feeding, we observe that ORFEE and GLOBIOM provide a total quantity of dry matter intake per year and per dairy cow of the same order of magnitude, but GLOBIOM increases feed quantity more with milk yields (Appendix 1 and 2). ORFEE instead increases energy density. A larger gap with ORFEE is found when accounting for replacement heifer diets due to a high replacement rate (36%) simulated in ORFEE, in line with what is currently observed in French farms with productive Prim'Holstein. For the BAU situation, "West" farms and "Mountain" farms have herd size, milk yield and crops in the same range in the different supply models.

Large differences in objective function are found between models, but AROPAj logically shows the highest objective function value, since it measures gross margin, and ORFEE the lowest, since fixed, depreciation, financial and labour costs are deducted.

To compare GHG emissions, emissions are expressed per unit milk produced. Despite some bias, since in supply models, a part of the arable land is not used to feed cattle, and in AROPAj some non-dairy animals are also present on the farm, it is still possible to compare the orders of magnitude of the different GHG estimates. Methane emissions were lowest in GLOBIOM (0.45 kg CO_2e/kg milk) and slightly higher in FARMDYN (between 0.44 and 0.60). These differences are explained by the smaller amount of feed consumed per cow in GLOBIOM. These methane values were slightly higher in ORFEE (between 0.66 and 0.76), since more feed is ingested per cow than in GLOBIOM, and the methane estimation method differs (CITEPA 2017). AROPAj gave the highest values (between 0.91 and 1.12), either because of the calibration factor, which may increase feed intake per animal or because of the evaluation method. In all the models, methane emissions per unit of milk decrease with milk yield increase. Regarding nitrous oxide emissions, large differences were found between models. Differences are explained by different levels of fertilization, types of manure and proportion of cash crops produced on the farm. Total N_2O emissions were lowest in GLOBIOM and highest in FARMDYN, probably because its default yield values are higher than those observed in France. In ORFEE, CO_2 emissions associated with the purchase of inputs are almost as high as nitrous oxide emissions and account for 20% of total emissions. Carbon sequestration in grassland represents an important lever to reduce net emissions. Land use change and carbon sequestration represent a rather small proportion of GHG emissions related to the French dairy sector in GLOBIOM (7%). The total GHG emissions ranges between 0.6 kg of CO_2e per kg of milk (GLOBIOM) and 1.6 (AROPAj).

Table 4. The farming system simulated in the BAU situations: main figures

	Number of dairy cow	**Milk yield** in kg/cow	**Grass--land** in ha	**Other crops** in ha	**N min.** in Kg/ ha	**Obj. funct** in k€	**CH_4 [a]** in tons CO2e	**N_20 [a]** in tons CO2e	**CO_2 [a]** In tons CO2e	**total [a]** in tons CO2e
GLOBIOM – dairy	3.8 millions	6 508	2312 [b]	577 [b]			11.0[b] (0.43)	3.9[b] (0.15)	1.1[bc] (0.04)	15.9 (0.63)
AROPAj – Mountain	69[d]	5 764	96	19	63	160	447 (1.12)	201 (0.51)	na	647 (1.63)
AROPAj – West	59[e]	7 143	59	41	113	181	383 (0.91)	219 (0.52)	na	601 (1.43)
ORFEE Mountain	63	5755	90	0	20	9.6	252 (0.75)	91 (0.24)	I=84 G=-188	228 (0.68)
ORFEE Mount.Q*	56	5755	90	0	13	8.6	226 (0.76)	78 (0.25)	I=71 G=-188	185 (0.62)
ORFEE West	74	7 928	26	35	37	19	361 (0.68)	121 (0.23)	I130 G=-24	588 (1.10
ORFEE West.Q*	54	7 928	27	34	43	16	255 (0.66)	95 (0.26)	I=79 G=-23	405 (1.06)
FARMDYN Mountain	60	5 785	90	0	72	52	208 (0.65)	284 (0.24)	na	492 (1.42)
FARMDYN West	50	8 264	37	24	159	95	183 (0.44)	348 (0.84)	na	531 (1.29)

*Note: na: not available; [a] in brackets emissions divided by total milk production (kg of CO_2 equivalent/kg milk); [b]in thousand tons; [c] soil carbon from land use change and croplands; [d] + 1 suckler cow + 1 goat + 2 swine; [e]+ 4 suckler cows, I: LCA on inputs; G: soil carbon in grassland ; *.Q: simulations with fixed quantity of milk sold.*

3.1 Mitigation strategies

All the models simulate a reduction in animal numbers with higher CO_2 tax levels (except for ORFEE Q_scenarios). 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. Some models reduce the number of all animals 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 USD 100 carbon tax. ORFEE operates a stronger reduction of herd size, up to −60%, whereas the other supply models maintain their dairy cow inventory. 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 consequently more sensitive to a carbon tax. AROPAj and FARMDYN keep their dairy cows but reduce the number of replacement females. In the case of FARMDYN, the rearing period is accelerated to make heifers calve younger (from 31 months old in the BAU scenario to 29 m.o. for a €100 tax). Although this leverage is also available in ORFEE, it is not used since the youngest age possible at first calving was already reached in the BAU situation. For AROPAj, the rearing of replacement females is largely externalized, even for low levels of tax (the number of replacement females is divided by 5). The West farm of AROPAj also eliminates two out of the four suckler cows to reduce its emissions. Increasing milk productivity per animal is often presented as a leverage to dilute emissions per animal and reduce animal stocking density. However, it can also increase feed concentrate consumption. This can explain why average milk yield is reduced in GLOBIOM (−0.9% for 100 USD tax). Milk yields are not modified in the other models; they were already at their maximum for the BAU situations. In ORFEE, spring calving increases to increase fresh grass intakes and reduce feed purchase.

To reduce nitrous oxide emissions related to fertilization, 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 in AROPAj the conversion of grassland into fallows, the reduction of wheat, and the marked increase in feed purchase. In FARMDYN, we also observe a reduction of crop and grassland yields due to the reduction of fertilizers, and so feed purchase increases. In ORFEE, corn is replaced by alfalfa and permanent grassland. ORFEE accounts for CO_2 emissions of purchased inputs and storage of carbon in grassland. This explains grassland expansion, particularly for permanent grassland, assumed to store more carbon. This reduction is made at the expense of corn silage and is associated with a maintenance or an increase in alfalfa and protein crops. The proportion of pasture only grazed also increases, since fresh grass has a better nutritional value than conserved grass. This goes with an increase of spring calving. When possible, herd size shrinks to reduce feed and fertilizer purchase. 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.

Table 5. Adjustments of the production system to the carbon tax (Change in % of the BAU situation)

		Number of dairy cows			Milk yield			Age at first calving[a]			Spring calving[b]			Externalization of Heifers			Min. Fertilizer application			Permanent grassland			Feed import (in % of €)		
	Carbon tax	**20**	**50**	**100**	**20**	**50**	**100**	**20**	**50**	**100**	**20**	**50**	**100**	**20**	**50**	**100**	**20**	**50**	**100**	**20**	**50**	**100**	**20**	**50**	**100**
Globiom	France	-1.3	-1.9	-3.5	-0.1	-0.5	-0.9	0	0	0	/	/	/	/	/	/	-2	-4	-6	0.4	1.3	1.6	/	/	/
Aropaj	Mnt.	0	0	0	/	/	/	0	0	0	/	/	/	100	100	100	0	-11	-60	-30	-30	-32	na	na	na
	West	0	0	0	/	/	/	0	0	0	/	/	/	100	100	100	3	3	-21	0	0	0	na	na	na
Orfee	Mnt.	-7	-27	-30	0	0	0	0	0	0	0	56	103	/	/	/	-38	-69	-68	/	/	/	-12	-35	-41
	Mnt.Q	0	0	0	0	0	0	0	0	0	0	32	32	/	/	/	-15	-14	-46	/	/	/	0	-4	-4
	West	-15	-51	-59	0	0	0	0	0	0	0	0	0	/	/	/	12	22	-4	11*	22*	27*	-37	-83	-86
	West.Q	0	0	0	0	0	0	0	0	0	0	0	0	/	/	/	-25	-23	-23	6*	26*	32*	-23	-11	-7
Farm-dyn	Mnt.	0	0	0	0	0	0	0	-3	-5	/	/	/	/	/	/	-24	-50	-67	/	/	/	na	na	na
	West	0	0	0	0	0	0	-2	-4	-7	/	/	/	/	/	/	-10	-11	-27	0	0	0	na	na	na

Note: / adjustment not possible, na: not available; [a] *age in months;*[b] *proportion of calving occurring between March and May; * change in ha (baseline = 0); *.Q: simulations with fixed milk production*

3.2 Impacts on farm profits and milk market

The carbon tax generates profit loss through additional production costs entailed by the tax itself or by the adoption of costlier technology and/or by weaker sales. These drawbacks can be partly or totally offset by macro-economic adjustments to prices.

In GLOBIOM, the reduction of milk production is explained by a reduction of milk consumption in a similar proportion (Figure 1). This means that trade is not affected by the tax: there is no leakage of milk production outside France. Simultaneously, milk price increases (Figure 2). For a tax of 100 USD /tCO_2, the increase in milk price is around 40 USD/t milk. Since GLOBIOM estimates the average emission at 0.63 tCO_2/t milk, almost 2/3 of the tax is transferred to milk price.

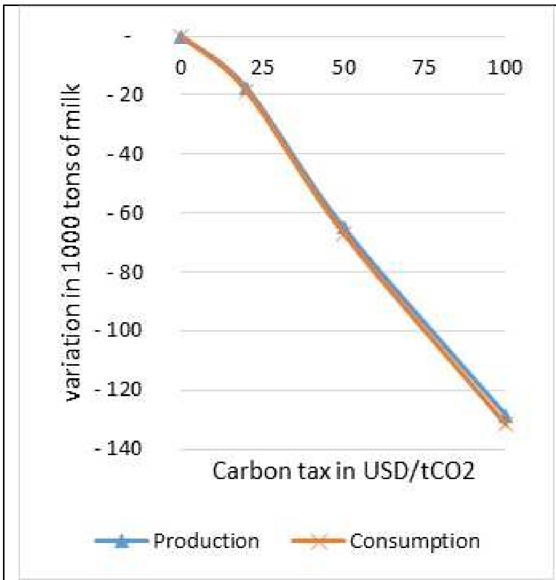

Figure 1. Evolution of milk production and consumption in France

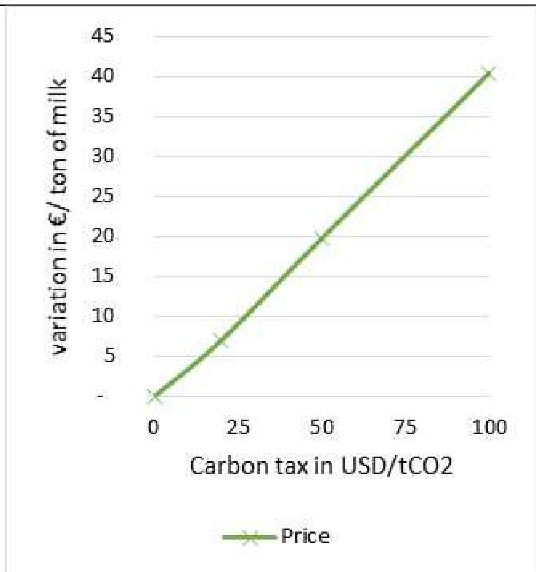

Figure 2. Evolution of milk price in France

For the supply models, no price feedback is introduced. Consequently, adaptations and profit losses are of greater magnitude than would have been simulated with price feedback. At farm level, the reduction of profit is roughly proportional to the carbon tax (Figure 3). In AROPAj, without adaptation (BAU), the loss of profit (in this case gross margin) would have been between 60 k€ and 65 k€ for a 100 €

carbon tax[2]. Owing to the externalization of feed and replacement heifer production, the loss is around 50 k€. In ORFEE, profit loss is smaller due to 'subsidies' provided for carbon storage in grassland. When variation of milk production is allowed, production adjustments reduce the profit loss up to 40%; when milk production cannot be reduced, this reduction is smaller (up to 25%).

For a 100 €/tCO_2 tax, the tax is almost as high as the farmer's income[3]. The cost of the tax becomes rapidly prohibitive for the simulated farms that have little possibility to reduce the impact of the carbon tax and still stay in production. Subsidies on carbon sequestration reduce this burden.

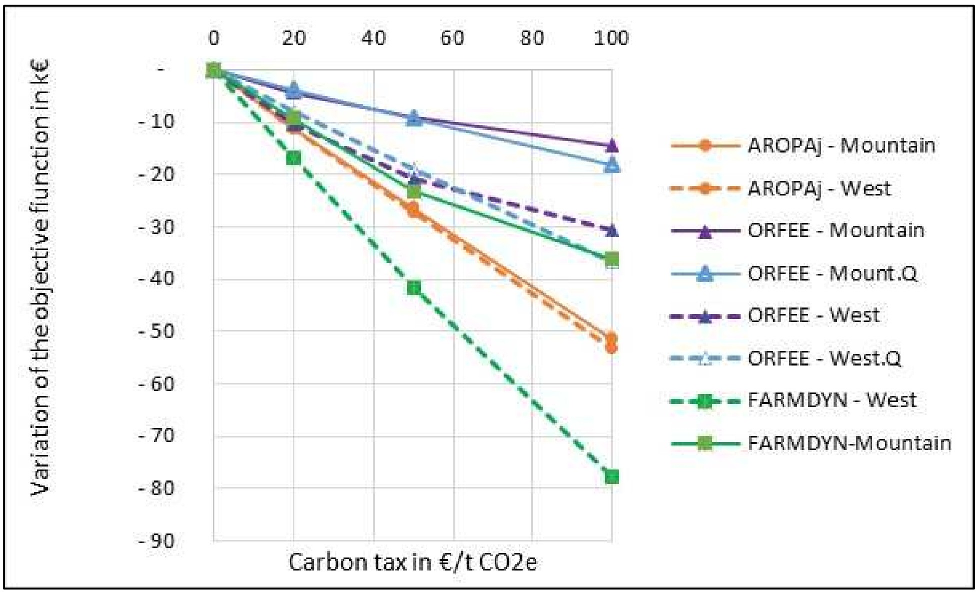

Figure 3. Sensitivity of the objective function of supply model to the carbon tax

3.3 Marginal abatement costs

All the models reduce their GHG emissions in response to a carbon tax, but the MAC curves have different shapes according to the model (Figure 4). In GLOBIOM, the abatement rate is almost constant. Emissions are reduced linearly along with herd reduction. In AROPAj, most emissions gains are obtained for a low level of tax. The externalization of feed and replacement heifer production appears

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[2] initial emissions in tons multiplied by 100 €/ton

[3] the simulated farms have between 1 and 2 worker units that earned around 30 k€/worker unit in BAU

as a cheap and efficient mitigation strategy if we consider that inputs will not be affected by the carbon tax outside the farm. In ORFEE, the highest abatement rate corresponds to the greatest herd size reduction. The abatement rate is far smaller when milk production is maintained. In FARMDYN, the higher rate of reduction is obtained for a 50 € carbon tax. The reduction of BAU GHG emissions obtained for a 100 € carbon tax ranges between 5% for the French dairy production in GLOBIOM and ORFEE Mount.Q (without possibility to modify milk production) to -70% in ORFEE West.

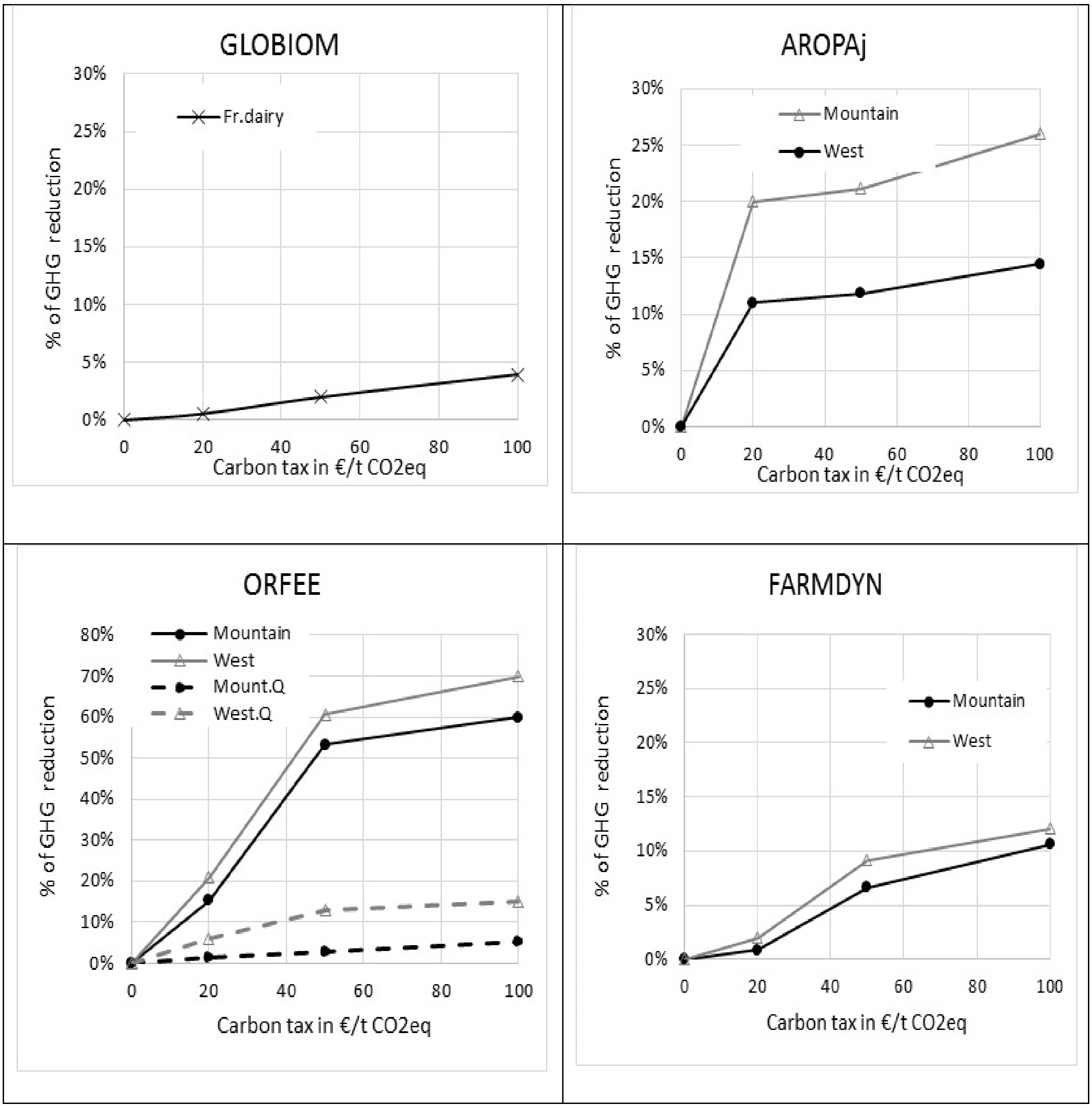

Figure 4. Marginal abatement cost curves: GHG reduction according to carbon tax level (in % of GHG emissions in BAU)

The distribution of this gain depends on the mitigation options used, emission sources or sink considered (Figure 5). The distribution between CO_2, methane and nitrous oxide reductions depends first on the degree of herd size reduction: a large reduction of methane means that the reduction of herd size has been significant. Second, the proportion of nitrous oxide reduction increases with mineral fertilization reduction. When CO_2 emissions related to land use change and sequestration in crop soil (GLOBIOM) are accounted for, they represent around 25% of the reduction. This proportion is greater in ORFEE when herd size is maintained.

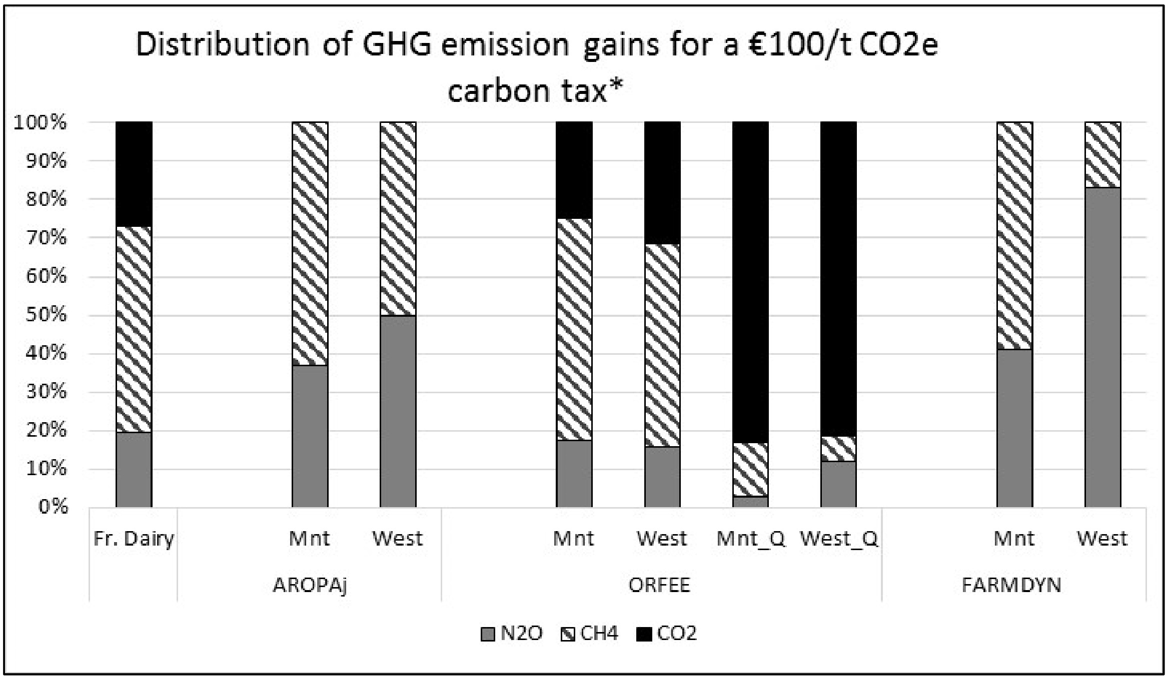

Figure 5. Distribution of GHG emission gains for a 100 €/t tax

4 Discussion

4.1 Mitigation strategies

We show that if a tax is implemented within a delimited system, one strategy to reduce GHG emissions is to partially or totally externalize the production process outside the modelled system. Although leakage occurs when one region has a less stringent environmental policy than another, (Juergens *et al.* 2013; Frank *et al.* 2015), unintended leakage is simulated in supply models such as the externalization of replacement heifers and feed production. These strategies could not conceivably be generalized to all farms without increasing the price of feed and heifers, either directly due to the tax or indirectly through market adjustments. The implementation of a life cycle analysis in ORFEE partly overcomes this leakage by considering emissions from the purchased inputs. This option has a strong impact on model results since we observe a reversal: a reduction of the purchased inputs and animal stocking rate in lines with previous farm level analysis (Adler *et al.* 2015). LCA is a valuable approach when the prime objective is to identity a strategy to reduce GHG emissions at farm level while avoiding pollution leakage. Nonetheless, it is 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 the externalization of the whole production process by lowering production levels. In GLOBIOM, pollution 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 reduction of milk production simulated directly reduces consumption. It avoids leakage, but raises questions about the impact of this change on human diet and health. This relatively small reduction of milk consumption may increase the demand for other products that may leave a larger carbon footprint (Esnouf *et al.* 2011). It can also induce a calorie deficit (Frank *et al.* 2017).

Apart from strategies resulting in a reduction of crop and animal production per unit of land, the simulated production per animal tends to increase with the tax, if not already at its maximum potential in the baseline. This corroborates previous findings (Monteny *et al.* 2006). However, in GLOBIOM, a reduction of the proportion of the most productive cows is simulated. 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 also explains why increasing the proportion of grassland emerges as an efficient strategy in ORFEE. We note that the cost-effectiveness of this strategy may be optimistic given the uncertainty in the estimated level of carbon stored in grassland soils (Mosnier *et al.* 2017a), which was high (570 kg C/ha/year) in comparison with other studies (Kragt *et al.* 2012).

4.2 Marginal abatement costs

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." In this study, we found the opposite: abatement rate was lower for GLOBIOM, which is a partial equilibrium model. We suggest that differences in abatement rates depend more on assumptions regarding costs and flexibility than on the type of model. Kuik *et al.* (2009) distinguish "where", "when'' and ''what' flexibilities. Simulation 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 −60% in ORFEE when milk production is allowed to decrease, up to −20% in AROPAj due to the externalization of heifer and feed production) for a relatively low carbon tax (50 €/t CO_2).

The "when" flexibility can be related to the transition or adjustment costs included in the model. Once buildings and machinery have been purchased, they may be difficult to move out, and so can be considered as sunk cost. In addition, structural rigidity can be added to the model. Capital is near-fixed in FARMDYN (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, which considered (in the simulations made here) that the current structure will not impact on its evolution in the next 20 years.

The "what" flexibility should be replaced by "how" in our context, since our question is what technologies will be used with dairy cattle. The range of technologies proposed to abate GHG emissions (younger age at first calving, calving period, animal diets, breed, producing below milk potential) has significant outcome on the MACCs. Among the different technologies proposed, the most cost-effective ones seem to be reduction of age at first calving (FARMDYN) and a higher proportion of grass in animal diets (GLOBIOM and ORFEE). They allow a large abatement of up to 10% (accounting for carbon storage). These abatement rates could have been greater if we had considered that some farm inefficiencies could be remedied cost-effectively (Pellerin *et al.* 2017), but in our baselines systems they are already optimized. Further promising strategies such as unsaturated fats and additives in animal diets

(Pellerin *et al.* 2017) were not introduced in the models we studied, and might have further increased the abatement rates.

5 Conclusion

Several studies have addressed the potential of agriculture to mitigate climate change, but their conclusions differ in many respects. This analysis compares mitigation strategies and abatement costs in dairy production across bio-economic models. Using different bio-economic models makes it possible to cover a larger range of mitigation strategies, since the different models were developed in different directions: when similarities are found, results are corroborated; when there is divergence, results are questioned. Coupling these models appears difficult since they optimize different things. However, the results reported here could help to improve each model by making more accurate assumptions on technology and flexibility.

We found that the main differences across studies were explained by the flexibility introduced into the optimization program. Simulation assuming a high "where" flexibility, meaning that the production process can be partly or totally externalized outside the system, achieved the highest abatement rates. Even so, these abatement strategies cannot be generalized at a large scale without inducing important leakage issues and market drawbacks. The "when" flexibility impacts on adjustment costs: a model that accounts for the dynamics of investments or that introduces structural rigidity reduces the sensitivity of milk production to a carbon tax. The "how" flexibility provides lower but more realistic perspectives of abatement rates (≈10%). Whether or not soil organic carbon is considered is important in explaining differences in results. From our findings, we can recommend favouring strategies that aim at reaching the full potential of animals, but without overly intensifying production per hectare, and partly replacing corn by permanent grassland and legume crops to feed animals.

Funding

This work was supported by the GloFoodS meta-program (ESPARE project) funded by the French National Institute for Agricultural Research (INRA) and the Agricultural Research Centre for Development (CIRAD).

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Appendix 1. Characteristics of animal production by technology for GLOBIOM 2030-BAU

		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 (tons of Dry Matter/year/cow)	*4.35*	*5.53*	*6.80*	*4.48*
	Grasss intake (% DM)	*71%*	*54%*	*44%*	*71%*
Replacement	Total intake (tons of Dry Matter/year/cow)	2.4	2.1	2.4	2.1
	Grasss intake (% DM)	87%	85%	74%	85%
	number of female replacements / cow	0.58	0.71	0.67	0.57
GHG	CH_4/milk	0.46	0.42	0.39	0.59
	Proportion in 2000	10%	32%	32%	26%
	Proportion in BAU	7%	26%	42%	26%

Note: characteristics of the production systems are the same in BAU as 2000

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

		Mountain.Q	West.Q
Production (kg /cow/year)	Milk	5755	7928
	Beef	140	275
Dairy cow	Total intake (tons of Dry Matter/year/cow)	5.6	6.3
	Grasss intake (% DM)	85	34
Replacement	Total intake (tons of Dry Matter/year/heifer)	2.4	2.4
	Grass intake (% DM)	94	73
	Number of female replacements / cow	0.66	0.81
GHG	CH_4/milk	0.73	0.66