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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

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

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

51 In this sense, the French government has pointed out the development of
52 PDO farming as a way to achieve a low carbon agriculture while

53 maintaining farmers' profitability (Ministère de la Transition Ecologique et
54 Solidaire, 2018).

55 Despite large market share of the PDO quality sign in the dairy sector (e.g.
56 10% in the EU for cheese (Chever et al., 2012) compared with around 3%
57 for the organic sign in France (Augere-Granier, 2018)), the economic and
58 environmental performances of the PDO dairy sector have never been
59 studied jointly. In the European dairy sector, this joint performance has only
60 been investigated, to the authors' knowledge, in extensive Irish systems
61 (O'Brien et al., 2015) and intensive Dutch systems (Thomassen et al.,
62 2009). The question of the relationship between economic and
63 environmental performances has also drawn a lot of interest with the
64 assessment of the cost-effectiveness of mitigation measures, such as
65 reducing stocking rates, nitrogen (N) fertilizers application or imported
66 concentrates (Beukes et al., 2010; Doole, 2014, for example). Moreover,
67 whether extensive or intensive dairy systems pollute more is still debated
68 and our study sheds some light on this issue, within PDO farms, which are
69 mostly towards the "extensive" end of the spectrum (Dollé et al., 2013).

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

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

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- 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.

93

94 **2. Methods and Data**

95 **2.1. Population characterization and notation**

96 Our main data source is the field survey of 95 PDO farms in the Franche-
97 Comté and Savoy regions, financed by the PDO consortia between 2013 and
98 2015 (Michaud, 2016; Perrard, 2016). These surveys gather all the
99 necessary technical and managerial information that is used to compute
100 GHG emissions via the CAP'2ER Life Cycle Analysis (LCA) tool. These
101 surveys also provide detailed information on farmers' practices and farms'
102 characteristics, such as the farm's and herd's sizes, the amount of
103 concentrate feed used, the cereals produced and used on farm, the fertilizer
104 use or the labor use. The average farm of our sample has 125 ($\sigma = 79$) ha
105 and 92 ($\sigma = 51$) cows, produces 348,158 ($\sigma = 231,096$) liters of milk per
106 year, which amount to a productivity of 3,792 ($\sigma = 758$) liters per cow and
107 2,773 ($\sigma = 1,205$) liters per ha. The detailed descriptive statistics of our
108 sample are provided in SM 2. In addition, PDO farms generally have
109 Montbéliarde cows, fed mostly with grass and hay from set stocked
110 pastures. The cows spend on average 208 days per year on pastures and
111 otherwise are kept in barns with free stalls. The manure is usually not
112 composted and stored in manure pit at least a week before being spread on
113 the fields using a liquid manure tank. The farms are located in mountainous
114 areas and do not use irrigation.

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

120 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
121 is a matrix of output prices and p_i^X a matrix of input prices.

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

126 To measure the economic performance, we consider two indicators, the
127 gross profit per liter of milk (fat-and-protein corrected, with 40g/kg and
128 33g/kg respectively) produced (variable output), $\frac{\Pi_i}{M_i}$ and per hectare (fixed
129 input), $\frac{\Pi_i}{A_i}$.

130 As indicators of the environmental performance we use the opposite of
131 gross and net GHG emission per liter (fat-and-protein corrected) and per
132 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-
133 based and an area-based indicator to account for two diverging hypotheses
134 on the elasticities of demand. Indeed, if demand is infinitely elastic or if
135 there is no substitute for PDO products, consumers will fully adjust to any
136 change in the quantity produced and the product-based indicators are
137 irrelevant. To the contrary, if demand is inelastic or if standard products are
138 perfect substitutes for PDO products, a reduced production in the PDO area
139 will be offset by an increase in production elsewhere, diminishing the
140 relevance of area-based indicators.

141 In sum, the variables of interest are Π_i , E_i and $E_i + C_i$ and the set of

142 indicators $\bar{y}_i = \left\{ \begin{array}{l} \frac{\Pi_i}{M_i}, \frac{\Pi_i}{A_i} \\ -\frac{E_i}{M_i}, -\frac{E_i}{A_i} \\ -\frac{E_i+C_i}{M_i}, -\frac{E_i+C_i}{A_i} \end{array} \right.$.

143 **2.2. Economic performance estimation**

144 The gross margin Π_i is defined in this study as the difference between the
145 farm's revenue and its costs, without accounting for taxes or subventions.

146 The former includes the revenues from the sale of the farm's outputs O_i :
147 PDO milk, animals, cereals and roughage. Factor costs include the buying
148 costs of the farm's inputs I_i : forage, concentrates, fertilizer, electricity and
149 fuel, contracted work and animals for the renewal of the herd. Family labor
150 costs are valued at the average wage of paid labor (€20,965 per year).

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

- 155 • Since the FADN does not identify whether a farm is PDO
156 certified, the price of PDO milk for each year and each PDO area
157 comes from the PDO unions (Agreste Bourgogne-France Comté,
158 2015; Les fromages de Savoie, 2017).
- 159 • The prices of fertilizers and concentrates, which cannot be
160 derived directly from the FADN, are obtained from Eurostat (2018).
- 161 • The buying and selling prices of dairy cows, cull cows and
162 heifers is gathered from the *Ministère de l'Agriculture et de*
163 *l'Alimentation*.

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

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168 **2.3. Estimation of the environmental performance**

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

185 To estimate land-use related carbon sequestration (C_i), we also deviate from
186 CAP'2ER for two main reasons. Firstly, CAP'2ER attributes carbon
187 sequestration to static land management – such as permanent pasture –
188 whereas the only stabilized results for cropland and grassland related carbon
189 fluxes in the literature concern land-use changes (LUC). Indeed, the latest
190 IPCC guidelines (IPCC, 2019) estimate carbon fluxes to be null for

191 croplands and grasslands which did not undergo recent land use or
192 management changes. Secondly because the sequestration factor used by
193 CAP'2ER for permanent grassland derived from Soussana et al. (2010) –
194 $2.09 \text{ t CO}_2\text{eq ha}^{-1} \text{ yr}^{-1}$ – has been criticized as being much too large to be
195 consistent with the current knowledge about carbon fluxes and stocks in
196 grassland (Smith, 2014).

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

204 The share of land uses (cropland vs permanent grassland) in our reference
205 farm is set to the sample average (82% permanent pasture, 18% temporary
206 pasture and cropland). Note that the choice of the reference farm does not
207 impact our results on the differences in environmental performance within
208 the sample. Carbon fluxes (sequestration or emission) associated to each
209 type of land-use changes include both the actual flux resulting from the
210 change and the alteration of future carbon fluxes implied by the change. For
211 example, a farm which has 100% of pasture on 100 ha of total land is
212 estimated to sequester $3.72 \text{ t CO}_2\text{eq. ha}^{-1} \cdot \text{yr}^{-1}$ on the 7 hectares which could
213 have been converted to cropland to match the reference farm. The actual
214 values and their sources are detailed in section 4.

215 Such an estimate is akin to direct LUC (*dLUC*) as defined by Herrero et al.
216 (2013). Indirect LUC (*iLUC*) is a more controversial topic and its estimates
217 are laden with high uncertainties. Nevertheless, we attempt to provide an

218 upper estimate of it in the context of French PDO farms. In our case, *iLUC*
 219 could occur because one hectare of cropland generally produces a higher
 220 nutritive capacity calorie-wise than grassland in our sample. Thus, assuming
 221 an inelastic demand, a farmer who converted some cropland into grassland
 222 would have to import feed to continue feeding the same herd. To produce
 223 this additional feed, either non-agricultural land is put into production
 224 (extensive margin) or the current production processes are intensified
 225 (intensive margin). We retain the extensive margin effect, and our study
 226 area being located in the Jura and Alps, non-agricultural land is most likely
 227 forest land. The combination of these two key hypothesizes – inelastic
 228 demand and extensive margin – yields an upper bound for the area estimate
 229 of *iLUC*. As such, they are not included in the indicator retained for “net
 230 environmental performance” and are only used as a robustness check (SM
 231 10).

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

$$235 \quad dLUCseq_i = -LUC_i * \frac{dEmissionFactor}{Period} \quad (1)$$

$$236 \quad iLUCseq_i = -LUC_i * DisplacementFactor_i * \frac{iEmissionFactor}{Period} \quad (2)$$

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

238 demonstration).

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

241 Table 1. Specification of the carbon sequestration methods

Emission factor cropland to grassland (<i>dEmissionFactor</i>)	-74.3 t CO ₂ eq.ha ⁻¹	Source: (EFESE, 2019).
Emission factor forest to cropland (<i>iEmissionFactor</i>)	749.4 t CO ₂ eq.ha ⁻¹	Source: (EFESE, 2019).
Nutritious content (<i>Nutri</i>)	$Nutri_C = 3840 \text{ kcal.kg}^{-1}$ $Nutri_G = 4010 \text{ kcal.kg}^{-1}$	feedtables.com
Yield (Y_d, 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 (<i>DisplacementFactor</i>)	0.55 on average (min = 0.10, max = 1.04)	Authors' calculation based on equation 3
Production Period (<i>Period</i>)	20 year	Default transition period in IPCC (2019).

242

243 In addition to the estimation of carbon sequestration from dLUC and iLUC,
244 our method allows the estimation of the impacts of some management
245 practices on biomass and soil carbon. Based on a recent review in France
246 (Pellerin et al., 2019), we identify three practices that are relevant in PDO
247 dairy farming and that change biomass and soil carbon stocks: the share of
248 temporary grasslands in crops rotation, the amount of nitrogen (mineral or
249 organic) fertilization in pastures and the amount of hedges. The carbon
250 impact of these practices follows a temporal pattern similar to the carbon
251 impact of LUC: a change in practice leads to carbon sequestration or
252 emissions which saturate over time as soil and biomass carbon reach a new
253 steady-state equilibrium. Similar to our LUC model, only the differences
254 from the reference farm are therefore considered. Pellerin et al (2019)

255 estimates that on average 63.7 linear meters of hedges sequesters 259 kg
256 C.ha⁻¹.yr⁻¹ in the soil and biomass on cropland and 242 kg C.ha⁻¹.yr⁻¹ on
257 pasture. Here, a linear meters of hedge is associated to 2 square meters of
258 hedge and 1.5 square meters of uncultivated area both side of the hedge. As
259 our dataset only contains the cumulative length of hedges for each farm, we
260 allocate these hedges proportionally to grassland and cropland, based on the
261 land-use of each farm. Emissions or sequestration are then added to the
262 carbon budget of each farm based on the difference with the reference farm
263 for both the amount of hedges in grassland and the amount of hedges in
264 cropland.

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

272 The share of temporary pasture in rotation with crops also improves carbon
273 sequestration in soil. For France, Pellerin et al. (2019) estimate that
274 including 50% of temporary pasture in rotation with crops, compared to
275 crops only, sequesters an additional 466 kgC.ha⁻¹.yr⁻¹. More generally, the
276 relationship between the annual increase of SOC and the share of temporary
277 pasture in the rotation follow a linear pattern from rotations dominated by
278 crop (0% of grass) to rotation dominated by grassland (100% of grass)
279 (Vertès and Mary, 2007). Accordingly, we assume that soil carbon
280 sequestration and the share of temporary pasture in the rotation are
281 positively and linearly correlated. To be consistent with our LUC estimates,

282 temporary grassland is therefore assumed to increase carbon sequestration
283 by 37.15 kgCO₂e/% of temporary grassland/year. For example, as
284 temporary grasslands represent 71% of the UAA (excluding permanent
285 grassland) in the reference farm, a farm with no temporary grassland would
286 be estimated to be emitting 2.6 tCO₂e.yr⁻¹.ha⁻¹ of UUA excluding
287 permanent pasture.

288 The results based on this estimation of GHGE including impacts of
289 management practices on carbon sequestration are however only used as
290 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 –

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

323

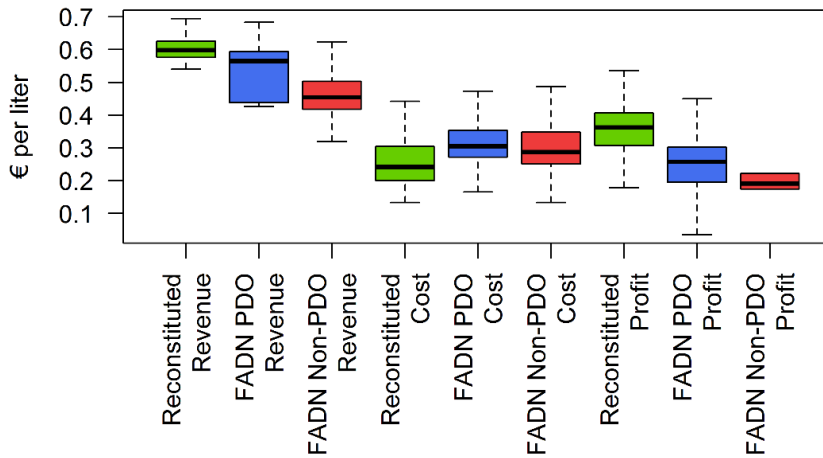
324 **3. Results**

325 **3.1. Economic and environmental performances of PDO** 326 **farms**

327 3.1.1. Economic performance of PDO farms

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

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



335

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

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

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

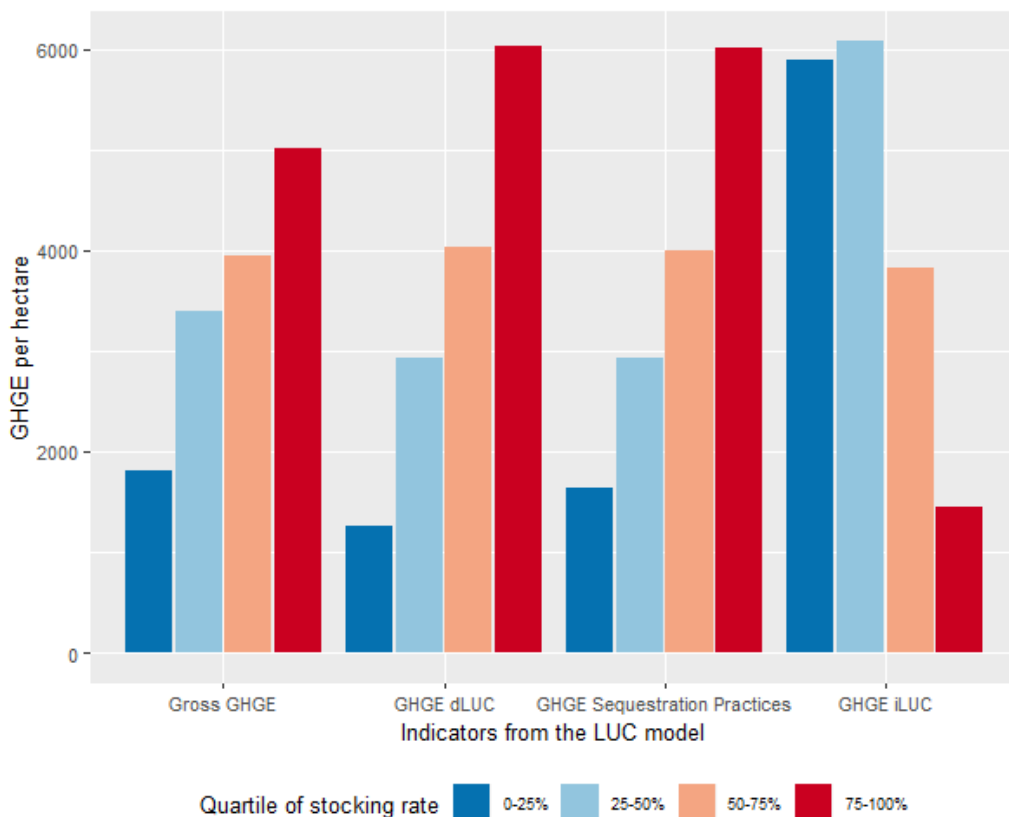
349

350 3.1.2. Impacts of stocking rate and system boundaries on GHGE

351 To illustrate the results of the theoretical LUC model, the GHGE are
 352 computed for each indicator, both harmonized per liter and hectare, and
 353 presented depending of the quartile of stocking rates, to represent the

354 variation of farming intensity in the sample. When the GHGE are measured
 355 per hectare, the most extensive farms emit less, except when iLUC are
 356 accounted for. The difference of GHGE between the most extensive and
 357 intensive farms becomes larger with the increasing comprehensiveness of
 358 the LCA perimeter, until iLUC are included (Figure 2). Indeed, when iLUC
 359 are accounted for in the LCA, the GHGE of extensive farms is higher than
 360 intensive farms' ones, because the difference in nutritive capacity between
 361 maize and grass is high in PDO farms and thus the iLUC effects attributed
 362 to extensive farms are large.

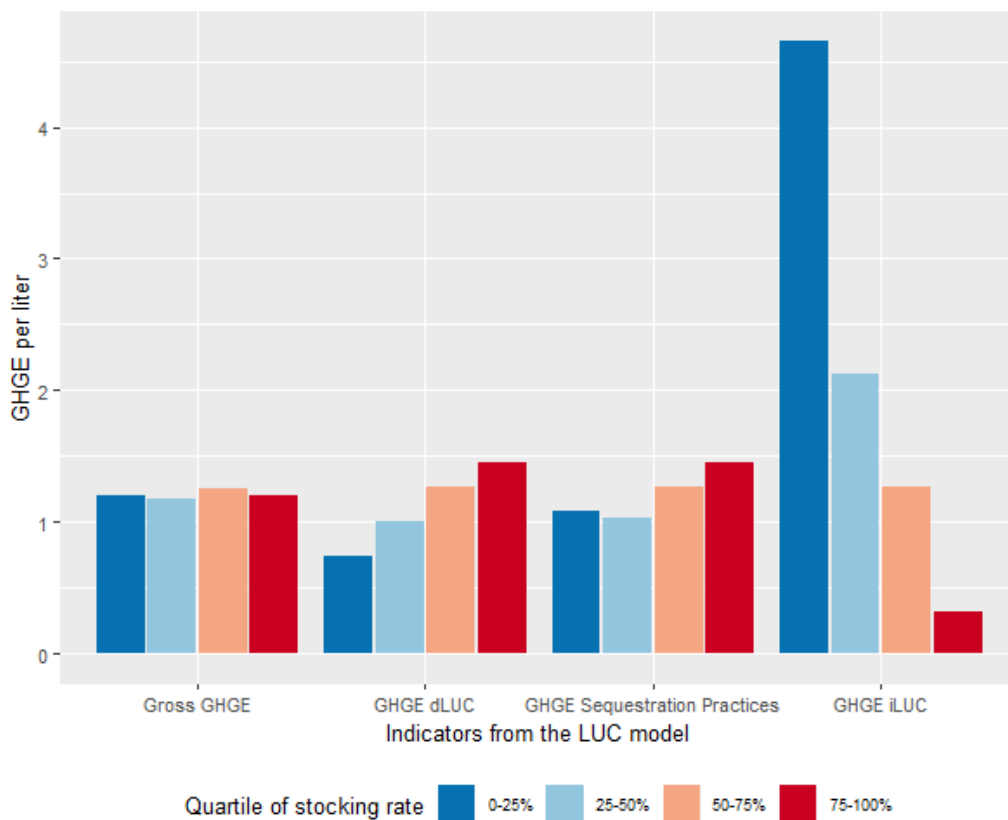
363 Figure 2. Carbon footprint of indicators per hectare– with different LCA
 364 perimeters – per stocking rate quartile



365

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

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



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372

373

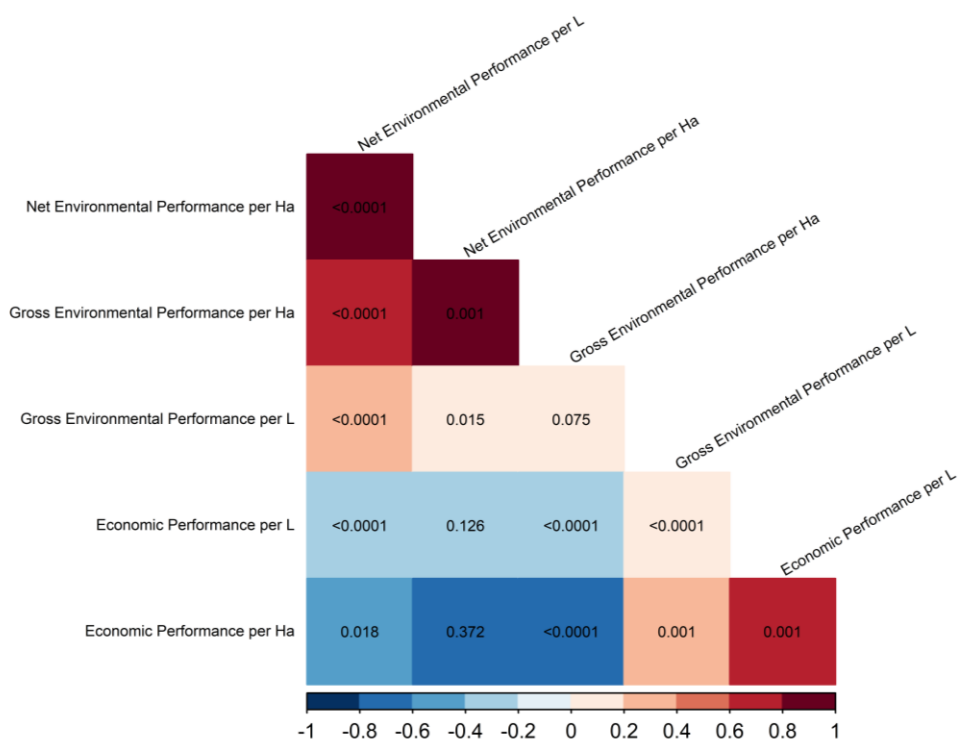
374 **3.2. Relationships between the environmental and economic**
 375 **performances**

376 3.2.1. Correlations between the environmental and economic
 377 performances

378

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

383 Figure 4. Correlation of environmental and economic performances



384

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

386

387 3.2.2. No synergetic practice but many levers on either the
 388 economic or environmental performance.
 389 No synergetic farming practice could be identified for the economic nor
 390 environmental performances: no variable with a significant regression
 391 coefficient for economic performance has a significant effect of the same
 392 sign on environmental performance and vice-versa (Figure 5, Table 2).
 393 Trade-offs are also scarce: only the organic and mineral N spread on
 394 pastures improve environmental performance per hectare at the expense of
 395 economic performance per hectare. Several levers are however identified,
 396 which may improve either the environmental or economic performances by
 397 7 to 21% without deteriorating the other.

398 Figure 5. Synergies, levers and antagonisms in economic and environmental
 399 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 ↑

400 *A greenup arrow indicates an improvement of the indicator whereas*
401 *a redden arrow indicates a deterioration of the indicator. Only*
402 *variables which have a significant and large impact on indicators*
403 *are represented (p.value <5% and relative effect size > 5%). In the*
404 *case of trade-offs, the first arrow always represent the impact on the*
405 *environmental performances.*
406

407 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 (3.38)	-1.04 (2.24)	-6.08*** (0.70)	1,745.81 (11,773.86)	6,819.09 (5,484.13)	-15,319.7*** (2,878.36)
Fuel per Ha	-0.002* (0.001)	-0.001 (0.001)	0.0002 (0.0002)	-4.31 (4.15)	-5.22*** (1.93)	0.61 (1.01)
Electricity per cow	0.0004** (0.0002)	0.0003** (0.0001)	-0.0000 (0.0000)	-0.03 (0.67)	-0.54* (0.31)	0.17 (0.16)
Concentrate per cow	-0.0000 (0.0001)	0.0000 (0.0001)	-0.0000 (0.0000)	-0.14 (0.46)	-0.42* (0.21)	0.02 (0.11)
Share protein in the diet	3.50 (3.99)	-1.91 (2.64)	-2.91*** (0.83)	2,058.35 (13,888.51)	-5,106.24 (6,469.11)	-8,415.21** (3,395.33)
Ecological Focus Area	-0.0001 (0.0002)	-0.0002 (0.0001)	-0.0001** (0.0000)	0.69 (0.69)	-0.17 (0.32)	-0.43** (0.17)
Mineral N spread on pasture	0.003 (0.003)	-0.0002 (0.002)	0.0001 (0.001)	-14.56 (9.10)	-19.47*** (4.24)	6.68*** (2.23)
Organic N on pasture	-0.004** (0.002)	0.0005 (0.001)	0.0000 (0.0003)	-38.55*** (5.81)	-32.19*** (2.71)	7.57*** (1.42)
Manure composting	-0.14** (0.07)	-0.09** (0.04)	-0.01 (0.01)	-306.13 (235.60)	-84.75 (109.74)	-97.04* (57.60)
Share of manure in organic fertilisers	-0.69 (0.49)	-0.08 (0.32)	0.01 (0.10)	-3,593.83** (1,705.98)	-305.90 (794.63)	222.04 (417.06)
Constant	1.01 (1.23)	-0.53 (0.81)	0.81*** (0.25)	2,645.66 (4,267.82)	-43.49 (1,987.90)	2,579.30** (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

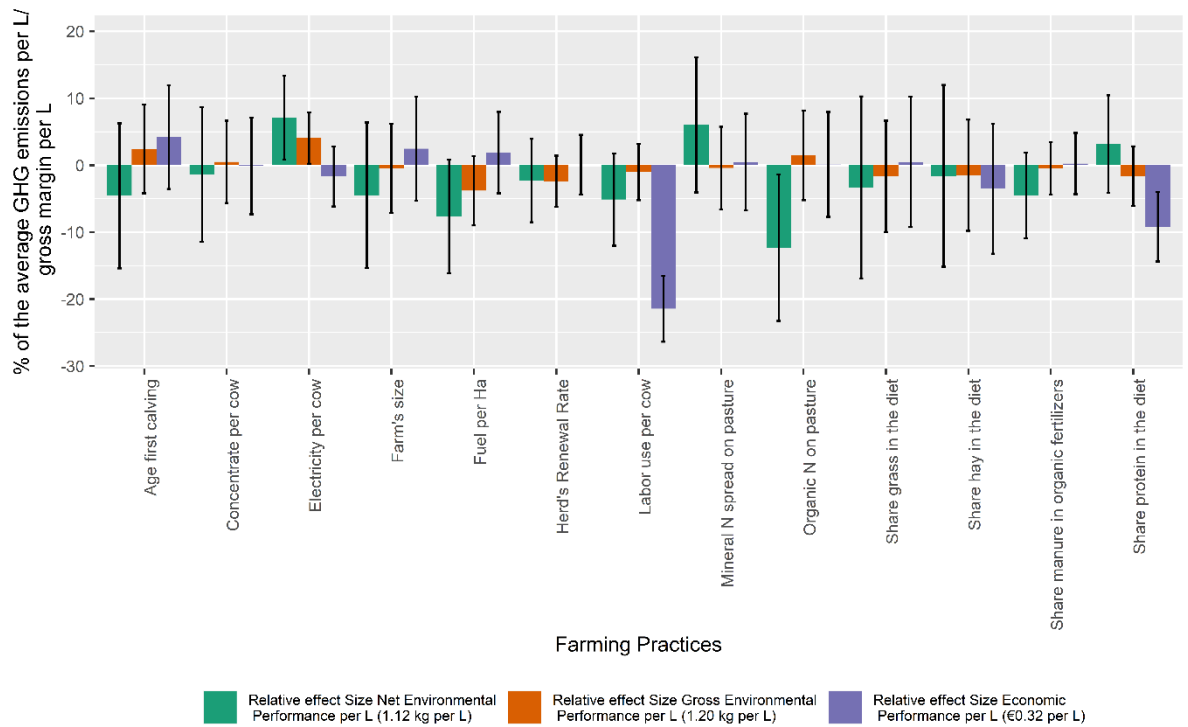
Note: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, standard deviations of the coefficients are included between brackets. Only variables which have a significant and large impact on indicators are represented (p .value $< 5\%$ and relative effect size $> 5\%$) The full table, including pedo-climatic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

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

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

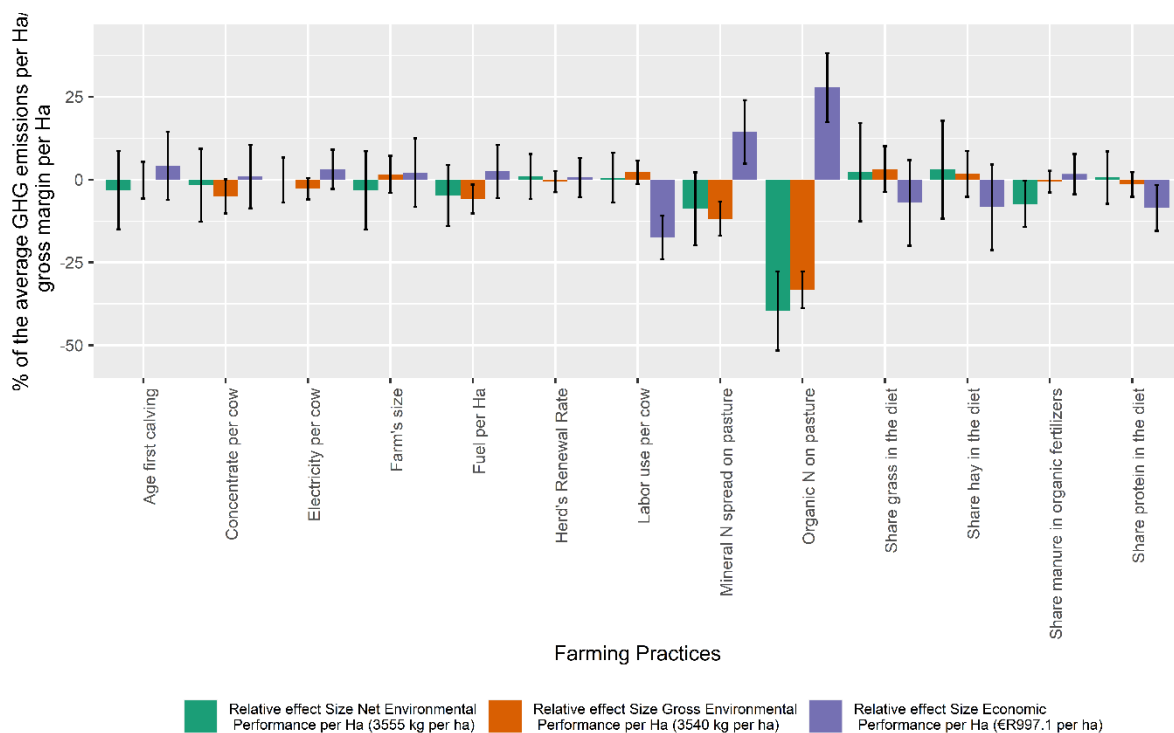
432 Although these alternative specifications are sometimes useful in
 433 interpreting the results, none of them trigger major changes in the estimators
 434 or their significance. A notable exception is the inclusion of our higher-end
 435 estimate of iLUC which turns the amount of organic N on pasture into a
 436 significant positive lever on net environmental performance per liter.
 437 Another exception is the inclusion of the impacts of management practices
 438 on carbon sequestration, which turns the labor use per cow into a significant
 439 and negative lever of the net environmental performance per liter and the
 440 age of first calving into a significant and negative lever of the net
 441 environmental performance per hectare.
 442

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



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

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



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

447 *Impacts of levers on the environmental performance per liter*

448 If the farmers of the quartile using the least electricity per cow could
 449 upgrade their hay drying equipment and reach the environmental
 450 performance of the upper quartile on electricity consumption, they would
 451 decrease their net GHG emissions by $0.08 \pm 0.07 \text{ kg CO}_2\text{eq.L}^{-1}$ (net
 452 environmental performance increased by 7.1% of total sample average)
 453 without any significant profitability change (Figure 6).

454 Similarly, farmers at the upper quartile of organic N on pasture would
 455 decrease their gross GHG emissions by $0.14 \pm 0.12 \text{ kg CO}_2\text{eq.L}^{-1}$ (12.3% of

456 total sample average) if they could move down to the lower quartile (Figure
457 6).

458 If farmers would stop the practice manure composting, they would decrease
459 their net GHG emissions by $0.14 \pm 0.13 \text{ kg CO}_2\text{eq.L}^{-1}$ (13% of total sample
460 average) (Figure 6).

461 *Impacts of levers on the economic performance per liter*

462 Reducing the labor use per cow, the share of protein in cows' diet and the
463 ecological focus area could increase the economic performance of the
464 highest half of the sample by $\text{€}0.07 \pm \text{€}0.02 \cdot \text{L}^{-1}$, $\text{€}0.03 \pm \text{€}0.02 \cdot \text{L}^{-1}$ and
465 $\text{€}0.02 \pm \text{€}0.02 \cdot \text{L}^{-1}$ respectively (21%, 9.2% and 7.2% of total sample
466 average), all without any significant environmental damage (Figure 6).

467 *Impacts of levers on the environmental performance per hectare*

468 As expected, reducing fuel use per hectare could increase the gross
469 environmental performance of the highest half of the sample by $208 \pm 153 \text{ kg}$
470 $\text{CO}_2\text{eq.ha}^{-1}$ (5.9% of total sample average) (Figure 7).

471 More interestingly, reducing the share of manure in organic fertilizers could
472 increase the gross environmental performance of the highest half of the
473 sample by $262 \pm 248 \text{ kg CO}_2\text{eq.ha}^{-1}$ (7.4% of total sample average) (Figure
474 7).

475 *Impacts of levers on the economic performance per hectare*

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

480 *Impacts of trade-offs on the performances per hectare*

481 Reducing mineral and organic N spread on pastures in the highest half of the
482 sample would increase their gross environmental performance by 419 ± 182
483 $\text{kg CO}_2\text{eq.ha}^{-1}$ and $1178 \pm 198 \text{ kg CO}_2\text{eq.ha}^{-1}$ respectively (11.8% and 33.3%
484 of total sample average) but decrease their economic performance by
485 $\text{€}143 \pm \text{€}96.\text{ha}^{-1}$ and $\text{€}277 \pm 104.\text{ha}^{-1}$ respectively (14.4% and 27.8% of total
486 sample average) (Figure 7).

487

488 **4. Discussion**

489 4.1. Possible levers for performance improvement: tillage,
490 logistics, milking equipment and labor efficiency

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

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

508 Manure composting deteriorates the environmental performances per liter
509 by 13%: most farm composters are not equipped to capture or flare methane,
510 thus releasing considerable amounts of it during composting (Hao et al.,
511 2004).

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

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

528 Lastly, the positive influence of nitrogen on profit shows that PDO farms
529 are not wasting nitrogen on pasture. However, the use of mineral and
530 organic nitrogen on pasture is detrimental to environmental performance.
531 Moreover, testing for an interaction between the amount of mineral and
532 organic N spread on pasture reveals a negative and significant interaction
533 effect on the environmental and economic performances. This indicates a

534 potential synergy: where organic N fertilization is already high, reducing
535 mineral fertilization would simultaneously increase both performances.

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

545

546 4.2. Correlation between environmental and economic 547 performances

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

552 When the performances are measured per liter, we find a weak positive
553 correlation between gross environmental and economic performances ($\rho =$
554 0.18) but a strong and negative correlation between the net environmental
555 and economic performances ($\rho = -0.33$). O'Brien et al. (2015), who only use
556 per liter indicators, finds a positive correlation between economic and
557 gross/net environmental performances ($\rho = 0.3$ to 0.5). This may be
558 explained by the difference in carbon sequestration estimation method.
559 Indeed, O'Brien et al. (2015) uses a sequestration factor of 1.36 t of CO_2eq

560 per ha of grassland and per year based on Soussana et al. (2010), which
561 overestimates carbon sequestration as discussed in section 2.3.
562 Thomassen et al. (2009) however find a negative correlation between the
563 gross environmental and economic performances per liter ($\rho = -0.31$), in the
564 case of intensive farms.

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

568

569 4.3. Diverging results on the effects of farms' characteristics and
570 practices on the performances

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

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

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

597 We think that farmer know how in the grass management may provide the
598 key to reconcile these contradictory results. Indeed, mowed grass tends to
599 lose rapidly its nutritious content. The antagonism identified in Thomassen
600 et al. (2009) may be explained by the limited presence of grazing in their
601 sample farms, associated with a limited farmer know-how on grass
602 management. In this context, a higher use of concentrates can be an
603 effective way to reduce GHG emissions by lowering enteric fermentation
604 (Lovett et al., 2008) and to increase profitability by rising the cows'
605 productivity (Thomassen et al., 2009). But, as our study and the Irish case
606 demonstrate, farms with high shares of pastures tend to create a synergy
607 between environmental and economic performances as increasing the grass
608 in the cows' diet can improve the digestibility of the forage and thus reduce
609 the enteric fermentation and the CH₄ emission (Dillon et al., 2002),
610 especially if the cut grass is harvested in an early maturity stage (Van
611 Middelaar et al., 2014). The positive influence of hay drying equipment and

612 positive – although not significant – effect of the square of the share of grass
613 on the gross environmental performance per liter are consistent with this
614 interpretation (SM 10): the grass management know-hows of extensive
615 farmers allow them to increase their environmental performance with a
616 higher share of grassland while intensive farmers would suffer from a
617 degraded digestibility of grass when their share of grassland increases.
618 Ultimately however, all these results rely on parameters choices for the
619 digestibility of feed which are known to be very uncertain (IPCC, 2019).

620

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

635 In this debate, the originality of our study is to propose another statistical
636 approach to this question and another method for the carbon sequestration,
637 as well as using both product-based and area-based indicators. We find that
638 the amount of concentrate only has a significant negative influence on the

639 gross environmental performance per hectare. It also decreases net
640 environmental performance per liter, but not significantly. As explained
641 above, product-based indicators strongly respond to practices influencing
642 cows' productivity. Thus, the non-significant effect of the concentrate use
643 on the environmental performance may be explained by its limited effect on
644 cows' productivity in our sample. Indeed, in our PDO sample, the capacity
645 of the farmers to buy fodder crops and feed from the outside the PDO area is
646 limited by the label's constraints, which forces them to develop other
647 feeding practices, such as grazing and mowing.

648

649 4.4. Methodological advantages of the study

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

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

672

673 4.5. Omitted variables bias

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

688 **5. Conclusion**

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

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

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

710 Beyond the methodological limit posed by a possible, although likely
711 moderate, omitted variable bias, the main limit of this paper comes from the
712 restricted study region and the possible sample selection. Indeed, we study
713 the performances of the PDO farms among the same region and using only
714 PDO farms in our statistical population. While this can be beneficial to limit

715 endogeneity, as we can compare farms that share a similar production
716 situation, it limits the validity of any comparison with conventional dairy
717 farming or PDO farming in other areas. Thus, the research on PDO farming
718 and sustainable practices in agriculture could be improved by an analysis
719 that would compare PDO farming in different countries or production
720 situations. Reproducing our analysis for the conventional dairy sector in
721 France and comparing the results could help determine if PDO dairy
722 farming is more economically and environmentally performant, so more
723 sustainable, than the conventional one. Furthermore, the levers of the
724 performances that we uncover in this paper could be compared to the ones
725 in the conventional dairy sector.

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