Carbon footprint and economic performance of dairy farms: the case of protected designation of origin dairy farms in France

Mathieu Lambotte, Stéphane de Cara, Catherine Brocas, Valentin Bellassen

Carbon footprint and economic performance of dairy farms: the case of Protected Designation of Origin farms in France

1. Introduction

With livestock supply chains accounting for 14.5% of global anthropogenic greenhouse gas (GHG) emissions (Gerber et al., 2013), the role of the animal sector is under increasing scrutiny in the climate change debate (Herrero et al., 2013). In France, meeting the ambitious GHG mitigation targets set by National Low Carbon Strategy – a reduction of its agricultural GHG emissions by 46% before 2050 (Ministère de la Transition Ecologique et Solidaire, 2018) – will require mitigation strategies in the livestock sector.

One major difficulty in reducing livestock-related emissions is that it may severely affect farm income (e.g. Pellerin et al, 2017). This is particularly true in the EU dairy sector, since the abolishment of milk quotas in 2015 has driven milk prices down which threatens the least productive farming systems (Salou et al., 2017b). Moreover, most farmers will only adopt greener farming practices if they do not threaten their profitability (Kiefer et al., 2014). While the classical economic response to this conundrum would be a tax on GHG emissions, the *gilet jaune* (Yellow Vests) uprising renders any new environmental tax very unlikely in the near future, which also pleads for addressing the environmental and economic performances simultaneously.

An interrogation that policy makers face and that we analyse is: can dairy farmers reduce GHG emissions while at the same time maintaining profits?

To approach this question in the case of extensive dairy farms, a rich and original dataset is mobilized (more than a thousand technical variables, used for life cycle inventories), with a relatively large sample size (n=95). Moreover, the farms observed in the dataset are all producing under a Protected Designation of Origin (PDO) label, with specific production constraints, in mountainous areas in eastern France. Thus, they share a homogeneously extensive "production situation", where the bio-physical and socio-economical drivers of the environmental and economic performances are common to all farms (Lechenet et al., 2016). In a specific production situation, as the external setting of the farms is homogenous, an analysis of the drivers of the performances will isolate the managerial and agricultural practices that explain the difference in performances among the farms, limiting endogeneity issues. Moreover, in French dairy systems, the variability in GHG emissions within each production system – intensive or extensive - is greater than the variations between production systems (Gac et al., 2014). Thus, there exists a knowledge gap in explaining the variability of the performances of farms sharing the same production conditions.

PDO farmers receive a "quality" premium (around 30%) on their milk selling price which enhances their profitability. To receive this premium, they must comply with specific requirements which limit both their production capacity and intensity, to enhance milk quality. These requirements are specifically related to extensive farming practices and could increase the environmental performance of PDO farming: low livestock density, lots of pastures, low use of concentrates, restricted use of fertilizers and so on (Hocquette and Gigli, 2005; Kop et al., 2006).

In this sense, the French government has pointed out the development of PDO farming as a way to achieve a low carbon agriculture while maintaining farmers' profitability (Ministère de la Transition Ecologique et Solidaire, 2018).

Despite large market share of the PDO quality sign in the dairy sector (e.g. 10% in the EU for cheese (Chever et al., 2012) compared with around 3% for the organic sign in France (Augere-Granier, 2018)), the economic and environmental performances of the PDO dairy sector have never been studied jointly. In the European dairy sector, this joint performance has only been investigated, to the authors' knowledge, in extensive Irish systems (O'Brien et al., 2015) and intensive Dutch systems (Thomassen et al., 2009). The question of the relationship between economic and environmental performances has also drawn a lot of interest with the assessment of the cost-effectiveness of mitigation measures, such as reducing stocking rates, nitrogen (N) fertilizers application or imported concentrates (Beukes et al., 2010; Doole, 2014, for example). Moreover, whether extensive or intensive dairy systems pollute more is still debated and our study sheds some light on this issue, within PDO farms, which are mostly towards the "extensive" end of the spectrum (Dollé et al., 2013).

Thus, in this paper, we analyze the link between economic performance – gross profit per liter of milk produced and per hectare – and environmental performance – GHG emissions – including or not carbon sequestration, also per liter and per hectare. We go beyond existing literature by:

- Quantifying the impact of farms' characteristics or practices on the environmental & economic performances of PDO farms simultaneously.

- Using a large sample size within a homogeneous production situation (PDO farms in mountainous Eastern France) which allows us to focus on the role of management practices.
- Designing and implementing a novel and simple approach to account for carbon sequestration related to land-use and land management changes in a net GHG emissions indicator for environmental performance.
- Outlining a lead that may reconcile the contradictory results on the relative merit of extensive and intensive systems with regards to climate mitigation: we confirm that more extensive systems perform better with a higher share of grass, possibly because grass is more expertly managed in extensive systems (e.g. through proper drying) than at the intensive end of the spectrum.

2. Methods and Data

2.1. Population characterization and notation

Our main data source is the field survey of 95 PDO farms in the Franche-Comté and Savoy regions, financed by the PDO consortia between 2013 and 2015 (Michaud, 2016; Perrard, 2016). These surveys gather all the necessary technical and managerial information that is used to compute GHG emissions via the CAP'2ER Life Cycle Analysis (LCA) tool. These surveys also provide detailed information on farmers' practices and farms' characteristics, such as the farm's and herd's sizes, the amount of concentrate feed used, the cereals produced and used on farm, the fertilizer use or the labor use. The average farm of our sample has 125 ($\sigma = 79$) ha and 92 ($\sigma = 51$) cows, produces 348,158 ($\sigma = 231{,}096$) liters of milk per year, which amount to a productivity of 3,792 ($\sigma = 758$) liters per cow and 2,773 ($\sigma = 1{,}205$) liters per ha. The detailed descriptive statistics of our sample are provided in SM 2. In addition, PDO farms generally have Montbéliarde cows, fed mostly with grass and hay from set stocked pastures. The cows spend on average 208 days per year on pastures and otherwise are kept in barns with free stalls. The manure is usually not composted and stored in manure pit at least a week before being spread on the fields using a liquid manure tank. The farms are located in mountainous areas and do not use irrigation.

Consider a population of N_i farms (indexed by $i = 1 \dots N$). Each farm is characterized by a matrix of outputs O_i (e.g. liters of milk produced (M_i), cereals and cows sold…) produced by combining two quasi-fixed inputs (land (A_i) and herd size) and a matrix of variable inputs X_i (e.g. fertilizer, concentrates, fuel…).

Denote by Π_i the gross profit, defined as $\Pi_i = p_i^O * O_i - p_i^X * X_i$ where p_i^O is a matrix of output prices and p_i^X a matrix of input prices.

Moreover, each farm emits an amount E_i of GHG as a negative externality of its production activity. As cropland and pastures can also sequester carbon in the soils, each farm sequesters an amount C_i of carbon. Thus, each farm has a gross GHG emission amount E_i and a net one, $E_i + C_i$.

To measure the economic performance, we consider two indicators, the gross profit per liter of milk (fat-and-protein corrected, with 40g/kg and 33g/kg respectively) produced (variable output), $\frac{\Pi_i}{M_i}$ and per hectare (fixed input), $\frac{\Pi_i}{A_i}$.

As indicators of the environmental performance we use the opposite of gross and net GHG emission per liter (fat-and-protein corrected) and per hectare, $-\frac{E_i}{M_i}, -\frac{E_i+C_i}{M_i}, -\frac{E_i}{A_i}, -\frac{E_i+C_i}{A_i}$ respectively. We use both a product-based and an area-based indicator to account for two diverging hypotheses on the elasticities of demand. Indeed, if demand is infinitely elastic or if there is no substitute for PDO products, consumers will fully adjust to any change in the quantity produced and the product-based indicators are irrelevant. To the contrary, if demand is inelastic or if standard products are perfect substitutes for PDO products, a reduced production in the PDO area will be offset by an increase in production elsewhere, diminishing the relevance of area-based indicators.

In sum, the variables of interest are $\Pi_i, E_i \; and \; E_i + C_i$ and the set of indicators $\bar{y}_i = \begin{cases} \frac{\Pi_i}{M_i}, \frac{\Pi_i}{A_i} \\ -\frac{E_i}{M_i}, -\frac{E_i}{A_i} \\ -\frac{E_i+C_i}{M_i}, -\frac{E_i+C_i}{A_i} \end{cases}$.

2.2. Economic performance estimation

The gross margin Π_i is defined in this study as the difference between the farm's revenue and its costs, without accounting for taxes or subventions. The former includes the revenues from the sale of the farm's outputs O_i : PDO milk, animals, cereals and roughage. Factor costs include the buying costs of the farm's inputs I_i: forage, concentrates, fertilizer, electricity and fuel, contracted work and animals for the renewal of the herd. Family labor costs are valued at the average wage of paid labor (€20,965 per year).

To estimate the gross margin Π_i of each farm, these physical flows need to be multiplied by prices. The prices of most inputs and outputs are estimated using the FADN average for the corresponding year and the corresponding NUTS2 region, with the following exceptions:

- Since the FADN does not identify whether a farm is PDO certified, the price of PDO milk for each year and each PDO area comes from the PDO unions (Agreste Bourgogne-France Comté, 2015; Les fromages de Savoie, 2017).
- The prices of fertilizers and concentrates, which cannot be derived directly from the FADN, are obtained from Eurostat (2018).
- The buying and selling prices of dairy cows, cull cows and heifers is gathered from the *Ministère de l'Agriculture et de l'Alimentation*.

To test the robustness of this estimation, the average estimated profit is compared to the average reported profit for dairy farms in the Franche-Comté and Rhône-Alpes NUTS2 regions from FADN.

2.3. Estimation of the environmental performance

To assess the environmental performance, we focus on GHG emissions for two reasons: first because climate change is arguably one of the most pressing environmental challenge of the 21st century and second because GHG emissions are correlated with environmental impacts such as eutrophication, acidification and energy use (Guerci et al., 2013). Gross GHG emissions E_i - without carbon emissions/sequestrations related to land use and management - are computed using CAP'2ER, a GHG emissions calculator developed by the *Institut de l'Elevage* and following Life Cycle Assessment (LCA) guidelines (Institut de L'Elevage, 2013). The system boundaries are therefore "cradle-to-farm gate", including enteric fermentation, manure management, fertilizers, fuel and energy use, but also the GHG emissions due to the production of concentrate feed and fertilizers. Contrary to the default "energetic allocation" of CAP'2ER, these emissions are then allocated to the three products of farms – milk, meat and crops – in proportion of the share of each product type in the farm revenue (Baldini et al., 2017).

To estimate land-use related carbon sequestration (C_i), we also deviate from CAP'2ER for two main reasons. Firstly, CAP'2ER attributes carbon sequestration to static land management – such as permanent pasture – whereas the only stabilized results for cropland and grassland related carbon fluxes in the literature concern land-use changes (LUC). Indeed, the latest IPCC guidelines (IPCC, 2019) estimate carbon fluxes to be null for croplands and grasslands which did not undergo recent land use or management changes. Secondly because the sequestration factor used by CAP'2ER for permanent grassland derived from Soussana et al. (2010) – 2.09 t CO_2eq ha^{-1} yr^{-1} – has been criticized as being much too large to be consistent with the current knowledge about carbon fluxes and stocks in grassland (Smith, 2014).

In order to bridge this pitfall and provide a more robust estimate of land-related GHG emissions, we develop an innovative methodology based on land use and land management changes. The land use and land management of each farm in our sample is compared to a reference, average farm. We then estimate the carbon fluxes which are being avoided by the choice of each farm to maintain its observed land use rather than transitioning towards the land use of the reference farm.

The share of land uses (cropland vs permanent grassland) in our reference farm is set to the sample average (82% permanent pasture, 18% temporary pasture and cropland). Note that the choice of the reference farm does not impact our results on the differences in environmental performance within the sample. Carbon fluxes (sequestration or emission) associated to each type of land-use changes include both the actual flux resulting from the change and the alteration of future carbon fluxes implied by the change. For example, a farm which has 100% of pasture on 100 ha of total land is estimated to sequester 3.72 t CO_2eq. ha^{-1}.yr^{-1} on the 7 hectares which could have been converted to cropland to match the reference farm. The actual values and their sources are detailed in section 4.

Such an estimate is akin to direct LUC (*dLUC*) as defined by Herrero et al. (2013). Indirect LUC (*iLUC*) is a more controversial topic and its estimates are laden with high uncertainties. Nevertheless, we attempt to provide an upper estimate of it in the context of French PDO farms. In our case, *iLUC* could occur because one hectare of cropland generally produces a higher nutritive capacity calorie-wise than grassland in our sample. Thus, assuming an inelastic demand, a farmer who converted some cropland into grassland would have to import feed to continue feeding the same herd. To produce this additional feed, either non-agricultural land is put into production (extensive margin) or the current production processes are intensified (intensive margin). We retain the extensive margin effect, and our study area being located in the Jura and Alps, non-agricultural land is most likely forest land. The combination of these two key hypothesizes – inelastic demand and extensive margin – yields an upper bound for the area estimate of iLUC. As such, they are not included in the indicator retained for “net environmental performance” and are only used as a robustness check (SM 10).

Using the formalization of Plevin et al. (2010), our reduced-form models of carbon sequestration for *dLUC* and *iLUC* are therefore expressed in equations 1 and 2.

$$dLUCseq_i = -LUC_i * \frac{dEmissionFactor}{Period} \qquad (1)$$

$$iLUCseq_i = -LUC_i * DisplacementFactor_i * \frac{iEmissionFactor}{Period} \qquad (2)$$

Where $DisplacementFactor_i = \frac{\frac{\mathrm{Nutri_G}}{\mathrm{Nutri_C}} * \mathrm{Yd_i^G} - \mathrm{Yd_i^C}}{\mathrm{Yd_{PDO}^C}}$ (see SM 1 for demonstration).

To compute the land-use related emissions (C_i), we use the parameters presented in Table 1.

Table 1. Specification of the carbon sequestration methods

Emission factor cropland to grassland (*dEmissionFactor*)	-74.3 t CO2eq.ha^{-1}	Source: (EFESE, 2019).
Emission factor forest to cropland (*iEmissionFactor*)	749.4 t CO2eq.ha^{-1}	Source: (EFESE, 2019).
Nutritious content (*Nutri*)	$Nutri_C$ = 3840 kcal.kg^{-1} $Nutri_G$ = 4010 kcal. kg^{-1}	feedtables.com
Yield (*Yd*, t.ha^{-1})	Yd^C= 10.43 on average (min = 4.5, max =16), Yd^G= 5.5 on average (min = 0.3, max =7.9)	Source : surveys by Michaud (2016) et Perrard (2016)
Displacement Factor (*DisplacementFactor*)	0.55 on average (min = 0.10, max = 1.04)	Authors' calculation based on equation 3
Production Period (*Period*)	20 year	Default transition period in IPCC (2019).

In addition to the estimation of carbon sequestration from dLUC and iLUC, our method allows the estimation of the impacts of some management practices on biomass and soil carbon. Based on a recent review in France (Pellerin et al., 2019), we identify three practices that are relevant in PDO dairy farming and that change biomass and soil carbon stocks: the share of temporary grasslands in crops rotation, the amount of nitrogen (mineral or organic) fertilization in pastures and the amount of hedges. The carbon impact of these practices follows a temporal pattern similar to the carbon impact of LUC: a change in practice leads to carbon sequestration or emissions which saturate over time as soil and biomass carbon reach a new steady-state equilibrium. Similar to our LUC model, only the differences from the reference farm are therefore considered. Pellerin et al (2019) estimates that on average 63.7 linear meters of hedges sequesters 259 kg $C.ha^{-1}.yr^{-1}$ in the soil and biomass on cropland and 242 kg $C.ha^{-1}.yr^{-1}$ on pasture. Here, a linear meters of hedge is associated to 2 square meters of hedge and 1.5 square meters of uncultivated area both side of the hedge. As our dataset only contains the cumulative length of hedges for each farm, we allocate these hedges proportionally to grassland and cropland, based on the land-use of each farm. Emissions or sequestration are then added to the carbon budget of each farm based on the difference with the reference farm for both the amount of hedges in grassland and the amount of hedges in cropland.

Nitrogen fertilisation on pasture stimulates the biomass growth and thus soil carbon sequestration. Several reviews conclude an almost linear relationship between nitrogen and carbon sequestration in grasslands, with an average ratio of 1.2 kg C per kg N (Eze et al., 2018; Fornara et al., 2012; Pellerin et al., 2019). Here again, differences in nitrogen fertilization – both mineral and organic – with the reference farm are translated into carbon emissions or sequestration, using the average ratio above.

The share of temporary pasture in rotation with crops also improves carbon sequestration in soil. For France, Pellerin et al. (2019) estimate that including 50% of temporary pasture in rotation with crops, compared to crops only, sequesters an additional 466 $kgC.ha^{-1}.yr^{-1}$. More generally, the relationship between the annual increase of SOC and the share of temporary pasture in the rotation follow a linear pattern from rotations dominated by crop (0% of grass) to rotation dominated by grassland (100% of grass) (Vertès and Mary, 2007). Accordingly, we assume that soil carbon sequestration and the share of temporary pasture in the rotation are positively and linearly correlated. To be consistent with our LUC estimates, temporary grassland is therefore assumed to increase carbon sequestration by 37.15 kgCO2e/% of temporary grassland/year. For example, as temporary grasslands represent 71% of the UAA (excluding permanent grassland) in the reference farm, a farm with no temporary grassland would be estimated to be emitting 2.6 $tCO2e.yr^{-1}.ha^{-1}$ of UUA excluding permanent pasture.

The results based on this estimation of GHGE including impacts of management practices on carbon sequestration are however only used as robustness check because of multicollinearity issues (SM 9).

2.4. Econometric analysis on the whole sample

We aim at identifying the practices which create synergies between economic and environmental performances i.e. that influence in the same direction both performances. The annual variation of weather, production or prices, that can impact the environmental or economic performances, is accounted for by using year dummies and pedo-climatic variables (slope, temperature, rainfall, type of soil).

We use six separate Ordinary Least Squares (OLS) regression models (Model 1 to 6), with each of the indicators in the set $\bar{y}_i$ being the dependent variable of a model. As independent variables, we use farms' characteristics and practices, described in SM 2. The 6 separate regression equations following the classical linear form:

$$Y = \beta X + \varepsilon \quad (3)$$

Where Y is a $[n * 1]$ matrix of one of the above 6 measures of performance for each farm, β is a $[k * 1]$ matrix of regression coefficients, different for each of the 6 models, X is a $[n * k]$ matrix, similar for each equation (SM 2) and ε is a $[n * 1]$ matrix of error terms, with n being the sample size and k the number of parameters.

The regression coefficients are compared to detect the explanatory variables that affect in the same direction both the environmental and economic performances (synergies). To identify practices which have an important effect on the performances, we calculate the effect size as the product of the difference between the first and third quartiles in X – to capture the actual variability in the sample – with the associated regression coefficients. Then, we divide these effect sizes by the average performance in the sample to obtain a relative effect size. For a given practice, this quantifies by how much the environmental or economic performance – per liter or hectare –

could be increased if the median farm in the worst half of the sample would adopt the same practice as the median farm in the best half. All the statistical analysis is performed using R language (R Core Team, 2020) and the data visualization is done with the ggplot2 (Wickham, 2016) and corrplot (Wei and Simko, 2017) packages.

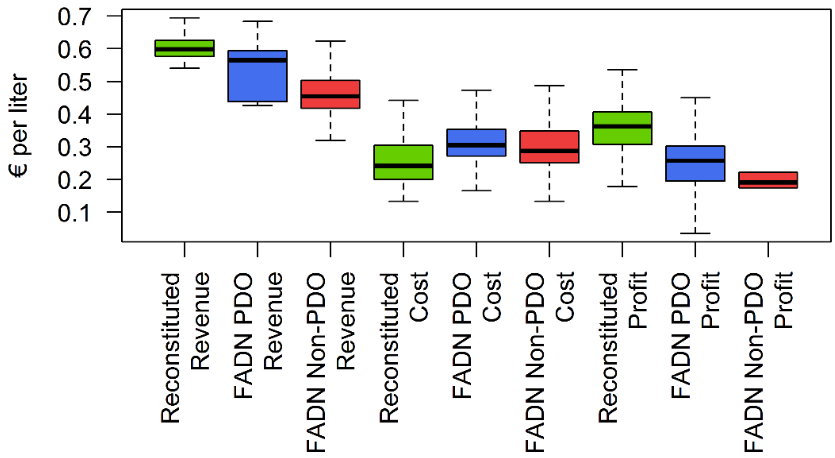
3. Results

3.1. Economic and environmental performances of PDO farms

3.1.1. Economic performance of PDO farms

The average estimated farm revenue in our sample is €210,813 and the average total factor cost amounts to €83,538. The average gross margin is thus €127,274. The averaged reconstituted revenue, cost and profit per liter are comparable to FADN averages for PDO farms in the same regions (Figure 1).

Figure 1. Comparison of the distribution of the estimated economic performance per liter and the FADN's value (2013-2015)



The whisker boxes represent the average, first and third quartiles, and minimum and maximum

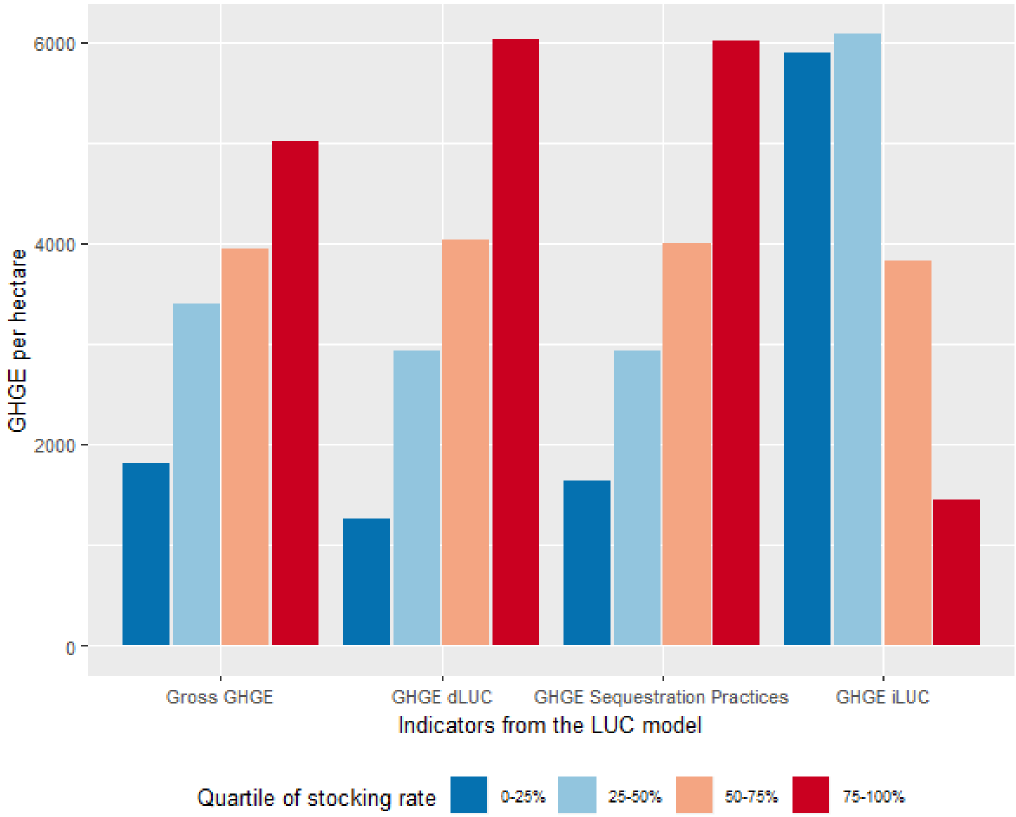
Gross profit per liter averages at €0.34 per liter and is higher than the FADN average for PDO, primarily because of lower costs. Indeed, concentrates costs may be underestimated in our estimation: it is one of the few cost categories for which we use prices from Eurostats (2018), as the FADN does not provide detailed prices for the concentrates purchased. These national prices underestimate this type of costs for PDO farms which are subject to specific constraints (many feed types are forbidden, local production of concentrates is mandatory, …). Otherwise, the higher revenues and profits of PDO farms is confirmed.

Note that the standard deviation of our two economic indicators, profit per liter and per hectare, is large: 32% and 49% respectively (SM 2). This important variability is promising for the econometrical analysis.

3.1.2. Impacts of stocking rate and system boundaries on GHGE

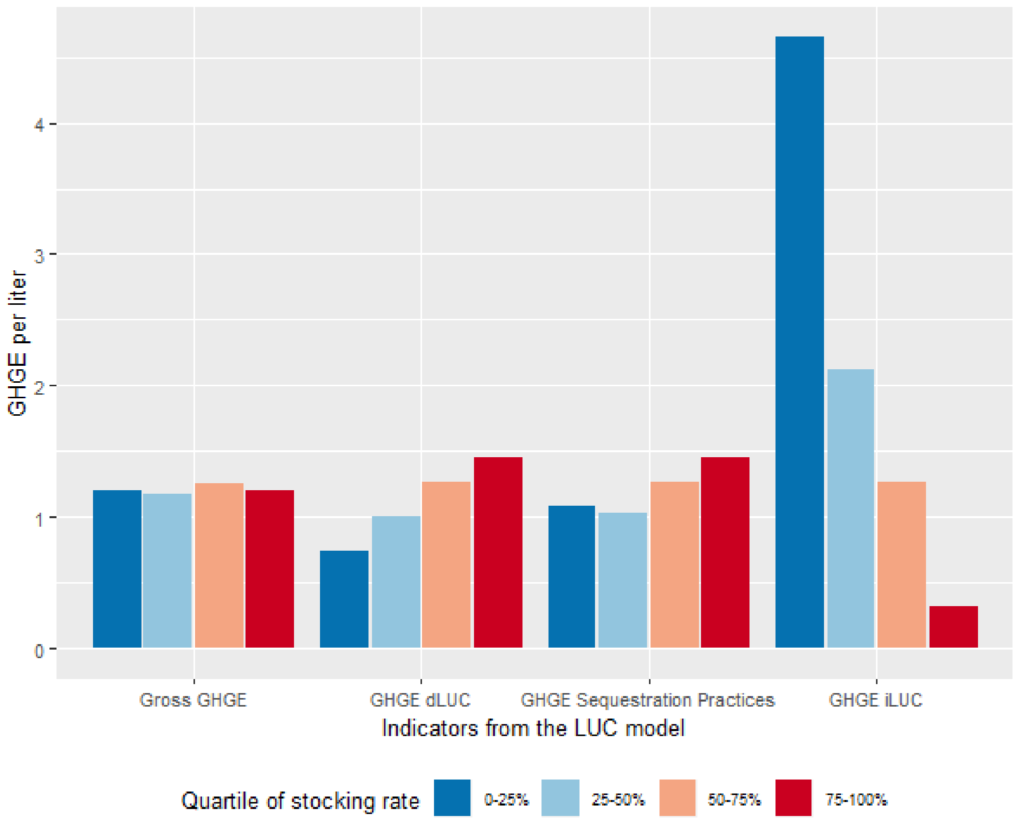
To illustrate the results of the theoretical LUC model, the GHGE are computed for each indicator, both harmonized per liter and hectare, and presented depending of the quartile of stocking rates, to represent the variation of farming intensity in the sample. When the GHGE are measured per hectare, the most extensive farms emit less, except when iLUC are accounted for. The difference of GHGE between the most extensive and intensive farms becomes larger with the increasing comprehensiveness of the LCA perimeter, until iLUC are included (Figure 2). Indeed, when iLUC are accounted for in the LCA, the GHGE of extensive farms is higher than intensive farms' ones, because the difference in nutritive capacity between maize and grass is high in PDO farms and thus the iLUC effects attributed to extensive farms are large.

Figure 2. Carbon footprint of indicators per hectare– with different LCA perimeters – per stocking rate quartile



The results are similar when the environmental performance is measured per liter, except that gross GHGE does not vary strongly with farming intensity (Figure 3).

Figure 3. Carbon footprint of indicators per liter– with different LCA perimeters – per stocking rate quartile

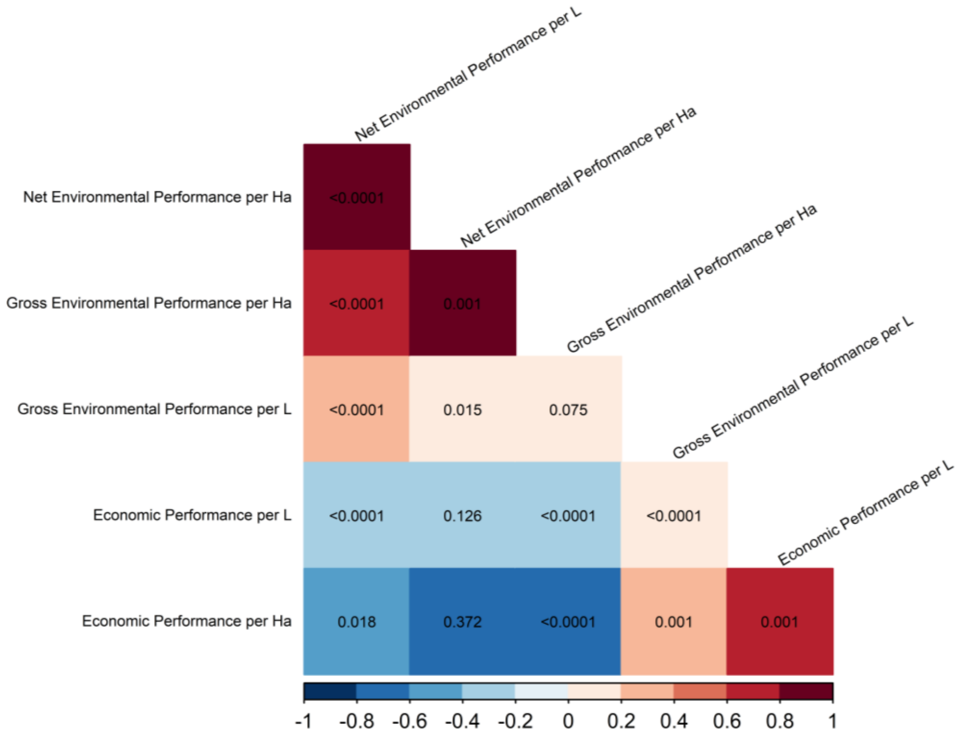


3.2. Relationships between the environmental and economic performances

3.2.1. Correlations between the environmental and economic performances

Analysing directly the correlation between the environmental and economic performances of the farms shows that environmental performance is mostly antagonistic to economic performance, with the exception of the gross environmental performance per liter (Figure 4).

Figure 4. Correlation of environmental and economic performances



The numbers in the cells indicates the p-values of the correlation tests.

3.2.2. No synergetic practice but many levers on either the economic or environmental performance.

No synergetic farming practice could be identified for the economic nor environmental performances: no variable with a significant regression coefficient for economic performance has a significant effect of the same sign on environmental performance and vice-versa (Figure 5, Table 2). Trade-offs are also scarce: only the organic and mineral N spread on pastures improve environmental performance per hectare at the expense of economic performance per hectare. Several levers are however identified, which may improve either the environmental or economic performances by 7 to 21% without deteriorating the other.

Figure 5. Synergies, levers and antagonisms in economic and environmental performance

	Indicators per liter	Indicators per Ha
Synergy		
Lever on the environmental performance	Electricity per cow ↑ Organic N on pasture ↓ Manure composting ↓	Fuel per ha ↓ Share manure in organic fertilizers ↓
Lever on the economic performance	Labor use per cow ↓ Share protein in the diet ↓ Ecological Focus Area ↓	Labor use per cow ↓ Share protein in the diet ↓ Ecological Focus Area ↓
Trade-off		Mineral N on pasture Organic N on pasture ↓↑

A greenup arrow indicates an improvement of the indicator whereas a reddown arrow indicates a deterioration of the indicator. Only variables which have a significant and large impact on indicators are represented (p.value <5% and relative effect size > 5%). In the case of trade-offs, the first arrow always represent the impact on the environmental performances.

Table 2. Selected results of the OLS models

	Net Environmental performance per L (1)	Gross Environmental performance per L (2)	Economic performance per L (3)	Net Environmental performance per Ha (4)	Gross Environmental performance per Ha (5)	Economic performance per Ha (6)
Labor Use per cow	-5.00	-1.04	-6.08***	1,745.81	6,819.09	-15,319.7***
	(3.38)	(2.24)	(0.70)	(11,773.86)	(5,484.13)	(2,878.36)
Fuel per Ha	-0.002*	-0.001	0.0002	-4.31	-5.22***	0.61
	(0.001)	(0.001)	(0.0002)	(4.15)	(1.93)	(1.01)
Electricity per cow	0.0004**	0.0003**	-0.0000	-0.03	-0.54*	0.17
	(0.0002)	(0.0001)	(0.0000)	(0.67)	(0.31)	(0.16)
Concentrate per cow	-0.0000	0.0000	-0.0000	-0.14	-0.42*	0.02
	(0.0001)	(0.0001)	(0.0000)	(0.46)	(0.21)	(0.11)
Share protein in the diet	3.50	-1.91	-2.91***	2,058.35	-5,106.24	-8,415.21**
	(3.99)	(2.64)	(0.83)	(13,888.51)	(6,469.11)	(3,395.33)
Ecological Focus Area	-0.0001	-0.0002	-0.0001**	0.69	-0.17	-0.43**
	(0.0002)	(0.0001)	(0.0000)	(0.69)	(0.32)	(0.17)
Mineral N spread on pasture	0.003	-0.0002	0.0001	-14.56	-19.47***	6.68***
	(0.003)	(0.002)	(0.001)	(9.10)	(4.24)	(2.23)
Organic N on pasture	-0.004**	0.0005	0.0000	-38.55***	-32.19***	7.57***
	(0.002)	(0.001)	(0.0003)	(5.81)	(2.71)	(1.42)
Manure composting	-0.14**	-0.09**	-0.01	-306.13	-84.75	-97.04*
	(0.07)	(0.04)	(0.01)	(235.60)	(109.74)	(57.60)
Share of manure in organic fertilisers	-0.69	-0.08	0.01	-3,593.83**	-305.90	222.04
	(0.49)	(0.32)	(0.10)	(1,705.98)	(794.63)	(417.06)
Constant	1.01	-0.53	0.81***	2,645.66	-43.49	2,579.30**
	(1.23)	(0.81)	(0.25)	(4,267.82)	(1,987.90)	(1,043.36)
Observations	95	95	95	95	95	95
R^2	0.75	0.35	0.82	0.87	0.94	0.86
Adjusted R^2	0.65	0.09	0.75	0.81	0.91	0.80

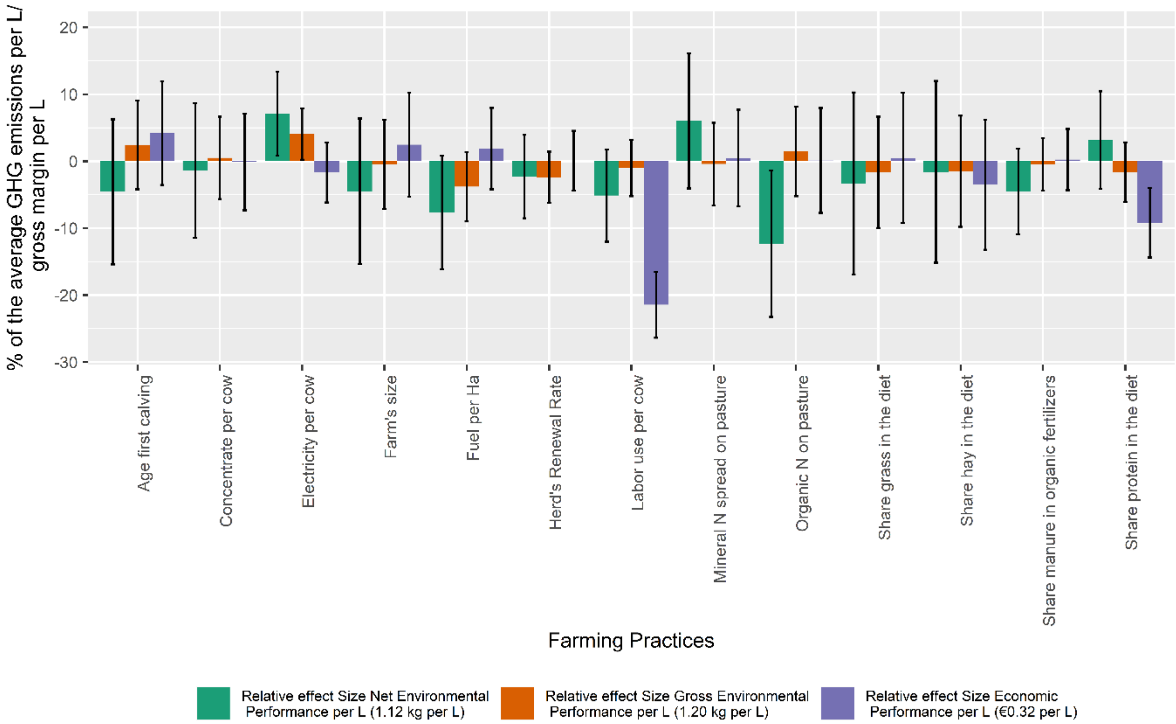
Note: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, standard deviations of the coefficients are included between brackets. Only variables which have a significant and large impact on indicators are represented (p.value <5% and relative effect size > 5%) The full table, including pedo-climatic variables and year dummies is provided in SM 4.

The independent variables retained in our models explain most of the variance of the indicators expressed on a per hectare basis, but a smaller share of per liter indicators (Table 2, SM 4). This could be expected as more independent variables are expressed on a per hectare basis. Residuals vs fitted values plots do not indicate heteroscedasticity of the residuals or non-linear relationships between the variables, even if some outliers can be detected (SM 6). Shapiro-Wilk tests successfully assert the normality of the distribution of the residuals. To further asses the linearity of the relationships between the indicators of performances and the farms' inputs, a general additive model specification was tested but produced lower R^2 (coefficient of determination). With the exception of organic N spread on pastures, whose positive coefficients for models 1,2 and 6 saturate after 120 N unit per ha, no other input shows nonlinear effects (labor per cow, concentrates, N, P and K spread on cereals or pastures).

Several alternative indicators have been attempted to test the robustness of these results such as allocating all GHG emissions to milk production or restricting the perimeter of GHG emissions to the farms by ignoring emissions from the production and transportation of concentrates and fertilizers (SM 7 & SM 8). Indicators including the impacts of several management practices on carbon sequestration in the farms' GHGE have been estimated (SM9). Similarly, indicators including an upper bound estimate of indirect land-use changes are summarized in SM 10. Alternative specifications, with interaction effects (SM 11) or variable selection (SM 12) have also been tested.

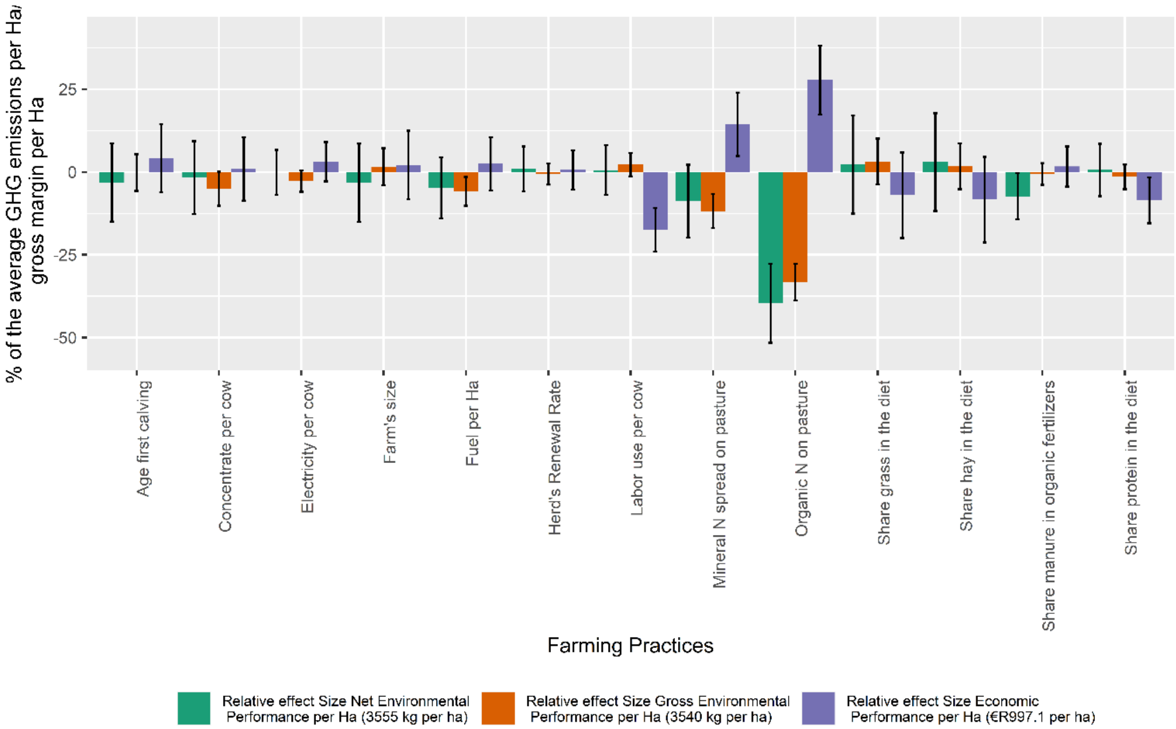
Although these alternative specifications are sometimes useful in interpreting the results, none of them trigger major changes in the estimators or their significance. A notable exception is the inclusion of our higher-end estimate of iLUC which turns the amount of organic N on pasture into a significant positive lever on net environmental performance per liter. Another exception is the inclusion of the impacts of management practices on carbon sequestration, which turns the labor use per cow into a significant and negative lever of the net environmental performance per liter and the age of first calving into a significant and negative lever of the net environmental performance per hectare.

Figure 6. Relative effect sizes of selected practices on the net environmental and economic performances per liter



The colored bars represent the relative effect sizes on the performance and the black lines the relative confidence intervals of the coefficients.

Figure 7. Relative effect sizes of selected practices on the net environmental and economic performances per hectare



The colored bars represent the relative effect sizes on the performance and the black lines the relative confidence intervals of the coefficients.

Impacts of levers on the environmental performance per liter

If the farmers of the quartile using the least electricity per cow could upgrade their hay drying equipment and reach the environmental performance of the upper quartile on electricity consumption, they would decrease their net GHG emissions by 0.08±0.07kg $CO_2eq.L^{-1}$ (net environmental performance increased by 7.1% of total sample average) without any significant profitability change (Figure 6).

Similarly, farmers at the upper quartile of organic N on pasture would decrease their gross GHG emissions by 0.14±0.12 kg $CO_2eq.L^{-1}$ (12.3% of total sample average) if they could move down to the lower quartile (Figure 6).

If farmers would stop the practice manure composting, they would decrease their net GHG emissions by 0.14±0.13 kg CO_2eq.L^{-1} (13% of total sample average) (Figure 6).

Impacts of levers on the economic performance per liter

Reducing the labor use per cow, the share of protein in cows' diet and the ecological focus area could increase the economic performance of the highest half of the sample by €0.07±€0.02. L^{-1}, €0.03±€0.02. L^{-1} and €0.02±€0.02. L^{-1} respectively (21%, 9.2% and 7.2% of total sample average), all without any significant environmental damage (Figure 6).

Impacts of levers on the environmental performance per hectare

As expected, reducing fuel use per hectare could increase the gross environmental performance of the highest half of the sample by 208±153 kg CO_2eq.ha^{-1} (5.9% of total sample average) (Figure 7).

More interestingly, reducing the share of manure in organic fertilizers could increase the gross environmental performance of the highest half of the sample by 262±248 kg CO_2eq.ha^{-1} (7.4% of total sample average) (Figure 7).

Impacts of levers on the economic performance per hectare

Reducing labor use per cow, the share of protein in cows' diet and the Ecological Focus Area of the highest half of the sample could increase their economic performance by €174±€65.ha^{-1}, €86±€68.ha^{-}1 and €120±€95.ha^{-1} respectively (17.5%, 8.6% and 12% of total sample average) (Figure 7).

Impacts of trade-offs on the performances per hectare

Reducing mineral and organic N spread on pastures in the highest half of the sample would increase their gross environmental performance by 419±182 kg CO_2eq.ha^{-1} and 1178±198 kg CO_2eq.ha^{-1} respectively (11.8% and 33.3% of total sample average) but decrease their economic performance by €143±€96.ha^{-1} and €277±104.ha^{-1} respectively (14.4% and 27.8% of total sample average) (Figure 7).

4. Discussion

4.1. Possible levers for performance improvement: tillage, logistics, milking equipment and labor efficiency

The econometric analysis shows that 6% can be gained on the environmental side by reducing fuel use without impairing economic performance. This possibility likely emerges from the potential to increase the share of grazed pasture (rather than mowed pasture): the share of grazing in the diet is negatively correlated with fuel use and when an interaction between the two is added in the regression model, its estimator is negative (although not significant, see SM 11). Another possible practice allowing the reduction of fuel use is the optimization of logistics, although this possibility may be constrained by the spatial distribution of fields and their distance from stables.

Conversely, a higher electricity use per cow increases the environmental performance per liter by 7% without decreasing the economic one. Indeed, electricity production results in little emissions in France (nuclear energy). Moreover, electricity use is mainly linked to milking equipment and the drying of hay, both of which increase milk production. Indeed, the share of hay is positively correlated to the electricity use and the estimator of the interaction is positive although not significant (SM 11).

Manure composting deteriorates the environmental performances per liter by 13%: most farm composters are not equipped to capture or flare methane, thus releasing considerable amounts of it during composting (Hao et al., 2004).

The share of protein in the diet largely reduces the economic performance, both per liter (21%) and per hectare (9%). Soy-based concentrates are indeed costlier and therefore do not seem to proportionally increase cow productivity. This practice is positively correlated with the amount of concentrates fed to the cows and thus decreases the environmental performance per ha, as the GHG emissions from the production and transportation costs of the concentrates are accounted for in our analysis.

Labor efficiency is also an avenue worth exploring to substantially improve economic performances per liter and per hectare without impairing environmental performance. Indeed, labor costs weight 53% of total costs, as PDO dairy farming is a labor-intensive technology (Bouamra-Mechemache and Chaaban, 2010). This lever seems partly related to economies of scale as our alternative models with variable selection mostly remove farm size from the set of dependent variables (SM 12). Natural constraints also play a role: labor intensity is correlated with steeper slope, scarcer rainfall and lower temperature.

Lastly, the positive influence of nitrogen on profit shows that PDO farms are not wasting nitrogen on pasture. However, the use of mineral and organic nitrogen on pasture is detrimental to environmental performance. Moreover, testing for an interaction between the amount of mineral and organic N spread on pasture reveals a negative and significant interaction effect on the environmental and economic performances. This indicates a potential synergy: where organic N fertilization is already high, reducing mineral fertilization would simultaneously increase both performances.

The share of grass in the diet, and in particular of grazing, is paramount in the technical specifications of these PDOs, but also in other quality signs such as organic farming. Here we do not identify these as important levers, neither for economic performance nor for environmental performance. This may be due to a rather small variance in these variables because all our farms follow the PDO specifications or to their correlation with fuel and electricity uses: the share of grass and hay in the diet are mostly excluded from the variables selection procedure, while the fuel and electricity uses are kept (SM 11).

4.2. Correlation between environmental and economic performances

The negative correlation between the environmental and economic performances per hectare is partly due to the intensification of farming practices: when production is intensified per unit of land, more feed, enteric fermentation and manure are taking place in the same area.

When the performances are measured per liter, we find a weak positive correlation between gross environmental and economic performances (ρ = 0.18) but a strong and negative correlation between the net environmental and economic performances (ρ = -0.33). O'Brien et al. (2015), who only use per liter indicators, finds a positive correlation between economic and gross/net environmental performances (ρ = 0.3 to 0.5). This may be explained by the difference in carbon sequestration estimation method. Indeed, O'Brien et al. (2015) uses a sequestration factor of 1.36 t of CO_2eq per ha of grassland and per year based on Soussana et al. (2010), which overestimates carbon sequestration as discussed in section 2.3.

Thomassen et al. (2009) however find a negative correlation between the gross environmental and economic performances per liter (ρ = -0.31), in the case of intensive farms.

In Italy, Fiore et al. (2018) choose to cluster farms by their environmental performance (GHG emissions) and finds 3 clusters, with an antagonism between environmental and economic performances in each cluster.

4.3. Diverging results on the effects of farms' characteristics and practices on the performances

In the case of extensive Irish farms (O'Brien et al. (2015)), the length of the grazing season is the most important lever on both the environmental and economic performances, i.e. creates a synergy. The conclusions drawn are that extensive livestock farming, limiting concentrate feed (which has a negative influence on both performances in their study) and better valorizing pastures and meadows can outperform more intensive systems (Ledgard et al., 2020), mainly because pastures imply carbon sequestration in soils. We verify these results, even when carbon sequestration is not accounted for (gross vs net GHG emissions), or integrates indirect land use changes (SM 9). Moreover, because both the length of the grazing season and the yield of milk per hectare or per cow are negatively correlated with GHG emissions per liter, O'Brien et al. (2015) show that extensive diets can also result in low carbon footprints. At the same time, by reducing feed costs, extensive grazing can reduce the farms' costs and thus extend their margins.

In the case of intensive Dutch farms, Thomassen et al. (2009) show that a high share of concentrate feed in cows' diet results in lower GHG emissions per liter thanks to higher milk productivity and lower emissions per unit of feed (Liang and Cabrera, 2015; Lovett et al., 2006). However, gross margin per liter is also reduced because of feed costs. Hence its conclusion is that environmental performance cannot be enhanced without decreasing farms' profitability.

Our results lie somewhat in between: similarly to O'Brien (2015), we find that concentrates may be overused in the sense that their reduction improves the economic performance in our sample of extensive farms. However, the environmental benefit is not sufficient to suggest a synergy when economic and environmental performances are expressed per liter.

We think that farmer know how in the grass management may provide the key to reconcile these contradictory results. Indeed, mowed grass tends to lose rapidly its nutritious content. The antagonism identified in Thomassen et al. (2009) may be explained by the limited presence of grazing in their sample farms, associated with a limited farmer know-how on grass management. In this context, a higher use of concentrates can be an effective way to reduce GHG emissions by lowering enteric fermentation (Lovett et al., 2008) and to increase profitability by rising the cows' productivity (Thomassen et al., 2009). But, as our study and the Irish case demonstrate, farms with high shares of pastures tend to create a synergy between environmental and economic performances as increasing the grass in the cows' diet can improve the digestibility of the forage and thus reduce the enteric fermentation and the CH4 emission (Dillon et al., 2002), especially if the cut grass is harvested in an early maturity stage (Van Middelaar et al., 2014). The positive influence of hay drying equipment and positive – although not significant – effect of the square of the share of grass on the gross environmental performance per liter are consistent with this interpretation (SM 10): the grass management know-hows of extensive farmers allow them to increase their environmental performance with a higher share of grassland while intensive farmers would suffer from a degraded digestibility of grass when their share of grassland increases. Ultimately however, all these results rely on parameters choices for the digestibility of feed which are known to be very uncertain (IPCC, 2019).

Kiefer, Menzel and Bahrs (2014) compare organic and conventional dairy farms in Germany and also find that limiting concentrates use reduces GHG emissions and increases profitability. Similarly, Thomassen, van Calker, Smits, Iepema and de Boer (2008) recommend to decrease concentrate use per kilogram of milk, especially concentrates with a high environmental impacts (soy). Moreover, Arsenault, Tyedmers and Fredeen (2009) find that the high concentrates use, fuel use and N fertilizers are the main drivers of environmental impacts in Canadian dairy farms. In their study, electricity is also an important contributor to GHG emissions, but our diverging results are straightforwardly explained by the sources of electricity: mainly nuclear energy in our French, context versus 75% of coal in Nova Scotia (Canada). Producing electricity with nuclear energy does not emit GHG whereas coal does, even if nuclear energy creates wastes that impact the environment but not through global warming.

In this debate, the originality of our study is to propose another statistical approach to this question and another method for the carbon sequestration, as well as using both product-based and area-based indicators. We find that the amount of concentrate only has a significant negative influence on the gross environmental performance per hectare. It also decreases net environmental performance per liter, but not significantly. As explained above, product-based indicators strongly respond to practices influencing cows' productivity. Thus, the non-significant effect of the concentrate use on the environmental performance may be explained by its limited effect on cows' productivity in our sample. Indeed, in our PDO sample, the capacity of the farmers to buy fodder crops and feed from the outside the PDO area is limited by the label's constraints, which forces them to develop other feeding practices, such as grazing and mowing.

4.4. Methodological advantages of the study

We find that using two indicators for performances, per liter and per hectare, is helpful in providing meaningful interpretations. Indeed, reasoning with product-based indicators presents the risk of underestimating the environmental impact of intensive practices (Salou et al., 2017a). As the per liter measure of the environmental performance is defined as the ratio between GHG emissions and milk production, if a practice increases the cows' productivity more than the GHG emissions, it will rise the environmental performance per liter. However, such practices would increase the absolute farm's GHG emissions, as well as GHG emissions per cow or per hectare. For example, in our study, only half of the significant practices impact both performances per liter and hectare (fuel per ha, share of protein in the diet and labor use per cow). The other identified levers are less robust and the recommendations to the farmers thus depend on the choice of the indicator. Note that the indicator selected for economic performance are correlated with other possible choices such as gross margin per labor unit.

Moreover, proposing several indicator of the environmental performances (gross GHGE, net GHGE and iLUC GHGE) increases the validity of the results, as including carbon sequestration and how management practices impact it as well as indirect land-use changes can by itself give the advantage to either intensive or extensive dairy farming as the most environmentally performant system (Meier et al., 2015).

4.5. Omitted variables bias

The main methodological limit in this study is related to the econometric models. Some important variables are likely to have been omitted, at least in the models with low adjusted r-square. Classical omitted variables, such as farmer's dynamism or competence, could be correlated with both the dependent variables and the practices, biasing the estimators (endogeneity). However, such omitted variable bias is limited: the heterogeneity of these classical omitted variables is likely to be limited in our sample (same production situation, same region, all PDO farms included in the same farmer association, …). However, we cannot fully rule out and the causality of the relationships we identify must be carefully pondered. Other methods, such as farm system modelling or Data Envelopment Analysis can also successfully identify mitigation practices that increase the economic or environmental performances of dairy farms and that are similar to the levers discussed above (Beukes et al., 2010; Doole, 2014; Iribarren et al., 2011).

5. Conclusion

Our regression models question the possibility of synergies between drivers of economic and environmental performance, but also the existence of necessary trade-offs. We identify however several levers: investing in milking equipment and hay drying equipment, reducing the livestock density, abandoning manure composting or optimizing fuel use increase the environmental performance by 5 to 13% without impairing gross margins, while increasing labor productivity and reducing the share of protein in the diet enhance the economic performance by 7 to 21% without increasing GHG emissions.

Our results also bring new insights on the debated merits of extensive milk farming, suggesting that concentrate use is detrimental to both economic and environmental performance as long as grass retains its nutritious content, for example via grazing. This would be worth confirming with a similar analysis on a sample containing both extensive and intensive dairy farms.

We also develop a novel and simple methodology for the estimation of land-use related emissions and sequestration based on potential land-use changes compared with a reference farm. By doing so, we provide new information on the sustainability of specific practices and a complete methodology that could be used in further studies on environmental and economic performances.

Beyond the methodological limit posed by a possible, although likely moderate, omitted variable bias, the main limit of this paper comes from the restricted study region and the possible sample selection. Indeed, we study the performances of the PDO farms among the same region and using only PDO farms in our statistical population. While this can be beneficial to limit endogeneity, as we can compare farms that share a similar production situation, it limits the validity of any comparison with conventional dairy farming or PDO farming in other areas. Thus, the research on PDO farming and sustainable practices in agriculture could be improved by an analysis that would compare PDO farming in different countries or production situations. Reproducing our analysis for the conventional dairy sector in France and comparing the results could help determine if PDO dairy farming is more economically and environmentally performant, so more sustainable, than the conventional one. Furthermore, the levers of the performances that we uncover in this paper could be compared to the ones in the conventional dairy sector.

References

Agreste Bourgogne-France Comté, 2015. Les chiffres du lait 2015.

Augere-Granier, M., 2018. The EU dairy sector. Main features, challenges and prospects. Brief. Eur. Parliam. 12.

Baldini, C., Gardoni, D., Guarino, M., 2017. A critical review of the recent evolution of Life Cycle Assessment applied to milk production. J. Clean. Prod. 140, 421–435. https://doi.org/10.1016/j.jclepro.2016.06.078

Beukes, P.C., Gregorini, P., Romera, A.J., Levy, G., Waghorn, G.C., 2010. Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand. Agric. Ecosyst. Environ. 136, 358–365. https://doi.org/10.1016/j.agee.2009.08.008

Bouamra-Mechemache, Z., Chaaban, J., 2010. Determinants of adoption of protected designation of origin label: Evidence from the french brie cheese industry. J. Agric. Econ. 61, 225–239. https://doi.org/10.1111/j.1477-9552.2009.00234.x

Chever, T., Renault, C., Renault, S., Romieu, V., 2012. Value of production of agricultural products and foodstuffs, wines, aromatised wines and spirits protected by a geographical indication (GI). Final Rep. to Eur. Comm. TENDER N° AGRI–2011–EVAL–04 85.

Dillon, P., Crosse, S., O'Brien, B., Mayes, R.W., 2002. The effect of forage type and level of concentrate supplementation on the performance of spring-calving dairy cows in early lactation. Grass Forage Sci. 57, 212–223. https://doi.org/10.1046/j.1365-2494.2002.00319.x

Dollé, J.-B., Moreau, S., Foray, S., 2013. Combiner production et environnement, un défi pour la filière laitière Les enjeux environnementaux majeurs Les enjeux relatifs au changement 1–16.

Doole, G.J., 2014. Least-cost greenhouse gas mitigation on New Zealand dairy farms. Nutr. Cycl. Agroecosystems 98, 235–251. https://doi.org/10.1007/s10705-014-9608-y

EFESE, 2019. La séquestration de carbon par les écosystèmes en France.

Eze, S., Palmer, S.M., Chapman, P.J., 2018. Soil organic carbon stock in grasslands: Effects of inorganic fertilizers, liming and grazing in different climate settings. J. Environ. Manage. 223, 74–84. https://doi.org/10.1016/j.jenvman.2018.06.013

Fiore, M., Spada, A., Contò, F., Pellegrini, G., 2018. GHG and cattle farming: CO-assessing the emissions and economic performances in Italy. J. Clean. Prod. 172, 3704–3712. https://doi.org/10.1016/j.jclepro.2017.07.167

Fornara, D.A., Tilman, D., Houlton, B.Z., 2012. Soil carbon sequestration in prairie grasslands increased by chronic nitrogen addition. Ecology 93, 2030–2036. https://doi.org/10.1890/12-0292.1

Gac, A., Agabriel, J., Dollé, J.-B., Faverdin, P., Van Der Werf, H., 2014. Le potentiel d'atténuation des gaz à effet de serre en productions bovines. Innov. Agron. 37, 67–81.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities, FAO. https://doi.org/10.1016/j.anifeedsci.2011.04.074

Guerci, M., Knudsen, M.T., Bava, L., Zucali, M., Schönbach, P., Kristensen, T., 2013. Parameters affecting the environmental impact of a range of dairy farming systems in Denmark, Germany and Italy. J. Clean. Prod. 54, 133–141. https://doi.org/10.1016/j.jclepro.2013.04.035

Hao, X., Chang, C., Larney, F.J., 2004. Carbon, Nitrogen Balances and Greenhouse Gas Emission during Cattle Feedlot Manure Composting. J. Environemntal Qual. 37–44.

Herrero, M., Havlik, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blummel, M., Weiss, F., Grace, D., Obersteiner, M., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc. Natl. Acad. Sci. 110, 20888–20893. https://doi.org/10.1073/pnas.1308149110

Hocquette, J.F., Gigli, S., 2005. Indicators of Milk and Beef Quality. https://doi.org/10.3920/978-90-8686-537-6

Institut de L'Elevage, 2013. GUIDE MÉTHOLOGIQUE CAP ' 2ER ® : Calcul Automatisé des Performances Environnementales en Elevage de Ruminants 1–12.

IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Chapter 4: Agriculture, Forestry and Other Land Uses (AFOLU). IGES, Hayama, Japan.

Iribarren, D., Hospido, A., Moreira, M.T., Feijoo, G., 2011. Benchmarking environmental and operational parameters through eco-efficiency criteria for dairy farms. Sci. Total Environ. 409, 1786–1798. https://doi.org/10.1016/j.scitotenv.2011.02.013

Kiefer, L., Menzel, F., Bahrs, E., 2014. The effect of feed demand on greenhouse gas emissions and farm profitability for organic and conventional dairy farms. J. Dairy Sci. 97, 7564–7574. https://doi.org/10.3168/jds.2014-8284

Kop, P. Van De, Sautier, D., Eds, A.G., 2006. Origin-based Products: Lessons for pro-poor market development. R. Trop. Inst. - CIRAD 53–63.

Lechenet, M., Makowski, D., Py, G., Munier-Jolain, N., 2016. Profiling farming management strategies with contrasting pesticide use in France. Agric. Syst. 149, 40–53. https://doi.org/10.1016/j.agsy.2016.08.005

Ledgard, S.F., Falconer, S.J., Abercrombie, R., Philip, G., Hill, J.P., 2020. Temporal, spatial, and management variability in the carbon footprint of New Zealand milk. J. Dairy Sci. 103, 1031–1046. https://doi.org/10.3168/jds.2019-17182

les fromages de Savoie, 2017. Prix du Lait 2017.

Liang, D., Cabrera, V.E., 2015. Optimizing productivity, herd structure, environmental performance, and profitability of dairy cattle herds. J. Dairy Sci. 98, 2812–2823. https://doi.org/10.3168/jds.2014-8856

Lovett, D.K., Shalloo, L., Dillon, P., O'Mara, F.P., 2008. Greenhouse gas emissions from pastoral based dairying systems: The effect of uncertainty and management change under two contrasting production systems. Livest. Sci. 116, 260–274. https://doi.org/10.1016/j.livsci.2007.10.016

Lovett, D.K., Shalloo, L., Dillon, P., O'Mara, F.P., 2006. A systems approach to quantify greenhouse gas fluxes from pastoral dairy production as affected by management regime. Agric. Syst. 88, 156–179. https://doi.org/10.1016/j.agsy.2005.03.006

Meier, M.S., Stoessel, F., Jungbluth, N., Juraske, R., Schader, C., Stolze, M., 2015. Environmental impacts of organic and conventional agricultural products - Are the differences captured by life cycle assessment? J. Environ. Manage. 149, 193–208. https://doi.org/10.1016/j.jenvman.2014.10.006

Michaud, Q., 2016. Mise en place d'une démarche d'évaluation et d'amélioration du bilan carbone des exploitations agricoles.

Ministère de la Transition Ecologique et Solidaire, 2018. National Low Carbon Strategy Project: The ecological and inclusive transition towards carbon neutrality 144.

O'Brien, D., Hennessy, T., Moran, B., Shalloo, L., 2015. Relating the carbon footprint of milk from Irish dairy farms to economic performance. J. Dairy Sci. 98, 7394–7407. https://doi.org/10.3168/jds.2014-9222

Pellerin, S., Bamière, L., Launay, C., 2019. Stocker du carbone dans les sols français , Quel potentiel au regard de l'objectif 4 pour 1000 et à quel coût? Synthèse du Rapp. d'étude, INRA 114.

Perrard, V., 2016. Mise en place d'une démarche d'évaluation et d'amélioration du bilan carbone des exploitations agricoles.

Plevin, R.J., O'Hare, M., Jones, A.D., Torn, M.S., Gibbs, H.K., 2010. Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated. Environ. Sci. Technol. 44, 8015–8021. https://doi.org/10.1021/es101946t

R Core Team, 2020. R: A Language and Environment for Statistical Computing.

Salou, T., Le Mouël, C., van der Werf, H.M.G., 2017a. Environmental impacts of dairy system intensification: the functional unit matters! J. Clean. Prod. 140, 445–454. https://doi.org/10.1016/j.jclepro.2016.05.019

Salou, T., van der Werf, H.M.G., Levert, F., Forslund, A., Hercule, J., Le Mouël, C., 2017b. Could EU dairy quota removal favour some dairy production systems over others? The case of French dairy production systems. Agric. Syst. 153, 1–10. https://doi.org/10.1016/j.agsy.2017.01.004

Smith, P., 2014. Do grasslands act as a perpetual sink for carbon? Glob. Chang. Biol. 20, 2708–2711. https://doi.org/10.1111/gcb.12561

Soussana, J.F., Tallec, T., Blanfort, V., 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Animal 4, 334–350. https://doi.org/10.1017/S1751731109990784

Thomassen, M.A., Dolman, M.A., van Calker, K.J., de Boer, I.J.M., 2009. Relating life cycle assessment indicators to gross value added for Dutch dairy farms. Ecol. Econ. 68, 2278–2284. https://doi.org/10.1016/j.ecolecon.2009.02.011

Thomassen, M.A., van Calker, K.J., Smits, M.C.J., Iepema, G.L., de Boer, I.J.M., 2008. Life cycle assessment of conventional and organic milk production in the Netherlands. Agric. Syst. 96, 95–107. https://doi.org/10.1016/j.agsy.2007.06.001

Van Middelaar, C.E., Dijkstra, J., Berentsen, P.B.M., De Boer, I.J.M., 2014. Cost-effectiveness of feeding strategies to reduce greenhouse gas emissions from dairy farming. J. Dairy Sci. 97, 2427–2439. https://doi.org/10.3168/jds.2013-7648

Vertès, F., Mary, B., 2007. Modelling the long term SOM dynamics in fodder rotations with a variable part of grassland. Agronomie 2007–2007.

Wei, T., Simko, V., 2017. R package “corrplot”: Visualization of a Correlation Matrix.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.