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Coût de la modification du régime alimentaire des vaches laitières permettant de réduire les émissions de méthane entérique dans les élevages

Résumé

L'introduction de fourrages riches en oméga 3 comme l'herbe ou le lin dans la ration alimentaire des vaches laitières permet à la fois d'améliorer le profil nutritionnel du lait et de réduire les émissions de méthane entérique par litre de lait. Ce levier est intéressant dans la lutte contre le changement climatique mais peut également engendrer des coûts supplémentaires pour les exploitations. Des Paiements pour Services Environnementaux, comme la démarche Eco-Méthane portée par l'association Bleu-Blanc-Cœur en France, peuvent encourager la modification du régime alimentaire dans les élevages laitiers en valorisant la réduction des émissions de méthane. L'efficacité d'un tel dispositif passe par la définition (i) d'un indicateur des émissions de méthane entérique suffisamment fin pour prendre en compte l'effet de l'alimentation, (ii) d'un niveau de paiement suffisamment incitatif pour compenser les éventuels surcoûts pour les éleveurs. Cette étude compare deux indicateurs d'émissions de méthane entérique permettant de mettre en évidence l'effet de la prise en compte de l'alimentation. Elle évalue également le surcoût de production laitière d'une augmentation des surfaces en herbe dans l'assolement fourrager des exploitations. L'estimation d'une fonction de coût variable à partir des données du Réseau d'Information Comptable Agricole met en évidence une augmentation significative du coût marginal de production laitière avec davantage d'hectares d'herbe dans les exploitations de montagne et dans les exploitations de plaine pour lesquelles le maïs ensilage représente moins de 30% de la surface fourragère principale.

Mots-clés : paiements pour services environnementaux, réduction des émissions de gaz à effet de serre, production laitière, coût marginal

Classification JEL : Q10, Q52, Q54

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Abstract

Introducing fodder with high omega 3 content such as grass or linseed in the feed ration of dairy cows both improves the milk nutritional profile and reduces enteric methane emissions per litre. This lever is interesting to contribute to climate change mitigation but can also generate additional farm costs. Payment for Environmental Services, such as the Eco-Methane programme implemented by the association Bleu-Blanc-Cœur in France, can support a change of cows' diet in dairy farms through the valorisation of methane emissions reduction. The effectiveness of such a scheme depends on (i) the definition of a precise indicator of enteric methane emissions capturing the feeding effect, (ii) a payment level that would be sufficiently attractive to compensate for the additional costs faced by farmers. This study compares two indicators of enteric methane emissions to show the effect of taking feeding into account. It also assesses the extra cost of milk production if the grassland areas in fodder crop rotation systems were to be increased in French dairy farms. The estimation of a variable cost function based on data from the Farm Accountancy Data Network (FADN) suggests a significant increase of the marginal cost of milk production with additional hectares of grass in mountainous areas, and in plains farms for which maize silage represents less than 30% of the fodder crop rotation system.

Keywords: payment for environmental services, reduction of greenhouse gas emissions, milk production, marginal cost

JEL classification: Q10, Q52, Q54

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1. Introduction

The agricultural sector is a major source of greenhouse gases (GHGs), accounting for 19% of French emissions and 10% of EU-KP's (European Union, United Kingdom and Iceland) in 2018 (Citepa, 2020a; European Environment Agency, 2020). The specificity of agricultural emissions is that they are mostly related to biological processes rather than energy processes (Pellerin *et al.*, 2013). 59% of the GHG emissions of the sector in the EU-KP comes from the enteric fermentation and manure of livestock farming, which mainly produce methane gas. Moreover, 81% of agricultural methane emissions results from enteric fermentation and 39% of those 81% are produced by dairy cows (European Environment Agency, 2020). In this study, we aim at providing more insights on the design of Payment for Environmental Services (PES) schemes targeting the reduction of enteric methane emissions in dairy farms.

Methane is the second contributor to radiative forcing. Currently, its Global Warming Potential is set at 28 times higher than carbon dioxide over 100 years, and 84 times higher over 20 years. However, as methane is a short-lived climate pollutant continuously destroyed in the atmosphere, its effect on climate change mostly depends on short-term emissions rate. In theory, decreasing methane emissions rate below its natural destruction rate would have a cooling effect (Cain *et al*., 2019). Therefore, a significant reduction of methane emissions would rapidly mitigate climate change and is a powerful lever to meet the European Union's 2050 climate targets (Dupraz, 2021).

Enteric fermentation is identified as the first source of GHG emissions in dairy farms in both developed and developing countries (Jayasundara *et al*., 2019; Wilkes *et al*., 2020). Enteric methane emissions are directly related to the feed ration composition and the proportion of carbohydrates it contains (Martin *et al.*, 2010). For a given productivity level, enteric methane emissions decline as dairy cows' feed is enriched with unsaturated omega-3 fatty acids (Grainger and Beauchemin, 2011). Moreover, as productivity per cow increases, methane emissions per kilogram of milk decreases (Martin *et al*., 2006). In order to accurately estimate and reduce methane emissions of dairy farms, one must consider both dimensions (productivity and feeding). In this study, we examine two aspects of a PES scheme for which failing to take into account the feeding dimension could undermine the effectiveness of the scheme: the choice of emissions indicator and the level of the payment.

Authors show enteric methane emissions can significantly differ from one indicator to another and recommended to take both production intensity and feed usage into account *(Hagemann et al.*, 2011). Numerous studies have been carried out to understand the connection between fat intake and methane emissions *(Dong et al., 1997; Grainger and Beauchemin, 2011; Martin et al*., 2011, 2010, 2008, 2006). They contributed to the identification of a formula linking methane emissions per litre of milk to the fatty acid profile of milk (Chilliard *et al.*, 2009), and to the development of the Eco-Methane methodology for calculating emissions. This scientific literature suggests that reducing enteric emissions is possible by enriching dairy cows' feed with Alpha Linolenic Acid ALA (polyunsaturated fatty acid of the omega 3 family), for which the main natural sources are linseed and grass fodders. Current bio-economic models estimating emissions abatement costs in the agricultural sector do not have a precise indicator of methane emissions that can assess the impact of adding more unsaturated fats in dairy cows diet (Lengers *et al*., 2013; Mosnier *et al.*, 2019). By examining how dairy cows' diet influences enteric emissions, our objective is to show the relevance of using an emission indicator sensitive to diet when defining economic incentives for the reduction of GES emissions.

In France, farmers can be rewarded for reducing enteric emissions by participating in Eco-Methane, a programme implemented by the Bleu-Blanc-Coeur (BBC) association. Although not qualified as a PES scheme by its initiators, the Eco-Methane programme meets the reference definition by Wunder. Private actors (service users) give financial support to volunteer farmers (service providers) for actions that contribute to climate change mitigation (environmental services) (Wunder, 2015). The payment level is conditional on the reduced amount of CO_2eq, which makes Eco-Methane a result-based PES. Eco-Methane brings together more than 600 farmers whose emissions reduction was estimated at 11% on average in 2017 (Bleu-Blanc-Coeur, 2020). The scheme's main strengths lie in the strong scientific foundations of the method for quantifying emissions and the easy participation procedure for dairy farmers. Each contract signatory commits to provide a monthly milk analysis to the association and to include feed with high content of sources of omega-3 in dairy cows' ration (alfalfa, extruded linseed, grass). The environmental service is measured each month based on the difference between farm's emissions per litre of milk and baseline values. BBC pays farmers according to their provision of units of reduction of methane emissions in CO2eq with a financial envelope resulting from the collection of donations from private actors. The amount of money given by each contributor is voluntary and can vary from one year to the next. The Eco-Methane programme is recognised by the United Nations as a GHG emission reduction project eligible for issuing carbon credits (UNFCCC, 2016).

To be efficient, the payment level of a PES scheme targeting GHG emissions should be equal to the optimal carbon tax (first best solution). In France, the closest financial tool to a carbon tax is the Climate and Energy Contribution proportional to the carbon dioxide content of energy products (fossil fuels) (Rogissart *et al*., 2018). The contribution level was 30€/tCO2eq in 2017, and raised to 40€/tCO2eq in 2018 and 2019. As a comparison, farmers participating in the Eco-Methane programme received an average of 15€/tCO2eq in 2017 (Bleu-Blanc-Coeur, 2020), suggesting that the scheme's payment is sub-optimal and provides little incentive. While numerous other motivations may encourage farmers to join the programme such as improving milk quality, the environment quality, zootechnical performances and the image of agriculture, economic interests are likely to be crucial factors. Changing cows' diet to improve the milk fatty acid profile can generate additional production costs that are not yet evaluated. Our study quantifies the additional cost of a change in cows' diet at the farm level in order to evaluate the economic incentives needed for improving dairy systems toward more environmentally friendly practices.

In the first section, we examine the impact of taking feeding into account in the calculation of enteric methane emissions of a panel of French dairy farms from the Farm Accountancy Data Network (FADN) by comparing an indicator constructed using the Eco-Methane methodology with an indicator that only takes into account productivity. In the second section, we estimate a variable cost function of milk production to assess marginal costs and evaluate the extra-cost associated with adding more grass in fodder crop rotation systems. Finally, we discuss our results.

2. Stylised facts on the effects of dairy cows' diet in the calculation of enteric emissions

In this section, we examine how feeding may influence enteric methane emissions using a panel of French dairy farms from the Farm Accountancy Data Network (FADN). We compare an indicator based on the Eco-Methane methodology that takes productivity and feeding into account with a second indicator calculated from productivity only. A balanced panel of 735 FADN dairy farms for the years 2016 to 2018 was selected for the study (Agreste, 2020). This database is available online and is representative for socio-economic and accountancy information of French medium and large farms, and is therefore relevant for assessing the financial needs of dairy farms to join a national programme such as Eco-Methane. As the compositions of the feed ration and milk are not provided, information on dairy cows' diet is limited. However, data on the fodder crop rotation systems are available, which allows us to assess a change of crop rotation to approximate a change of feed composition. Some descriptive statistics of our sample are presented in Appendix A.

2.1. Baseline enteric emissions using the Eco-Methane methodology

Enteric methane emissions (gCH_4/L) can be calculated from milk productivity (kg/cow/year) and the ratio of the sum of fatty acids with 16 carbon atoms or less $FA \leq C16$ over the total amount of fatty acids $totalFA$. This ratio has a strong biological causal relationship with methanogenesis in the rumen, and is significantly reduced by omega-3 intakes.

$$Methane = 11.368 * Productivity^{-0.4274} * \frac{FA \leq 16}{totalFA} \quad (1)$$

This formula was co-invented by teams from the animal feed manufacturing company Valorex (P. Weill and G. Chesneau) and the French National Institute for Agricultural Research (INRA) (Y. Chilliard, M. Doreau and C. Martin). It received a patent under the title "Method for evaluating the quantity of methane produced by a dairy ruminant and method for decreasing and controlling such quantity" (WO2009156453A1) (Weill *et al.*, 2009). The equation allows the calculation of enteric methane emissions per unit of product by taking into account both milk productivity and feed quality, and is used in the Eco-Methane programme to evaluate the reduction of methane emissions in participating farms.

Table 1: Characteristics of the eleven baseline scenarios of the Eco-Methane programme

Scenario	Maize silage in the fodder area	Production basin	Baseline emissions (gCH_4/L) (annual mean)
1	More than 30%	Plains outside the western region	15.75
2		Plains of the western region	15.92
3	Between 10 and 30%	Plains outside the western region	15.83
4		Plains of the western region	16.43
5	Less than 10%	Plains outside the western region	16.56
6		Plains of the western region	17.38
7	More than 10%	Mountains	15.96
8	Less than 10%	Mountains of the Massif Central	17.13
9		Mountains of the Northern Alps	17.83
10		Mountains of Franche Comté	16.22
11		Other mountains	17.20

Source: Bleu-Blanc-Coeur.

The Eco-Methane methodology defines eleven baseline scenarios according to large production basins and fodder crop rotation systems (Table 1). These scenarios correspond to the eleven fodder systems of French specialised dairy farms characterised in 2009 by the French Dairy Interbranch Organization (CNIEL) in collaboration with the French Livestock Institute (IDELE) (CNIEL, 2015). The baseline values of enteric methane emissions used in 2019 were obtained from the association Bleu-Blanc-Cœur. The emissions of each scenario are available per month. We keep the annual average to define the Eco-Methane baseline emissions indicator.

An individual baseline scenario was assigned to each farm of the sample based on two criteria: the location and the share of maize silage in the fodder area of the farm. The FADN data are too limited to estimate individual enteric methane emissions of French farms using Equation 1. Nevertheless, they are sufficient to identify their Eco-Methane scenario and therefore their baseline emissions if they enter the programme. In the FADN database, the farm location variable corresponds to the 21 old French administrative Regions (the administrative divisions were changed in 2015), while the Eco-Methane scenarios are defined according to large production basins built from a lower administrative level (Departments). It was therefore necessary to allocate a production basin to each administrative Region. For the

Regions with Departments belonging to different production basins, we allocated the basin of the Departments producing the highest volumes of milk to the entire Region. This attribution was made using the 2018 annual dairy survey (Agreste, 2019) (Appendix B). Thus, our scenario allocation is based on, but less accurate than the one undertaken in Eco-Methane.

2.2. Enteric methane emissions according to an IPCC Tier 2 method

In order to obtain an indicator of individual enteric emissions of the sample farms using the data available in the FADN, we use the calculation method of Intergovernmental Panel on Climate Change (IPCC) rank 2 currently used by the French Technical Reference Center for Air Pollution and Climate Change (Citepa) to make the national inventory of GHG emissions (Citepa, 2020b). Unlike the Eco-Methane baseline emissions indicator, the emission factor EF does not take into account feeding information. EF (kgCH_4/dairy cow/year) is calculated from the herd's milk production (L/year).

$$EF = 0.0105 * \frac{Herd\ production}{Number\ of\ dairy\ cows} + 48.971 \quad (2)$$

We obtain a "Tier 2" indicator of emissions per litre of milk of the same unit as the Eco-Methane baseline emissions indicator (gCH_4/L) from the dairy cows' productivity (L/cow).

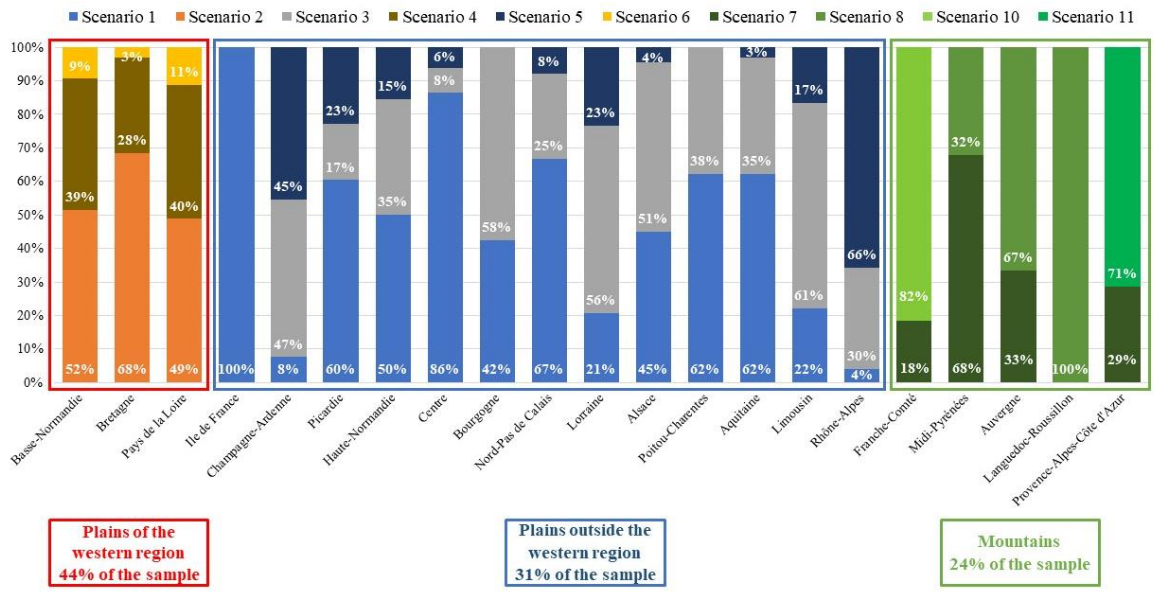
$$Tier\ 2 = \frac{EF}{Productivity} \quad (3)$$

2.3. Allocation of scenarios and distinction of three milk production basins

Following the allocation of the Eco-Methane baseline scenarios to the sample's farms, we observe their proportion within each former administrative Region (Figure 1). Farms in the Regions of the western plains basin represent 44% of the sample and are characterised by a strong dominance of silage maize and therefore few grasslands in their forage crop rotation system. For example, 68% of farms in Brittany would be assigned scenario 2 with more than 30% of maize in the forage crop rotation, and 28% scenario 4 with 10 to 30%. We note that Nord-Pas de Calais has a similar profile to Brittany. The administrative Regions of the production basins of the plains outside the western region (31% of the sample) and the mountainous areas (24% of the sample) are quite different one from another. Some Regions such as Rhône-Alpes contain a high proportion of systems dominated by grasslands (less than 10% of maize silage in the fodder crop rotation), while others such as Centre have more intensive systems dominated by maize silage. All the observations in our sample from the Languedoc-Roussillon Region correspond to systems with less than 10% maize in the forage crop rotation (grazing systems), while those from the Midi-Pyrénées Region have a relatively small proportion (32%) of systems with less than 10% maize. Note that due to the missing information on Departments in the FADN dataset and our scenario allocation procedure, some farms have been allocated to a plain system scenario while in reality they are located in a mountainous Department and vice versa. It might partly explain the large share of farms with grazing systems in the Rhône-Alpes Region. Nevertheless, those farms produce relatively low volumes of milk in comparison with farms from the plains Departments.

In the rest of the study, we work at the scale our three major production basins previously defined: the western plains, the plains outside the western region and the mountainous regions.

Figure 1: Distribution of Eco-Methane baseline scenarios among French old administrative Regions.



Source: The authors based on French FADN and Bleu-Blanc-Coeur data.

2.4. Enteric emissions: relation with productivity and fodder system

The average of the Tier 2 indicator for the sample is 18.5 gCH_4/L while it is 16.3 gCH_4/L for the Eco-Methane baseline indicator. Hence, taking the fodder cropping system into account in the calculation in addition to productivity makes it possible to revise enteric methane emissions downwards. Both indicators show a decrease in emissions per litre of milk as milk productivity increases (Table 2). Farms in mountains emit significantly more methane per litre of milk according to indicator Tier 2 than those in the lowlands, which can be explained by their lower productivity. The same observation is made with the Eco-Methane indicator, but the difference between the groups is significantly less (Table 2 and Figure 2). It fits with the hypothesis that a diet dominated by fodder rich in omega-3 (dairy farms typically feed cows with more grass in mountains) reduces emissions per litre of milk.

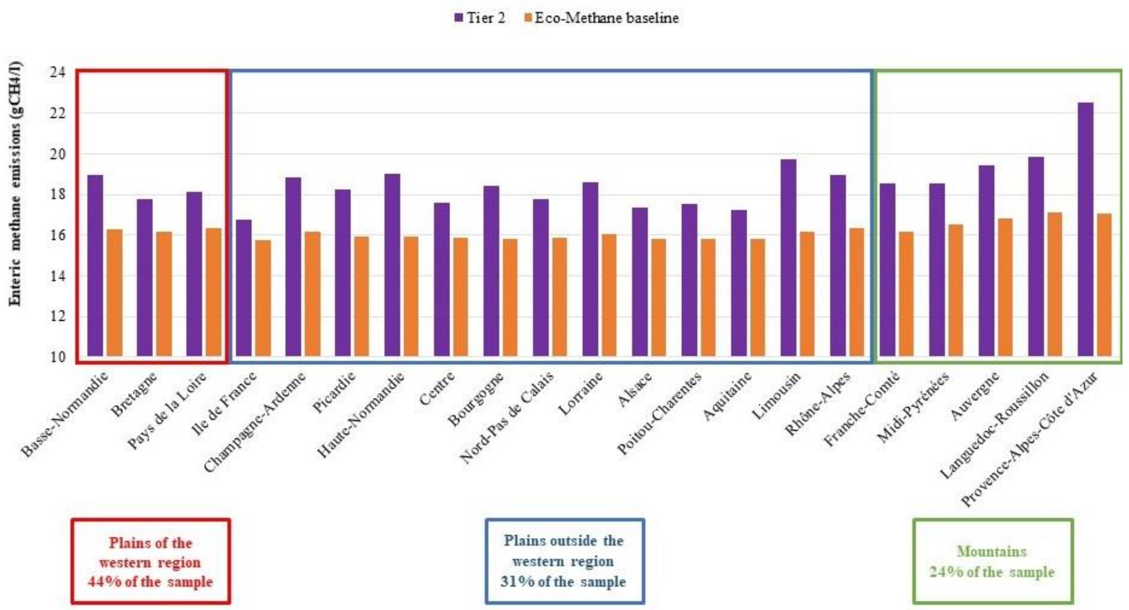
Our observations are in line with the literature (Grainger and Beauchemin, 2011; Martin *et al*., 2006). A recent meta-analysis of life cycle assessments also highlighted the negative relationships between milk yield and enteric methane emissions on the one hand, and pasture intake and enteric methane emissions on the other hand (Lorenz *et al*., 2019). Other authors also show that enteric methane emissions can significantly differ from one indicator to another, particularly in grazing systems, (Hagemann *et al*., 2011). Choosing the adequate indicator of enteric methane emissions is the topic of on-going debates. Most bio-economic models applied to the agricultural sector do not integrate a precise indicator of methane emissions capturing the impact of adding more unsaturated fats in dairy cows diet, making it impossible to evaluate the costs of implementing this lever to reduce enteric emissions (Lengers *et al*., 2013; Mosnier *et al*., 2019). The Eco-Methane methodology could contribute to improve those models.

Table 2: Average enteric emissions in Eco-Methane scenarios according to the two indicators

Scenario	Maize in the fodder area	Production basin	Productivity (L/cow)		Tier 2 (gCH_4/L)		Eco-Methane baseline (gCH_4/L)		Difference of emissions by taking into account the feeding system	
1	> 30%	Plains outside the western region	7654.6	6986.2	17.35	18.48	15.75	16.07	-9%	-13%
3	10-30%		6944.4		18.14		15.83		-13%	
5	< 10%		5717.8		19.75		16.56		-16%	
2	> 30%	Plains of the western region	7331.8	6976.0	17.70	18.14	15.92	16.24	-10%	-10%
4	10-30%		6789.3		18.30		16.43		-10%	
6	< 10%		5586.5		20.20		17.38		-14%	
7	≥ 10%	Mountains	6910.1	6201.8	18.10	19.01	15.96	16.55	-12%	-13%
8 to 11	< 10%		5943.8		19.35		16.69		-14%	

Source: The authors based on French FADN and Bleu-Blanc-Coeur data.

Figure 2: Average enteric emissions in French old administrative Regions according to the two indicators



Source: The authors based on French FADN and Bleu-Blanc-Coeur data.

Although methane emissions calculated according to the IPCC rank 2 method are not significantly different between the western plains and the other plains, their Eco-Methane baselines are (Table 2). Taking into account the fodder crop rotation system, enteric methane emissions are higher in the western plains. As the productivity of the two groups is not significantly different, we can assume their fodder systems explain the better environmental performance of the plains outside the western region. As suggested by the distribution of Eco-Methane scenarios (Figure 1), maize silage dominates more in the western plains (32% of the fodder area on average) than in the other plains (21%). It can be assumed that in the plains outside the western region, the feed ration of dairy cows includes more grass or other fodders with high omega 3 content. In addition, the lower the share of maize silage in the fodder area (and therefore the more grasslands), the higher the difference in emissions provided by the two indicators.

It is worth mentioning that the data do not allow us to calculate individual methane emissions from the FADN farms according to the Eco-Methane method. Therefore, we only observe the effect of feeding through the baselines of the 11 scenarios. In particular, the construction of the baselines is based on the location and the share of maize in the forage area. They contain indirect information on the share of other fodders such as grass in the diet of dairy cows, but not on the use of complements rich in omega-3 such as extruded linseed. However, while the positive effect of grass on methane emissions is likely to be partly offset by a drop in cows' productivity, linseed presents the advantage of reducing emissions by providing a high level of omega-3 while maintaining a good level of productivity (Fuentes *et al*., 2008).

3. Estimation of the extra cost of milk production when adding grass in fodder cropping systems

Since the composition of cows' feed ration and milk are not available in the FADN, the effect of an improvement of the fatty acid profile cannot be directly analysed. Instead, we assume an evolution of the fodder crop rotation. As grass is a high source of omega 3 fatty acids strongly encouraged in Eco-Methane, we assume that a commitment to the programme would lead to an increase in grassland surfaces in farms. This hypothesis is quite strong and implies that our estimation of extra-costs does not take into account neither the strategy of supplementing the ration with other feeds with high omega-3 content such as extruded linseed, nor the optimisation of grazing increasing grass yield and quality without necessarily increasing grassland surfaces.

Using the same balanced panel as in section 2. , we evaluate the additional costs associated with an increase in grassland areas in French dairy farms. Based on the dual production theory

(McFadden, 1978), we estimate a variable cost function VC describing expenditures in variable production factors x with exogenous input prices w that minimise variable costs given the production level y targeted by the farmer and available quasi-fixed inputs z such as land, labour and equipment that are assumed predetermined on the short-term.

$$VC(w, y, z) = \min_{x} wx \;\; subject\ to\ y \leq f(x,z) \tag{4}$$

The variable cost function is concave, non-decreasing and homogeneous of degree 1 in input prices, decreasing with fixed factors of production, and convex according to output levels.

3.1. Econometric model

We estimate a system of equations comprising a homogeneous translog cost function (5) in which variable costs VC correspond to intermediate consumption, and the variable inputs cost shares functions (6) and (7).

The Translog functional form is commonly used in the literature on the cost structure and efficiency of dairy farms because of its flexibility and the possibility to impose homogeneity of degree 1 (Alvarez and Arias, 2003; Moschini, 1988; Mosheim and Lovell, 2009; Nehring *et al.*, 2009; Singbo and Larue, 2016; Sobczyński *et al.*, 2015; Wimmer and Sauer, 2020). *i* and *t* are indices for individuals and years respectively. Dairy farms produce one output, the quantity Y_1 of cow's milk produced per year (*Milk production*). We consider two variable inputs, fuel X_1 and cattle feeding stuffs X_2, for which their expenses represent a high share of intermediate consumptions. The choice of including fuel rather than fertilizer expenses is motivated by the possibility of calculating farm-level fuel prices and therefore capture more heterogeneity. The price of fuel W_1 (*Fuel price*) is calculated from the non-road gas oil expenses and volumes. As individual cattle feeding stuffs prices are not available in the data, W_2 (*Feed price*) is measured by the index of purchase prices of the means of agricultural production (IPAMPA) for adult cattle feeding stuffs of year *t-1*, available for each French current administrative Regions. Grassland surfaces Z_1 (*Grassland*) include permanent and temporary pastures, alfalfa for dehydration and other artificial fodders. We include two other assumed quasi-fixed factors of production: machinery and constructions fixed assets Z_2 (*Capital*) and annual work units Z_3 (*Labour*). The aggregated volume Y_2 of the other products of the farm (*Other productions*) is included as a control variable to capture the heterogeneity linked to diversification. Y_2 is calculated as the total gross product of the year (crop products, livestock products and other products) net of animal purchases and cow's milk production, deflated by the French agricultural producer price index (API) of year *t*.

The homogeneous translog variable cost function is given by:

$$\ln\frac{VC_{it}}{W_{1it}} = \alpha_0 + \sum_{r=1}^{2}\beta_r \ln Y_{rit} + \alpha_2 \ln\frac{W_{2it}}{W_{1it}} + \frac{1}{2}\alpha_{22}\left(\ln\frac{W_{2it}}{W_{1it}}\right)^2 + \sum_{h=1}^{3}\delta_h \ln Z_{hit} + \frac{1}{2}\beta_{11}\ln Y_{1it}{}^2 + \frac{1}{2}\sum_{h=1}^{3}\sum_{k=1}^{3}\delta_{hk}\ln Z_{hit}\ln Z_{kit} + \sum_{h=1}^{3}\nu_{2h}\ln\frac{W_{2it}}{W_{1it}}\ln Z_{hit} + \sum_{h=1}^{3}\rho_{1h}\ln Y_{1it}\ln Z_{hit} + \zeta_{12}\,ln\,Y_{1it}\,ln\frac{W_{2it}}{W_{1it}} + u_{3it} \quad (5)$$

The variable input cost shares (6) and (7) are derived from Shephard's lemma.

$$\frac{X_{1it}W_{1it}}{VC_{it}} = 1 - \alpha_2 - \alpha_{22}\ln\frac{W_{2it}}{W_{1it}} - \sum_{h=1}^{3}\nu_{2h}\ln Z_{hit} - \zeta_{12}\,ln\,Y_{1it} + u_{1it} \quad (6)$$

$$\frac{X_{2it}W_{2it}}{VC_{it}} = \alpha_2 + \alpha_{22}\ln\frac{W_{2it}}{W_{1it}} + \sum_{h=1}^{3}\nu_{2h}\ln Z_{hit} + \zeta_{12}\,ln\,Y_{1it} + u_{2it} \quad (7)$$

As grassland areas, milk production and input use can be simultaneous decisions, $\ln Z_{1it}$ and $\ln Y_{1it}$ are likely to be correlated with the error terms. To correct for endogeneity, we adopt a Three-Stage Least Squares regression analysis with instrumental variables (3SLS-IV). We include as instrumental variables the milk selling price P_1 (*Milk price*), the Utilised Agricultural Area (UAA) Q_1 (*Utilised agricultural area*), the permanent pastures area Q_2 (*Permanent pastures*), the number of dairy cows in the farm Q_3 (*Number of dairy cows*) and 20 regional dummies D_{ri} approximating the pedoclimatic conditions. These variables were chosen to capture important factors influencing farmers' simultaneous decisions of cattle feeding strategy and output level each year. By doing so, we assume the UAA and surfaces of permanent pastures (installed for at least 5 years) are exogenous over the period of the analysis (3 years). We include the number of dairy cows as instrumental variable based on the observation that Q_3 presents little intra-individual variability from one year to the next. We therefore consider the number of dairy cows to be a quasi-fixed decision on the short term and keep it in the model. The instrument M_{it} comprising all the exogenous and instrumental variables of the model is used to regress the endogenous variables in the three equations of the system and is presented in Appendix C.

The system of equations (5) + (6) + (7) is estimated for all the farms of the sample, and then for the three major production basins and groups of Eco-Methane scenarios defined in 2.3 in order to identify potential differences of extra-costs according to the type of dairy system. The descriptive statistics of the model variables are presented in Appendix D.

3.2. Estimation of variable costs

The detailed results of the estimations are presented in Appendix E. Several model specifications were tested and the results are robust to a change of estimation procedure (single variable costs equation, system of equations with and without imposing constraints on the parameters). The estimation of variable inputs shares provides additional information and improves the quality of the variable cost estimation (measured by the R^2). Consistent with the hypothesis of cost minimisation, imposing restrictions on the parameters across equations also improved the variable cost estimation quality. Therefore, we present the results of the constrained system estimation. All the reported first-stage F-statistics were above 10, suggesting no weak instruments.

We verify that the variable cost function is non-decreasing with input prices (positive estimated variable input cost shares). However, some of the empirical models do not respect all the theoretical properties of a cost function. In particular, variables costs are decreasing with at least one quasi-fixed factor of productions only in the model applied to the entire sample and for the sub-sample of plain farms with less than 30% of maize silage in the fodder area.

3.3. Impact of increasing the grassland area on the marginal cost of milk production

The first-order derivative of the variable cost function (5) gives us the marginal cost function (8) in which parameter ρ_{11} corresponds to the effect of grassland surfaces on the marginal cost of milk.

$$\frac{\partial VC_{it}}{\partial Y_{1it}} = \frac{VC_{it}}{Y_{1it}}\left(\beta_1 + \beta_{11}\ln Y_{1it} + \sum_{h=1}^{3}\rho_{1h}\ln Z_{hit} + \zeta_{12}\, ln\frac{W_{2it}}{W_{1it}}\right) \tag{8}$$

The results presented in the following paragraphs are calculated from the regression results presented in Appendix E.

When applied to all farms of the sample and on the sub-samples of farms from the two plain production basins, the model suggests that producing milk with more grass does not significantly affect variable costs (Table 3). There are significant extra-costs per additional hectare of grassland in mountainous areas (+3€6/1000L/ha) already facing high marginal production costs and lower productivity.

Table 3: Extra-cost of milk production with an increase of grassland areas per production basin

Production basin	Eco-Methane baseline (gCH_4/L)	Productivity (L/cow/year)	Marginal cost (€/1000L)	Extra-cost (€/1000L/ha)	R^2 of the variable cost regression
France	16.26	6708	274.2	0.41	0.81
Plains of the western region	16.24	6976	166.7	7.74	0.43
Plains outside the western region	16.07	6720	286.0	-0.17	0.86
Mountains	16.55	6202	302.5	3.59^{+}	0.79

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: The authors based on French FADN and Bleu-Blanc-Coeur data.

Behind the non-significant extra-costs found in plain production basins lies a disparity depending on the type of fodder system (Table 4). Considering all lowland farms (within and outside the western region), we compare those with a share of silage maize in the forage area greater than 30% to those with a maize share of less than 30%. Extra-costs are significantly lower when the share of maize is high (or the share of grasslands low). Indeed, we find non-significant extra-costs per additional hectare of grass for farms with more than 30% of maize in the fodder area, but positive additional costs of 7€1/1000L/ha for those with less than 30%. Again, we observe lower extra production costs per hectare of grass for farms with higher productivity and lower marginal costs.

Table 4: Extra-cost of milk production with an increase of grassland areas per fodder system in plains

% maize silage in the fodder area	Eco-Methane baseline (gCH_4/L)	Productivity (L/cow/year)	Marginal cost (€/1000L)	Extra-cost (€/1000L/ha)	R^2 of the variable cost regression
≥30%	15.87	7427.4	211.8	-11.64	0.75
< 30%	16.41	6422.2	231.2	7.08^{***}	0.76

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: The authors based on French FADN and Bleu-Blanc-Coeur data.

Our results suggest that the financial needs for dairy farms to incorporate more grass in their fodder crop rotation system are different from one system to another. In particular, we show that dairy farms with already high shares of grasslands might require higher levels of economic incentives to adopt this climate change mitigation lever.

4. Discussion

The choice of environmental indicator in a PES scheme targeting the reduction of enteric methane emissions in dairy farms is likely to affect its environmental performance. An indicator such as the one constructed through the Eco-Methane methodology presents several advantages to be implemented at a large scale and be a better proxy compared with current IPCC tier 2. It is precise enough to capture farmers' efforts on both cows' productivity and the feed ration composition. Therefore, it takes into account the potential of an omega-3-rich diet as a climate change mitigation practices. This feeding strategy is already implemented in dairy systems integrating a large share of grasslands in their fodder crop rotation systems, with the side provision of other environmental benefits (biodiversity maintenance). The Eco-Methane methodology estimates enteric methane emissions from the fatty acids composition of milk obtained with infrared spectroscopy. Milk infrared spectroscopy is relatively simple to integrate in the milk analysis routine of dairy farms and involve low costs. However, the accuracy of indicators based on milk analyses could be further improved by controlling for factors likely to affect the correlation between milk fatty acids composition and enteric emissions such as the lactation stage (Negussie *et al.*, 2017). By calculating emissions per litre of milk, the Eco-Methane indicator takes into account both the issue of climate change mitigation and food security. Additionally, the fatty acids composition of milk provides information on the complementary health benefits for consumers of an increase of sources of omega-3 fatty acids in dairy cows' diet (Weill *et al*., 2002).

Nevertheless, the environmental performance of PES schemes targeting specifically enteric methane emissions depends on the absence of negative spill-overs on other factors of GHG emissions in dairy farms (fertilisation management). Farm level assessments of GHG emissions remain crucial to support effective mitigation strategies.

Not taking into account the feeding strategy of dairy farmers, and in particular the type of fodder system, could also lower the attractiveness of a payment scheme. Our study confirms the relevance of considering the variability of dairy systems when studying farmers' willingness to accept for entering a PES programme, as we find different extra production costs linked to the modification of fodder crop rotations (increase of the grassland area). It would be relevant to consider this heterogeneity when establishing an optimal payment for environmental services. An increase in grassland areas seems to imply additional variable costs per litre of milk in mountainous farms with already a high share of grasslands in the fodder crop rotation. The marginal cost of milk production is not significantly increased at the scale of France and at the scale of the plain production basins. Other authors found evidence of differences of emissions abatement costs among dairy farms according to their geographical location (Njuki and Bravo-Ureta, 2015). Our results also highlight differences according to the fodder system among plain farms. We find non-significant additional costs in productive farms with a high share of maize silage in the fodder area (few grasslands), and positive additional costs in those with a relatively low share of maize silage (more grasslands) and lower productivity.

Those findings support our hypothesis that extra-costs of milk production may be a factor explaining the low participation in the Eco-Methane programme. Additional costs can be explained by an increase in energy consumption (machinery) and other expenses (seeds, fertilisers, etc.) related to pastures and alfalfa management. However, joining a programme such as Eco-Methane and producing milk with more grasslands by replacing hectares of cereals with grass or by increasing the fodder area with new grass plots could represent a positive economic incentive in the most intensive lowland farms. Indeed, current dominant fodder systems involve high expenditures on specific maize inputs (seeds, herbicides, etc.) and high protein content complements (soya, rapeseed) to balance dairy cows feed ration. Adding more grass and benefiting from an Eco-Methane payment would therefore reduce dependence on costly inputs. Synergies between the reduction of GES emissions and the economic performance of intensive dairy farms have already been pointed out in the literature (Borreani *et al*., 2013; Jayasundara *et al.*, 2019).

By allocating a fixed financial support per unit of reduction of enteric methane emissions, the Eco-Methane programme could potentially "overpay" some dairy farms for which the extra-costs of feed modification would be less than the payment, and "underpay" other dairy farms for which the same actions imply higher additional costs. Through the definition of different baseline scenarios, the programme's design partially takes into account the variability in the potentiality of environmental services provision according to the production basin and the fodder system. Hence, rather than rewarding farms that produce the least emissions per unit of product (which would tend to favour the most productive farms), Eco-Methane supports all efforts of emission reductions.

Given the low level of Eco-Methane payment, it seems reasonable to assume that participating farms already had a good economic profitability and/or feeding practices compatible with emission reductions when entering the programme. In the prospect of engaging more farmers and more litres of milk in the feed ration transition, we identify three additional types of dairy farms that could integrate Eco-Methane. Farms for which reducing enteric emissions is already profitable (no or negative extra-costs) (type 1), farms for which it requires little financial support (low but positive extra-costs) (type 2), and farms for which it requires high financial support (high positive extra-costs) (type 3). Our study suggests that plain intensive farms broadly correspond to type 1. Although their individual willingness to accept is likely to be low, the programme would still need important financial means to offer a payment given the large number of unit of emissions reductions to compensate (high milk productivity). On the contrary, dairy farms located in mountainous regions or with a high share of grasslands are more likely to correspond to type 3 and exhibit a high individual willingness to accept. Attracting them into the programme would require a high level of payment per tCO_2eq for fewer units (lower milk productivity). For those farms, increasing milk productivity might be a cheaper lever to reduce enteric emissions per litre. Most French dairy farms are likely to be of type 2, with an intermediate individual willingness to accept but a large number of units to compensate given the large number of potential participants.

In order for the Eco-Methane payment to efficiently subsidise the reduction of enteric methane emissions through an increase in grassland areas, it will have to cover both the additional costs per litre of milk and the other extra-costs per hectare of grass. Beyond impacting production costs per unit of milk, a new hectare of grassland can have a direct effect on farm costs. In this study, we only consider variable costs (intermediate consumption). There may also be fixed costs (specific machinery for grass cultivation, buildings for storage) or other constraints (access to land) increasing the overall extra-costs of participation. A study considering all farm costs (variable and fixed costs) found higher GHG emissions abatement costs per litre of milk in large farms (with a high number of dairy cows) compared with smaller ones (Njuki *et al*., 2016).

5. Conclusion

The Eco-Methane programme implemented by the association Bleu-Blanc-Cœur is an example of Payment for Environmental Services scheme supporting dairy farmers engaged in modifying the diet of dairy cows to reduce enteric methane emissions per litre of milk. The reduction of emissions is favoured on the one hand by improving cows' productivity, and on the other hand by integrating more fodder rich in omega-3 fatty acids such as grass and extruded linseed in cows' diet. Through the comparison of two indicators, our study verifies that enteric emissions per litre of milk are higher in mountains farms than in plains farms, but the difference is lower when the indicator takes into account the diet, which tends to be richer in omega-3 in mountainous areas (more grass fodders).

In Eco-Methane, the payment level is conditional on the reduced amount of CO_2eq, which makes the scheme a result-based PES. The programme's funding capacity depends on private donations and is currently not sufficient to induce a massive farms adhesion at the country level, limiting the scheme's environmental impact. To evaluate the willingness to accept of farmers for entering a PES scheme for the reduction of enteric methane emissions and its optimal payment level, it is necessary to know the additional costs of reducing emissions per litre of milk, and therefore of modifying dairy cows' diet.

In this study, we estimate a variable cost function based on French data from the Farm Accountancy Data Network. We evaluate the additional costs per litre of milk of dairy farms due to an increase in grassland area. For a given production level, producing milk with more grass fodder leads to no significant additional cost at the country level and in intensive plain production basins. We find significant extra-costs in dairy systems already relying substantially on grass fodders to feed the cattle (in mountainous areas and plain farms with less than 30% of maize silage in the fodder area). Our conclusions are robust to a change of estimation procedure. These results provide first insights about how supporting a change in cows' diet could reduce GHG emissions. To strengthen their validity, this study could be pursued by an analysis of economic and fodder system data of farms already participating in Eco-Methane. It would allow linking grassland areas, marginal costs of milk production and reduction of enteric emissions, and estimate a cost function for the reduction of enteric emissions per litre of milk. In addition, the estimation of the extra-costs of modifying cows' feed could be improved by taking into account extruded linseed complementation. This research should contribute to define an optimal Eco-Methane payment for a given abatement target, hence reducing uncertainties regarding the compensation level for dairy farmers' and the amount actually abated by donors' contributions.

On a broader level, more insights on the impact of methane emissions reduction on production costs of livestock farms makes it possible to improve support for pressing abatement measures, and contribute effectively to achieve climate targets.

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Appendix A: Descriptive statistics of the sample

Table A1: Description of the sample (2205 observations)

Variable[1]	1st quartile	Median	Mean	3rd quartile
Utilised Agricultural Area (ha)	50.0	80.0	87.4	110.0
Fodder area (ha)	40.0	60.0	67.4	80.0
Maize silage area (ha)	1.0	10.0	14.1	20.0
Pasture area (permanent and temporary) (ha)	26.0	40.0	50.3	61.0
Productivity (L/cow)	5593.4	6676.4	6707.9	7851.1
Number of dairy cows	35	55	58	70
Agricultural Work Unit	1.0	2.0	1.8	2.1
Purchase of cattle feed concentrates (€)	14326.0	24996.5	32853.2	43645.0

Source: The authors based on French FADN data.

[1] Information on surfaces and the number of dairy cows available in the database are ranges of values. We constructed the variables used in the analysis by taking the lower value of the range for each observation.

Appendix B: Eco-Methane scenarios attribution to the old French administrative Regions using the 2018 annual dairy survey

Table B1: Attribution of Eco-Methane scenarios in the FADN 1/2

Administrative Region	Department	Eco-Methane scenarios of the Department	Share of milk production volume in 2018 in the Region	Eco-Methane scenarios of the Region
Ile de France	77	1, 3 or 5		1, 3 or 5
	78	1, 3 or 5		
	91	1, 3 or 5		
	95	1, 3 or 5		
Champagne Ardennes	8	1, 3 or 5		1, 3 or 5
	10	1, 3 or 5		
	51	1, 3 or 5		
	52	1, 3 or 5		
Picardie	2	1, 3 or 5		1, 3 or 5
	60	1, 3 or 5		
	80	1, 3 or 5		
Haute Normandie	14	1, 3 or 5		1, 3 or 5
	50	1, 3 or 5		
	61	1, 3 or 5		
Centre	18	1, 3 or 5		1, 3 or 5
	28	1, 3 or 5		
	36	1, 3 or 5		
	37	1, 3 or 5		
	41	1, 3 or 5		
	45	1, 3 or 5		
Basse Normandie	27	2,4,6		2, 4 or 6
	76	2,4,6		
Bourgogne	21	1, 3 or 5		1, 3 or 5
	58	1, 3 or 5		
	71	1, 3 or 5		
	89	1, 3 or 5		
Nord Pas De Calais	59	1, 3 or 5		1, 3 or 5
	62	1, 3 or 5		
Lorraine	54	1,3 or 5	59%	1,3 or 5
	55	1,3 or 5		
	57	1,3 or 5		
	88	7 or 11	41%	
Alsace				1, 3 or 5
Franche Comté	25	7 or 10	76%	7 or 10
	39	7 or 10		
	70	1, 3 or 5	24%	
Pays de la Loire	44	2, 4 or 6		2, 4 or 6
	39	2, 4 or 6		
	F	2, 4 or 6		
	JG	2, 4 or 6		
Bretagne	22	1, 3 or 5		1, 3 or 5
	29	1, 3 or 5		
	35	1, 3 or 5		
	56	1, 3 or 5		
Poitou Charentes		1, 3 or 5		1 3 or 5
Aquitaine		1, 3 or 5		1 3 or 5

Source: The authors based on the French 2018 annual dairy survey and Bleu-Blanc-Coeur data.

Table B2: Attribution of Eco-Methane scenarios in the FADN 2/2

Administrative Region	Department	Eco-Methane scenarios of the Department	Share of milk production volume in 2018 in the Region	Eco-Methane scenarios of the Region
Hautes Pyrénées	46	7 or 8	60%	7 or 8
	12	7 or 8		
	9	1, 3 or 5	40%	
	31	1, 3 or 5		
	32	1, 3 or 5		
	65	1, 3 or 5		
	81	1, 3 or 5		
	82	1, 3 or 5		
Limousin				1, 3 or 5
Rhône Alpes	1	1, 3 or 5	75%	1, 3 or 5
	7	1, 3 or 5		
	26	1, 3 or 5		
	38	1, 3 or 5		
	42	1, 3 or 5		
	69	1, 3 or 5		
	73	7 or 8	25%	
	74			
Auvergne				7 or 8
Languedoc-Roussillon	11	1, 3 or 5	10%	7 or 8
	30	1, 3 or 5		
	34	1, 3 or 5		
	66	1, 3 or 5		
	48	7 or 8	90%	
Provence Alpes Côte d'Azur	5	7 or 11	87%	7 or 11
	4	1, 3 or 5	13%	
	6	1, 3 or 5		
	13	1, 3 or 5		
	83	1, 3 or 5		
	84	1, 3 or 5		

Source: The authors based on the French 2018 annual dairy survey and Bleu-Blanc-Coeur data.

Appendix C: Matrix of instruments

$$M_{it} = \gamma \begin{bmatrix} P_{1it} \\ {P_{1it}}^2 \\ Q_{1it} \\ {Q_{1it}}^2 \\ Q_{2it} \\ {Q_{2it}}^2 \\ Q_{3it} \\ {Q_{3it}}^2 \\ P_{1it}Q_{1it} \\ P_{1it}Q_{2it} \\ P_{1it}Q_{3it} \\ D_{1i} \\ \dots \\ D_{20i} \\ \ln Y_{2it} \\ \dfrac{\ln W_{2it}}{\ln W_{1it}} \\ (\dfrac{\ln W_{2it}}{\ln W_{1it}})^2 \\ \ln Z_{2it} \\ \ln {Z_{2it}}^2 \\ \ln Z_{3it} \\ \ln {Z_{3it}}^2 \\ \ln Z_{2it} \ln Z_{3it} \\ \ln \dfrac{W_{2it}}{W_{1it}} \ln Z_{2it} \\ \ln \dfrac{W_{2it}}{W_{1it}} \ln Z_{3it} \end{bmatrix} + v_{it}$$

Appendix D: Descriptive statistics of the variables used in the estimation of variable costs

Table D1: Descriptive statistics of the model variables (1/2)

	France		Western plains		Plains outside the western region	
Variable	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
Variable Costs (€/year)	128 073.5	105 612.7	139 405.3	107 167.1	136 399.4	112 800.6
Milk production (L/year)	398 594.1	297 513.2	446 128.0	328 781.5	402 355.2	296 923.0
Other productions (€/base 100/year)	498.6	671.5	581.3	642.3	554.6	770.2
Fuel price (€/L)	0.60	0.10	0.59	0.10	0.59	0.11
Feed price (base 100)	96.6	2.4	96.5	2.4	96.6	2.4
Grassland (ha)	51.1	41.0	42.1	31.5	52.7	38.6
Capital (1000€)	171.0	155.9	160.5	146.8	179.4	163.7
Labour	1.8	1.0	1.9	1.0	1.9	1.0
Milk price (€/1000L)	362.3	74.1	343.5	41.1	367.0	61.2
UAA (ha)	87.4	58.1	84.3	55.3	92.6	60.0
Permanent pastures (ha)	30.7	41.9	14.6	31.9	40.0	36.9
Number of dairy cows	58.0	36.7	63.2	42.5	57.9	34.0

Source: The authors based on French FADN data.

Table D2: Descriptive statistics of the model variables (2/2)

	Mountains		Plains with more than 30% of maize silage in the fodder area		Plains with less than 30% of maize silage in the fodder area	
Variable	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
Variable Costs (€/year)	96 533.0	80 772.0	170 654.1	124 937.8	112 079.6	58 355.4
Milk production (L/year)	306 703.0	226 416.1	526 707.0	333 580.8	348 741.1	254 671.3
Other productions (€/base 100/year)	274.4	413.0	750.2	871.1	425.9	512.3
Fuel price (€/L)	0.61	0.10	0.59	0.10	0.60	0.10
Feed price (base 100)	96.8	2.3	96.6	2.4	96.6	2.4
Grassland (ha)	65.5	47.8	34.2	25.8	56.3	39.2
Capital (1000€)	179.5	160.8	189.1	161.8	151.6	145.9
Labour	1.7	1.0	2.0	1.1	1.7	1.0
Milk price (€/1000L)	390.5	101.3	333.1	27.3	369.4	66.7
UAA (ha)	86.3	57.8	93.3	60.6	83.2	55.8
Permanent pastures (ha)	48.0	49.4	13.9	23.0	34.2	41.3
Number of dairy cows	48.4	30.9	70.5	40.7	53.5	32.7

Source: The authors based on French FADN data.

Appendix E: Results of the estimations

Table E1: Result of the system estimation for France

	Fuel cost share		Feed cost share		Variable cost	
	$\frac{X_1W_1}{VC}$		$\frac{X_2W_2}{VC}$		$\frac{\ln VC}{W_1}$	
$\ln Y_1$	-0.010^{**}	(0.002)	0.010^{**}	(0.002)	4.302^{***}	(0.000)
$\ln \frac{W_2}{W_1}$	-0.008	(0.120)	0.008	(0.120)	0.484^{***}	(0.000)
$\ln Z_1$	-0.008^{***}	(0.000)	0.008^{***}	(0.000)	-0.099	(0.881)
$\ln Z_2$	0.001	(0.578)	-0.001	(0.578)	0.379^{+}	(0.095)
$\ln Z_3$	0.001	(0.669)	-0.001	(0.669)	-4.039^{**}	(0.003)
$\ln Y_1{}^2$					-0.704^{***}	(0.001)
$\ln Y_1 \ln Z_1$					0.041	(0.724)
$\ln Y_1 \ln Z_2$					0.006	(0.915)
$\ln Y_1 \ln Z_3$					0.765^{**}	(0.001)
$\ln Y_1 \ln \frac{W_2}{W_1}$					0.010^{**}	(0.002)
$(\ln \frac{W_2}{W_1})^2$					0.004	(0.120)
$\ln Z_1 \ln \frac{W_2}{W_1}$					0.008^{***}	(0.000)
$\ln Z_2 \ln \frac{W_2}{W_1}$					-0.001	(0.578)
$\ln Z_3 \ln \frac{W_2}{W_1}$					-0.001	(0.669)
$\ln Z_1{}^2$					0.303^{***}	(0.000)
$\ln Z_1 \ln Z_2$					-0.212^{***}	(0.000)
$\ln Z_1 \ln Z_3$					-0.156	(0.304)
$\ln Z_2{}^2$					0.067^{**}	(0.001)
$\ln Z_2 \ln Z_3$					0.080	(0.137)
$\ln Z_3{}^2$					-0.479^{+}	(0.067)
$\ln Y_2$					0.043^{***}	(0.000)
Constant	0.516^{***}	(0.000)	0.484^{***}	(0.000)	-5.881^{+}	(0.054)
Observations	2205					
R^2	-306.452		-14.437		0.805	

p-values in parentheses. $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: The authors based on French FADN data.

Table E2: Result of the system estimation for the plains of the western region

	Fuel cost share		Feed cost share		Variable cost	
	$\frac{X_1 W_1}{VC}$		$\frac{X_2 W_2}{VC}$		$\ln \frac{VC}{W_1}$	
$\ln Y_1$	-0.033***	(0.000)	0.033***	(0.000)	-5.275	(0.442)
$\ln \frac{W_2}{W_1}$	-0.014+	(0.082)	0.014+	(0.082)	0.409***	(0.000)
$\ln Z_1$	0.022***	(0.000)	-0.022***	(0.000)	-3.672	(0.127)
$\ln Z_2$	0.002	(0.438)	-0.002	(0.438)	-2.539	(0.232)
$\ln Z_3$	-0.010+	(0.064)	0.010+	(0.064)	14.770+	(0.088)
$\ln Y_1{}^2$					0.036	(0.979)
$\ln Y_1 \ln Z_1$					0.742	(0.152)
$\ln Y_1 \ln Z_2$					0.734	(0.164)
$\ln Y_1 \ln Z_3$					-2.235	(0.174)
$\ln Y_1 \ln \frac{W_2}{W_1}$					0.033***	(0.000)
$(\ln \frac{W_2}{W_1})^2$					0.007+	(0.082)
$\ln Z_1 \ln \frac{W_2}{W_1}$					-0.022***	(0.000)
$\ln Z_2 \ln \frac{W_2}{W_1}$					-0.002	(0.438)
$\ln Z_3 \ln \frac{W_2}{W_1}$					0.010+	(0.064)
$\ln Z_1{}^2$					-0.080	(0.834)
$\ln Z_1 \ln Z_2$					0.125	(0.624)
$\ln Z_1 \ln Z_3$					-1.309+	(0.051)
$\ln Z_2{}^2$					-0.449+	(0.074)
$\ln Z_2 \ln Z_3$					0.313	(0.415)
$\ln Z_3{}^2$					2.929+	(0.061)
$\ln Y_2$					0.040*	(0.044)
Constant	0.591***	(0.000)	0.409***	(0.000)	32.432+	(0.088)
Observations	645					
R^2	-363.168		-18.822		0.430	

p-values in parentheses. $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: The authors based on French FADN data.

Table E3: Result of the system estimation for the plains outside the western region

	Fuel cost share		Feed cost share		Variable cost	
	$\frac{X_1 W_1}{VC}$		$\frac{X_2 W_2}{VC}$		$\ln \frac{VC}{W_1}$	
$\ln Y_1$	-0.025***	(0.000)	0.025***	(0.000)	1.830+	(0.085)
$\ln \frac{W_2}{W_1}$	-0.002	(0.750)	0.002	(0.750)	0.429***	(0.000)
$\ln Z_1$	-0.011***	(0.000)	0.011***	(0.000)	0.776	(0.349)
$\ln Z_2$	0.000	(0.977)	-0.000	(0.977)	0.641**	(0.007)
$\ln Z_3$	0.028***	(0.000)	-0.028***	(0.000)	-2.274	(0.120)
$\ln Y_1{}^2$					-0.127	(0.519)
$\ln Y_1 \ln Z_1$					-0.014	(0.925)
$\ln Y_1 \ln Z_2$					-0.075	(0.228)
$\ln Y_1 \ln Z_3$					0.090	(0.700)
$\ln Y_1 \ln \frac{W_2}{W_1}$					0.025***	(0.000)
$(\ln \frac{W_2}{W_1})^2$					0.001	(0.750)
$\ln Z_1 \ln \frac{W_2}{W_1}$					0.011***	(0.000)
$\ln Z_2 \ln \frac{W_2}{W_1}$					-0.000	(0.977)
$\ln Z_3 \ln \frac{W_2}{W_1}$					-0.028***	(0.000)
$\ln Z_1{}^2$					-0.046	(0.529)
$\ln Z_1 \ln Z_2$					-0.136*	(0.024)
$\ln Z_1 \ln Z_3$					0.297+	(0.092)
$\ln Z_2{}^2$					0.043+	(0.084)
$\ln Z_2 \ln Z_3$					0.189***	(0.000)
$\ln Z_3{}^2$					-0.351	(0.204)
$\ln Y_2$					0.045***	(0.000)
Constant	0.571***	(0.000)	0.429***	(0.000)	-1.125	(0.753)
Observations	975					
R^2	-276.247		-12.399		0.860	

p-values in parentheses. $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: The authors based on French FADN data.

Table E4: Result of the system estimation for the mountainous areas

	Fuel cost share		Feed cost share		Variable cost	
	$\frac{X_1 W_1}{VC}$		$\frac{X_2 W_2}{VC}$		$\ln \frac{VC}{W_1}$	
$\ln Y_1$	-0.010	(0.138)	0.010	(0.138)	0.131	(0.940)
$\ln \frac{W_2}{W_1}$	-0.012	(0.257)	0.012	(0.257)	0.467^{***}	(0.000)
$\ln Z_1$	-0.021^{***}	(0.000)	0.021^{***}	(0.000)	-2.828	(0.114)
$\ln Z_2$	0.010^{***}	(0.000)	-0.010^{***}	(0.000)	2.295^{***}	(0.001)
$\ln Z_3$	0.009	(0.193)	-0.009	(0.193)	3.166	(0.142)
$\ln Y_1{}^2$					0.451	(0.363)
$\ln Y_1 \ln Z_1$					0.524^{+}	(0.088)
$\ln Y_1 \ln Z_2$					-0.650^{**}	(0.001)
$\ln Y_1 \ln Z_3$					-0.634	(0.107)
$\ln Y_1 \ln \frac{W_2}{W_1}$					0.010	(0.138)
$(\ln \frac{W_2}{W_1})^2$					0.006	(0.257)
$\ln Z_1 \ln \frac{W_2}{W_1}$					0.021^{***}	(0.000)
$\ln Z_2 \ln \frac{W_2}{W_1}$					-0.010^{***}	(0.000)
$\ln Z_3 \ln \frac{W_2}{W_1}$					-0.009	(0.193)
$\ln Z_1{}^2$					-0.231	(0.257)
$\ln Z_1 \ln Z_2$					0.219^{+}	(0.063)
$\ln Z_1 \ln Z_3$					-0.689	(0.129)
$\ln Z_2{}^2$					0.049	(0.112)
$\ln Z_2 \ln Z_3$					0.490^{***}	(0.000)
$\ln Z_3{}^2$					1.082^{*}	(0.046)
$\ln Y_2$					0.018^{*}	(0.024)
Constant	0.533^{***}	(0.000)	0.467^{***}	(0.000)	4.394	(0.322)
Observations	585					
R^2	-289.395		-12.933		0.793	

p-values in parentheses. $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: The authors based on French FADN data.

Table E5: Result of the system estimation for plains with more than 30% of maize in the fodder area

	Fuel cost share		Feed cost share		Variable cost	
	$\frac{X_1W_1}{VC}$		$\frac{X_2W_2}{VC}$		$\ln\frac{VC}{W_1}$	
$\ln Y_1$	-0.038***	(0.000)	0.038***	(0.000)	-6.551*	(0.039)
$\ln\frac{W_2}{W_1}$	-0.005	(0.518)	0.005	(0.518)	0.421***	(0.000)
$\ln Z_1$	0.012**	(0.009)	-0.012**	(0.009)	2.191	(0.414)
$\ln Z_2$	0.005+	(0.094)	-0.005+	(0.094)	3.125**	(0.003)
$\ln Z_3$	0.004	(0.534)	-0.004	(0.534)	2.961	(0.303)
$\ln Y_1{}^2$					2.594***	(0.001)
$\ln Y_1 \ln Z_1$					-0.776	(0.181)
$\ln Y_1 \ln Z_2$					-1.017***	(0.000)
$\ln Y_1 \ln Z_3$					-1.007	(0.138)
$\ln Y_1 \ln\frac{W_2}{W_1}$					0.038***	(0.000)
$(\ln\frac{W_2}{W_1})^2$					0.002	(0.518)
$\ln Z_1 \ln\frac{W_2}{W_1}$					-0.012**	(0.009)
$\ln Z_2 \ln\frac{W_2}{W_1}$					-0.005+	(0.094)
$\ln Z_3 \ln\frac{W_2}{W_1}$					-0.004	(0.534)
$\ln Z_1{}^2$					0.255**	(0.009)
$\ln Z_1 \ln Z_2$					0.312+	(0.060)
$\ln Z_1 \ln Z_3$					0.427	(0.353)
$\ln Z_2{}^2$					0.351***	(0.001)
$\ln Z_2 \ln Z_3$					0.277	(0.126)
$\ln Z_3{}^2$					0.448	(0.365)
$\ln Y_2$					0.113***	(0.000)
Constant	0.579***	(0.000)	0.421***	(0.000)	13.227+	(0.057)
Observations	767					
R^2	-320.209		-17.680		0.754	

p-values in parentheses. $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: The authors based on French FADN data.

Table E6: Result of the system estimation for plains with less than 30% of maize in the fodder area

	Fuel cost share		Feed cost share		Variable cost	
	$\frac{X_1 W_1}{VC}$		$\frac{X_2 W_2}{VC}$		$\ln \frac{VC}{W_1}$	
$\ln Y_1$	-0.009^{+}	(0.086)	0.009^{+}	(0.086)	0.348	(0.770)
$\ln \frac{W_2}{W_1}$	-0.010	(0.226)	0.010	(0.226)	0.463***	(0.000)
$\ln Z_1$	-0.007	(0.102)	0.007	(0.102)	-3.733***	(0.000)
$\ln Z_2$	-0.002	(0.263)	0.002	(0.263)	0.699*	(0.016)
$\ln Z_3$	-0.001	(0.904)	0.001	(0.904)	3.091^{+}	(0.050)
$\ln Y_1{}^2$					-0.617*	(0.023)
$\ln Y_1 \ln Z_1$					0.874***	(0.000)
$\ln Y_1 \ln Z_2$					0.111	(0.135)
$\ln Y_1 \ln Z_3$					-0.370	(0.170)
$\ln Y_1 \ln \frac{W_2}{W_1}$					0.009^{+}	(0.086)
$(\ln \frac{W_2}{W_1})^2$					0.005	(0.226)
$\ln Z_1 \ln \frac{W_2}{W_1}$					0.007	(0.102)
$\ln Z_2 \ln \frac{W_2}{W_1}$					0.002	(0.263)
$\ln Z_3 \ln \frac{W_2}{W_1}$					0.001	(0.904)
$\ln Z_1{}^2$					0.313^{+}	(0.078)
$\ln Z_1 \ln Z_2$					-0.369***	(0.000)
$\ln Z_1 \ln Z_3$					-0.732**	(0.002)
$\ln Z_2{}^2$					-0.007	(0.789)
$\ln Z_2 \ln Z_3$					0.303***	(0.000)
$\ln Z_3{}^2$					0.621*	(0.019)
$\ln Y_2$					0.039***	(0.000)
Constant	0.537***	(0.000)	0.463***	(0.000)	10.451**	(0.004)
Observations	853					
R^2	-317.339		-13.522		0.759	

p-values in parentheses. $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: The authors based on French FADN data.

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