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1 **Does pig production improves cattle farm sustainability in the**
2 **French massif central? A hierarchical constrained directional**
3 **Benefit-of-the-Doubt approach**

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8
9 **Abstract**

10 *CONTEXT:* Pig production systems in the Massif Central are almost all associated with herbivore farms.
11 However, in a context characterized by the specialization of farms and a decline in the attractiveness of
12 the pig farming profession, pig production systems are declining, whereas diversification of production
13 now appears to be an interesting lever for sustainability.

14 *OBJECTIVE:* The objective of this study was to assess the impacts of adding pig production on the
15 sustainability of beef and dairy farms and to assess the pros and cons of a DEA based multicriteria
16 evaluation model

17 *METHODS:* The Orfee bioeconomic model was used to simulate 17 -beef or dairy farms with and
18 without a pig production system. This pig production system consists of either a farrow-to-finish sow
19 production system or a pig fattening production system only. The structural and technical parameters of
20 these farms were established from a farm survey. The sustainability of the farms was assessed using 17
21 indicators. These indicators were hierarchically aggregated into a single sustainability composite
22 indicator using an innovative method, the constrained directional benefit of doubt (D-BoD) method.

23 *RESULTS AND CONCLUSIONS:* The results indicate that the addition of a pig production system has
24 an overall positive impact on the sustainability of cattle farms. Mixed cattle-pig systems score
25 significantly better on the social dimension as they generate more jobs and contribute more to food
26 security. The overall economic performance is not significantly better than that of specialised systems
27 for the price context from 2012 to 2022. The pig production system increases the average income per
28 work unit for cattle farms but needs more purchased inputs to produce. This reduces but not offsets the
29 risk reduction advantage of diversification. Mixed farms do not score higher than specialised beef farms
30 on the environmental dimension. Mixed farms contribute less to global warming per kg of protein
31 produced but have more excess nitrogen and phosphorus. The constrained D-BoD method is a useful
32 tool for endogenously aggregating indicators without having to arbitrarily set weights and thresholds to

33 evaluate performance, but with certain limitations, such as the possibility that a farm may be judged
34 efficient if it performs better on some indicators while being relatively weak on others.

35 *SIGNIFICANCE:* Favouring mixed farming appears to be an interesting lever for territorial
36 development, but with two important issues: local supply of pig feed at a secure price and improved
37 manure management to allow a virtuous cycle of nutrients.

38

39 **Keywords:** diversification; mixed livestock farming system; bioeconomic model, sustainability;
40 composite indicator; farm design

41

42 **1 Introduction**

43 The French Massif Central is largely dedicated to ruminant farming, but farms specialising in cattle
44 production, especially for meat production, have been facing low incomes for several years despite
45 significant public support (Colas et al., 2019). Mixed systems are increasingly attracting the attention of
46 researchers and stakeholders as a way to apply agro-ecological principles, increase on-farm value
47 creation and better manage risks (Altieri, 1999; Dumont et al., 2020). More specifically, Martin *et al.*,
48 (2020) emphasized the potential of multi-species livestock farming to improve farm sustainability.
49 Different definitions exist for the sustainability of farming systems. ten Napel *et al.*, (2011) posits that
50 a farm is sustainable when the farmers get a reasonable and stable income, without negative side effects
51 on the environment, and with a production system socially acceptable to society. FAO (Campanhola, F.,
52 2014) adds that sustainable food and agriculture should contribute to all four pillars of food security –
53 availability, access, utilization and stability – in addition to the three dimensions of sustainability
54 (environmental, social and economic).

55 The diversification of farms by pig production could be of interest to improve the sustainability of cattle
56 farms in the Massif Central. In this region, pig farming has historically been developed on farms as a
57 complement to a main cattle farm. Today, 74% of the remaining pig production system in this territory
58 are still associated with the production of herbivores, mainly cattle (Rapey et al., 2021). In a context
59 characterised by a decline in the attractiveness of the pig profession and its acceptance by society (Rapey
60 et al., 2021), and a decline in the profitability of cattle farms, this paper aims to study the sustainability
61 of mixed pig-cattle farms relative to specialized cattle farms.

62 Several studies have analysed the potential benefits of diversifying cattle farms. Brewin *et al.*, (2014)
63 simulated the net profit gains from integrating a beef and a pig production system in Canada compared
64 to managing them separately. The economic gains came from the application of pig manure to fields
65 producing forage for cattle. However, they did not explore sustainability indicators related to the

66 environmental and social sustainability pillars. Some studies have been conducted to assess the benefits
67 of diversifying livestock systems in the French Massif Central (Dumont *et al.*, 2021; Mosnier *et al.*,
68 2021a) but without considering pig production. Using organic farm data, Steinmetz *et al.*, (2021)
69 compared different farm performance indicators of organic mixed livestock farms. They found that
70 systems with large monogastric production (pigs and poultry) had a poor agricultural nitrogen balance
71 without gaining economic efficiency (measured by the ratio of added value to gross farm output).
72 Mischler (2019) also found that mixed monogastric and ruminant systems had a higher nitrogen balance
73 and energy consumption per ha but lower income variability than specialist or mixed ruminant farms.
74 However, these studies did not distinguish between the different types of pig and ruminant production
75 systems, although there is significant heterogeneity. Furthermore, they did not provide an overall
76 assessment of the sustainability of mixed farms based on aggregations of indicators.

77 Aggregation of indicators makes it possible to summarise all the information into a limited number of
78 scores to more easily conclude about the sustainability of systems (El Gibari *et al.*, 2019). Aggregation
79 has several methodological pitfalls (Schärlig 1985), including: incommensurability, i.e. the fact that
80 there is no common unit for all indicators, subjectivity of weights, compensation between indicators and
81 loss of information during aggregation. Several aggregation methods have been proposed in the
82 literature: (i) methods for *a priori* aggregation of criteria into a single criterion based on a hierarchy and
83 weighting of all criteria considered in the decision, such as the Analytic Hierarchy Process (Saaty 1980),
84 and (ii) approaches based on over-ranking, which relies on the comparison of systems before
85 aggregating them, such as the ELECTRE method (Roy 1968) or the PROMETHEE method (Brans *et al.*,
86 1986). Based on one of the over-ranking approaches, we use here the 'directional benefit of doubt'
87 approach (Melyn & Moesen 1991; Zanella *et al.*, 2015), which is a type of data envelopment analysis
88 (Charnes *et al.*, 1978). It allows for the assessment of overall performance by aggregating the
89 performance of central indicators without having to weight them subjectively. More specifically, the
90 directional Benefit-of-the-Doubt approach presented in Rogge *et al.*, (2017) was applied to allow for the
91 consideration of desirable and undesirable indicators without changing the indicator values.

92 The objectives of this study are to assess how pig production improves or worsens the aggregate
93 sustainability indicators and scores of farms according to the type of pig production system added
94 (farrow-to-finish sow production system or a pig fattening production system only) and the type of initial
95 cattle production system (beef or dairy cattle).

96 Although the analysis of real farms makes it possible to evaluate the farm functioning under real
97 conditions for both mixed and specialized farm, modelling allows for the control of the effects of
98 production system size and efficiency. It avoids biases in the comparison of different farms such as the
99 Fox paradox (Karagiannis 2012) that can occur when firms producing several goods produce a smaller
100 proportion of the good for which they are less efficient than others. Modelling also allows the estimation

101 of indicators that cannot be estimated directly base on a farm survey. The farm model Orfee (Mosnier
102 et al., 2017) is particularly suited to simulate mixed production systems as it takes into account several
103 complementarities between different farm production systems that are parameterized according to
104 current knowledge about the value of organic fertilization, on-farm production of feed and litter for
105 animals, possibility to use machines, building and labor for different productions (Mosnier *et al.*, 2021a).
106 We used Orfee to simulate the sustainability of 17 mixed pig-cattle farms surveyed in the French Massif
107 Central., The same 17 farms were simulated with and without the pig production system in order to
108 assess the changes in farm sustainability caused by the pig production system.

109 **2 Method**

110 2.1 Multi-criteria sustainability assessment

111 1. The evaluation tree

112 We have defined a hierarchical evaluation tree (Figure 1) in which each sustainability pillars is
113 characterized by different components, which are themselves assessed by a number of criteria measured
114 by indicators. These provide information at farm or animal production system level on the three pillars
115 of sustainability. Only those indicators that were potentially impacted by pig production system and can
116 be calculated by the Orfee model were selected. Consequently, indicators that might have been of
117 interest such as return on capital and farm transferability, welfare, biodiversity, landscape quality and
118 air quality were not included.

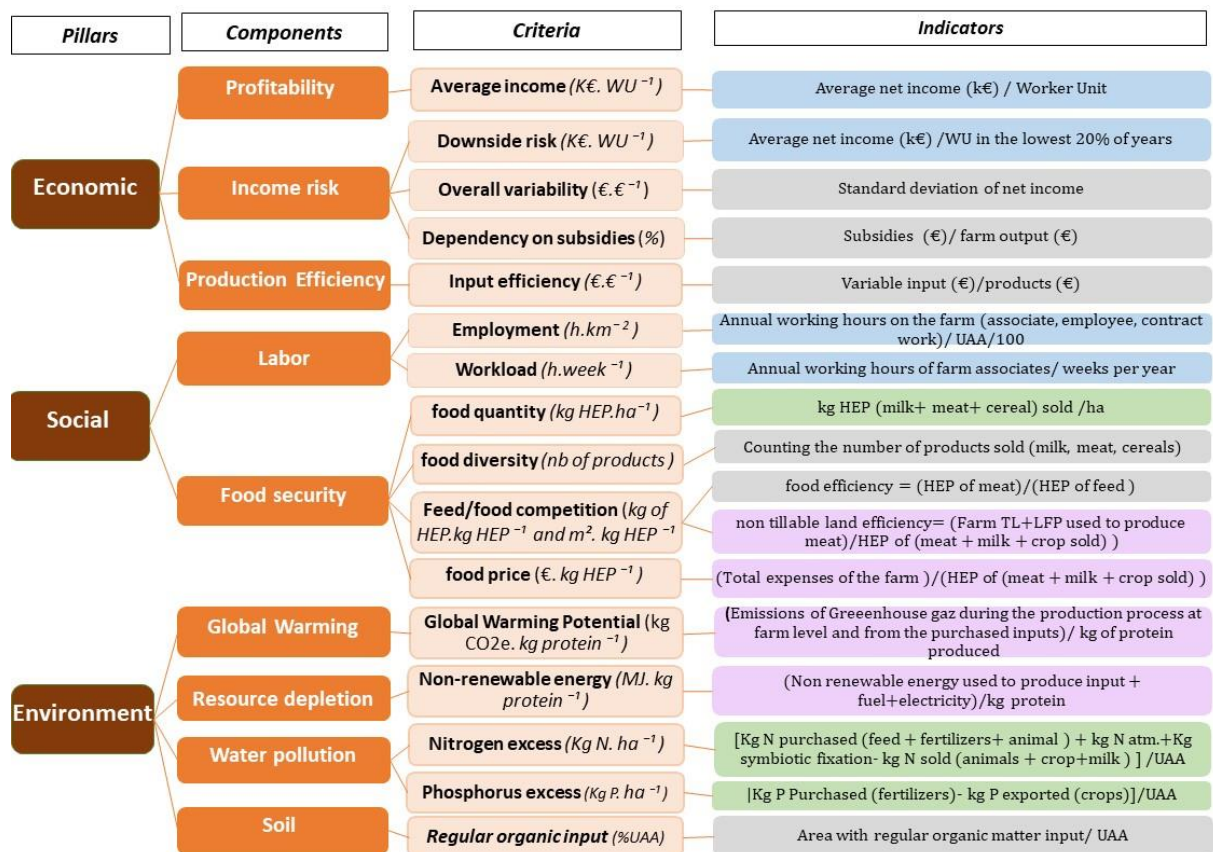
119 All the components studied are linked to the agricultural production process and could thus be included
120 in the economic pillar. However, we have chosen to distinguish three pillars: 1) the economic pillar,
121 which assesses the good management of the farm's resources in order to generate an income for its
122 managers, 2) the social pillar, which takes into account the services rendered by the farm to humans,
123 and 3) the environmental pillar, which assesses the impacts of the production process on the
124 environment. The economic pillar included four components: profitability, income risk and efficiency.
125 The farm profitability component was assessed by the average net income per worker associate. Net
126 income is calculated as the difference between farm outputs plus subsidies minus variable costs, fuel,
127 water and electricity, maintenance and depreciation of machines and buildings, employee wages, cost
128 of contract work and social taxes, land rental and financial costs. The income risk component was
129 measured by (1) the conditional value at risk (CVaR) which is the average net income in the lowest 20%
130 of years and indicates downside risk, (2) the standard deviation of net income as a measure of overall
131 variability and (3) the dependency on subsidies. We argue that since the share of subsidies in the outputs
132 and income of cattle farmers is already very high, it is desirable to reduce their dependence on public
133 subsidies to the extent that public policies can change as the objectives of successive governments
134 evolve. The efficiency of the input used was measured as the ratio of variable input costs including feed,
135 seed and energy to sales of animal and crop products. A farm with a low ratio consumes less inputs to

136 produce the same amount of outputs and is considered more sustainable. Capital such as labour, land
137 and machinery is not included in this ratio because it can be used in several production cycles provided
138 it is maintained in good condition.

139 Two components were considered for the social pillar. The first component was labour appreciated by
140 (1) the labor density and (2) the workload. A higher labor density creates more paid jobs for the farm
141 and the territory and was considered positive. In France, rural areas far from cities often have very low
142 population densities. Maintaining employment and therefore families in these areas is therefore an
143 important issue. A higher workload per worker means that a full-time worker has a greater number of
144 hours of work per week. A larger workload is seen as negative, as farmers are often already overworked.
145 The second component was the production of human edible food. Only the amount of human edible
146 protein (HEP) was taken into account (Supplementary Material A). Although energy, minerals and
147 amino-acid are also very important for a balanced diet, the contribution of animal derived food is
148 particularly important for protein (Capper *et al.*, 2013). The high amount of HEP produced per hectare,
149 the high diversity of agricultural products and the low production costs of HEP were considered
150 beneficial for people to access a diverse and affordable diet in their territory. Two additional indicators
151 targeting resources competing with human food production used for animal production were considered:
152 tillable land used to produce HEP since this type of land could directly produce human food (van Zanten
153 *et al.*, 2016), and the HEP efficiency of animal feed (Laisse *et al.*, 2018) since ruminants are criticized
154 for their low efficiency in converting natural resources into edible food (Gerber *et al.*, 2015).

155 For the environmental pillar, three components and five indicators were considered. The Global
156 Warming Potential (GWP) quantified the emissions of methane (CH₄), nitrous oxide (N₂O) and carbon
157 dioxide (CO₂) at all stages of agricultural production and for all inputs (except machinery and buildings),
158 from cradle to farm exit gate (Mosnier *et al.*, 2017; Mosnier *et al.*, 2021b) (Supplementary Material B).
159 The functional unit chosen for this global indicator is one kg of protein (this includes proteins that are
160 not edible by humans but used for other purposes as this indicator does not only concern food
161 production). We have not opted for a functional unit per hectare because climate change is a global
162 issue; the aim is to produce efficiently independently from the location where the emission is produced.
163 The depletion of non-renewable resources was also calculated per kg of protein. This is the sum of the
164 fuel and electricity consumed on the farm and the amount of non-renewable energy used to produce the
165 purchased input. Livestock manure contains a significant amount of nutrients such as nitrogen and
166 phosphorus, which at low concentrations, make the soil more fertile. However, in excess, they are
167 responsible for water pollution. Too much nitrogen and phosphorus in the water causes eutrophication
168 then algae blooms, often at the cost of other species. Since it is the excessive local concentration that
169 induces pollution, the unit function is the hectare. This pollution was assessed by two per hectare
170 indicators of excess nutrients: the nitrogen balance and the average phosphorus balance. The nitrogen
171 balance is the difference between N entries (N in purchased animals, fertilizers and feed, N fixed by

172 leguminous crops and crop residues, atmospheric deposition) and N exits (N retained by animals, sold
 173 crops) at farm level (Simon & Le Corre, 1992). Phosphorus surplus was assessed with a simpler method
 174 since phosphorus cannot be absorbed in the atmosphere: it is the difference between the P content of
 175 applied fertilizers on the farm and crop exports. The quality of the soil depends on several factors
 176 including its organic matter content. The regular application of organic fertilizers can contribute to
 177 increase the organic matter of the soil (Diacono & Montemurro 2011). The indicator used is the share
 178 of land that has received at least 5 t of organic matter every two years (equivalent to 24 tons of solid
 179 farmyard manure) to maintain organic matter content above 2% (Thiery *et al.*, 2023).



180

181 **Figure 1: Evaluation tree**

182 Notes: hr= hour; WU=Worker Unit; ha= hectare; HEP= Human Edible Protein; N= nitrogen; P= Phosphorus; UAA= Usable
 183 Arable Area; total expense includes variable costs, fixed costs and labor costs; TL= Tillable land, LFP= land used to produce
 184 feed purchased. In green: Functional Unit (FU) is 1 hectare; blue: FU is one full time worker; pink: FU is one kg of protein
 185 or 1 kg of HEP, grey : without unit.
 186

187 2. Sustainability score aggregated by the D-Bod model

188 A composite indicator (CI) is a mathematical aggregation of a set of sub-indicators that measure multi-
 189 dimensional concepts but generally do not have common units of measurement (Nardo *et al.*, 2005). The
 190 benefit of the doubt (BoD) addresses many of the methodological criticisms associated with composite
 191 indicators. In particular, insufficiently precise knowledge of the underlying structure of a farm's multi-
 192 performance, uncertainty or lack of a standard construction methodology and disagreement among
 193 experts on the importance of the underlying performance indicators used for each dimension (Cherchy

194 *et al.*, 2007). The weighting of sub-indicators has always been the most problematic methodological
 195 element in the construction of composite indicators (Nardo et al., 2005). The BoD method does not
 196 require arbitrarily setting the weight of each indicator to be aggregated. Each farm evaluated has the
 197 benefit of the doubt in selecting its relative weights. The model endogenously selects the best possible
 198 weights for each evaluated farm to maximise its aggregate score. Recent developments in production
 199 systems research suggest the use of a directional benefit of the doubt model (D-BoD model) (Rogge et
 200 al., 2017). The D-BoD model combines the methodological advantages of the traditional BoD model
 201 with those of the directional distance function (Rogge et al., 2017; D'Inverno and De Witte, 2020). One
 202 of these advantages is that it satisfies the unit invariance property, i.e., the aggregate performance score
 203 is not affected by the scale of the performance indicators. For example, measuring an indicator in tons
 204 or kilos has no impact on the overall performance score. Another practical advantage of the D-BoD
 205 model is that it is flexible enough for performance evaluations in real-life decision-making situations by
 206 reflecting the evaluation attitude of the decision maker. The D-BoD model maximizes desirable
 207 indicators and minimizes undesirable indicators without transforming them, by specifying a direction
 208 vector, denoted $g(\cdot)$.

209 For a sample of N farms, a vector of s desirable indicators, and a vector of m undesirable indicators per
 210 farm, the D-BoD model (see Zanella et al., 2015; Rogge et al., 2017) the dual¹ formulation of the D-
 211 BoD model (see Zanella et al., 2015; Rogge et al., 2017) is given by :

$$212 \quad D_k(y_k^-, y_k^+, g_r^+, g_l^-) = \min_{w_{k,r}^+, u_{k,l}^-} (-\sum_{r=1}^s w_{k,r}^+ y_{k,r}^+ + \sum_{l=1}^m u_{k,l}^- y_{k,l}^- + v) \quad (1)$$

213 subject to

$$214 \quad -\sum_{r=1}^s w_{k,r}^+ y_{j,r}^+ + \sum_{l=1}^m u_{k,l}^- y_{j,l}^- + v \geq 0 \quad (j = 1, \dots, k, \dots, N) \quad (2)$$

$$215 \quad \sum_{r=1}^s w_{k,r}^+ g_r^+ + \sum_{l=1}^m u_{k,l}^- g_l^- = 1 \quad (3)$$

$$216 \quad w_{k,r}^+ \geq 0 \quad (r = 1, \dots, s) \quad (4)$$

$$217 \quad u_{k,l}^- \geq 0 \quad (l = 1, \dots, m) \quad (5)$$

$$218 \quad v \in \mathbb{R} \quad (6)$$

219

220 The objective function (1) minimizes the weighted sum of the desirable ($y_{k,r}^+$) and the undesirable ($y_{k,l}^-$)
 221 indicators, provided that no farm in the sample reaches a value lower than zero when computing a similar
 222 measure using the same weights as the farm under assessment (see constrain 2). The optimal value,
 223 $D_k(y_k^-, y_k^+, g_r^+, g_l^-)$, of the objective function corresponds to the maximal feasible expansion of desirable
 224 indicators and contraction of undesirable indicators that can be achieved simultaneously. The direction
 225 vector $(g_l^-, g_r^+) \in \mathbb{R}^{m+s}$ specifies the exact direction in which improvements can be sought. The
 226 direction vector is defined such that $g(g_l^-, g_r^+) = (-y_l^-, y_r^+)$, which is the direction along which desirable

¹ The dual formulation of the D-BoD model is preferred because it allows for the inclusion of weight restrictions.

227 indicators are expanded and undesirable indicators contracted simultaneously. This definition of
228 $g(\cdot)$ allows each farm to follow its own improvement path, and thus ensures a high level of flexibility;
229 it also preserves the invariance of the D-BoD model units (Zanella et al., 2015). The variable v comes
230 from an equality constraint in the primal formulation of the D-BoD model that ensures the construction
231 of an appropriate frontier to compute the composite indicators. It can also be seen as a factor that will
232 be determined by the optimization process to ensure the non-negativity of the distance function. The
233 second constraint (3) is a normalization condition, which ensures that the weights ($w_{k,r}^+$ and $u_{k,l}^-$) are
234 relative. It is assumed that the weights should be not negative and subsequently non-negativity
235 constraints (constraints 4 and 5) are imposed in the model. Before aggregating the indicators, they are
236 interpreted to determine whether a higher value for an indicator reflects an improvement or, on the
237 contrary, a deterioration in performance. In this way, it is possible to determine which indicators to
238 maximize and which to minimize.

239 In addition, to limit compensations between indicators and allow all performance sub-indicators to be
240 included in the composition of overall scores, we follow the existing literature on the BoD model (e.g.,
241 Rogge et al., 2017; Lavigne et al., 2019) by imposing the restriction that all sub-indicators receive
242 minimum weights. In order to have the same minimum weight constraint on each component
243 independently of the number of criteria defined for each of them, a hierarchical assessment was made
244 by creating intermediate composite indicators for components with multiple criteria. The minimum
245 weights were defined to be as high as possible while allowing the model to find a solution, i.e. between
246 6% and 30% depending on the number of indicators included in the composite index and the composite
247 indicator considered.

248

249 The previous program (eq. 1-6) and the additional weights constraints is solved for each farm of our
250 sample using the R package “Composite Indicators Functions” (Compind), and the composite indicator
251 for the k^{th} farm (CI_k) is obtained as:

$$252 \quad CI_k = 1/(1 + D_k) \quad (7)$$

253 and it ranges between zero (worst performance) and one (best performance), i.e., $CI_k \in]0,1]$.

254 **2.2 Simulation of farm functioning and performance with the model Orfee**

255 2.2.1 Model overview

256 To estimate technical, accounting and sustainability indicators for mixed cattle-pig farms and
257 specialized beef and dairy farms, the Orfee (Optimization of Ruminant Farm for Economic and
258 Environmental assessment) bioeconomic farm model was used (Figure 2). Orfee is run on the General
259 Algebraic Modelling System mathematical modelling platform (GAMS Development Corporation,
260 Washington, DC, USA) and solved by the CPLEX (linear programming with binary variables) solver.

261 Orfee was initially developed to simulate the functioning of a farm with cattle, grasslands and crops, its
262 economic performance and its greenhouse gas emissions (Mosnier *et al.*, 2017). Orfee has previously
263 been expanded to include sheep production and additional sustainability indicators (Mosnier *et al.*,
264 2021a). For this study, a pig production module was added (Supplementary Material C) but with less
265 mechanistic production processes than for ruminants (Mosnier *et al.*, 2017). For instance, the amount of
266 feed consumed per pig is set exogenously, whereas the model optimizes the amounts and types of feed
267 consumed by ruminants to meet their protein and energy requirements (INRA, 2007) based on feed
268 availability and cost.

269 Orfee is an optimisation model. Livestock, crop production and equipment can be optimised to maximise
270 a Markovitz-Freund mean-variance function of net profit. This function is linearised by the MOTAD
271 formulation (Mosnier *et al.*, 2009). The risk aversion coefficient that weights the variance with respect
272 to the mean is fixed at -0.5. Net profit is defined as the differential between 1) total gross product which
273 includes animal and crop revenues plus subsidies and 2) total expenses which include production
274 systemal costs (purchase of feed, veterinary costs, seeds, fertilizers, etc.), structural costs (employee
275 salaries, maintenance costs, fuel, etc.), annuities (capital repayment) and opportunity labor costs for
276 associated workers. The variability comes from the different prices and the level of subsidies over the
277 period 2012-2022, which is the main cause of the variability in profits for beef and pig production.

278 Price changes were calculated as a reference price calibrated to each farm reference, multiplied by the
279 price change index (respectively the producer price index for agricultural products, PPAPI, and the
280 purchase price index for agricultural inputs, PPMAPI, for products and inputs), and deflated annually
281 by the consumer price index. These indices were calculated by the National Institute of Statistics and
282 Economic Studies. The main national and European subsidies granted to cattle and crop production
283 between 2012 and 2022 were taken into account (Mosnier *et al.*, 2017). Optimization is carried out under
284 a series of agronomic, structural and regulatory constraints.

285

286 2.2.2 Interactions between the different farm production systems included in the model

287 The interactions between the different production of the farm (culture, cattle and pigs)- concern first of
288 all the exchanges of materials between crops and animals. Plant products produced on the farm can be
289 used for animal feed or bedding. Cattle mainly consume products from grasslands and fodder crops,
290 supplemented by grains. Pigs consume mainly grains. The arable land can thus either be used to produce
291 feed and litter for cattle and pigs or can be sold directly while permanent grasslands are exclusively used
292 by cattle. Feed, excluding green or silage fodder, and straw can also be purchased. Pig feeding can be
293 based solely on the purchase of complete industrial feed. Constraints in the model specify the types of
294 feed that are possible for each farm and type of animal production. Animals provide in return, organic
295 matter and minerals to soils and plants. The composition of manure varies according to the type of
296 bedding and the type of animal. Manures containing straw are richer in organic matter and will feed the

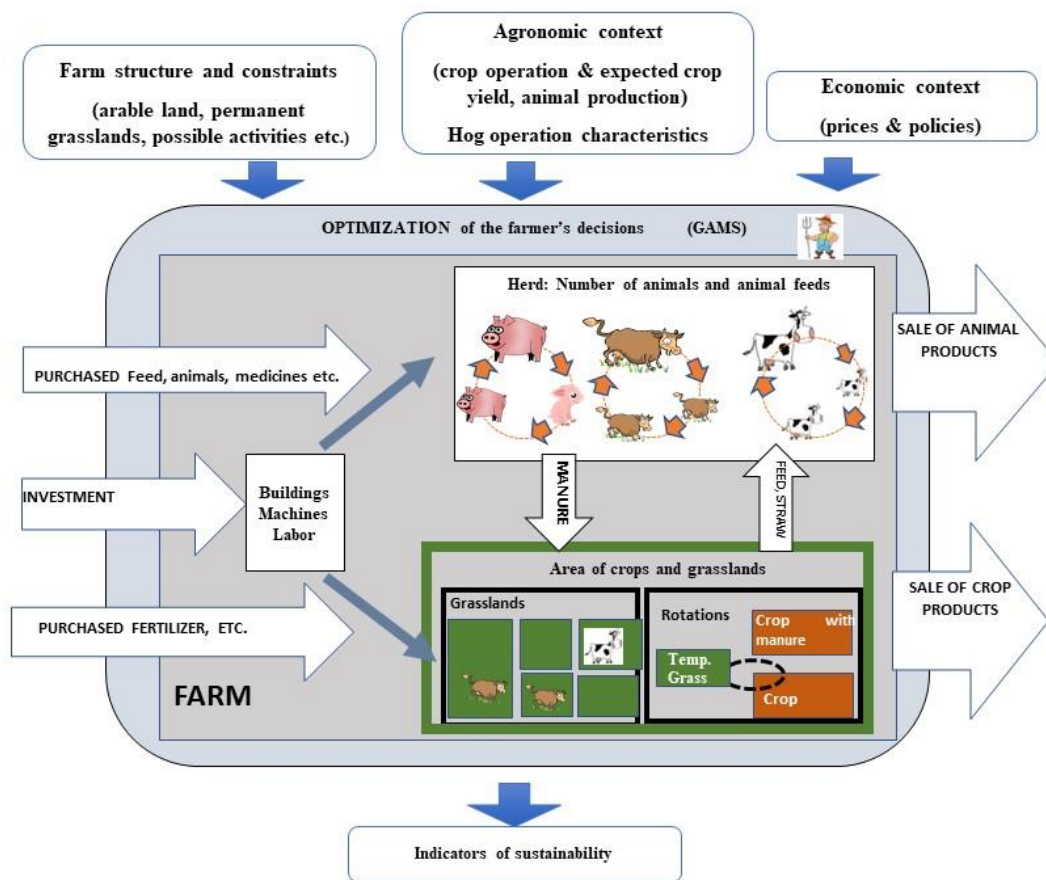
297 soil more, while liquid manures contain nitrogen that is more rapidly available to plants (Supplementary
298 data C, Table C6). Pig manures that are most often liquid, have higher nitrogen levels than cattle manures
299 and are more balanced in N, P, K elements. The model requires that sufficient minerals be applied to
300 balance crop export and other nitrogen transfers to the soil or to the atmosphere. However, mineral
301 inputs can exceed plant exports for several reasons: 1) only a fraction of the minerals in manure can be
302 used by plants in the short term, 2) organic fertilizers have an composition of N, P, K that is not perfectly
303 balanced for plant needs, and 3) in the case where manure exports are not possible, the farmer has an
304 interest in spreading all of his manure within regulatory limits.

305 Cattle and pig production systems can share common equipment such as manure spreaders or feed, straw
306 harvesting equipment or manure storage. The model calculates the equipment needs for the cultivation
307 production systems and optimizes the type of machinery used (owned or not, machine power). If both
308 workshops use owned machines, then the fixed costs can be divided between the workshops.

309 Concerning labour, the work needs for the cattle production system, the pig production system, the field
310 crops and the management of the farm (18% of the total work time) are calculated by the model. The
311 hours of work that exceed the amount of work that can be done by the associated workers present on the
312 farm (parameterized in the model input for each farm) are automatically assigned to salaried work. The
313 workforce is assumed to be perfectly flexible in the model, whereas in reality the workers are sometimes
314 specialized on a given production.

315

316



317

318 **Figure 2: representation of the Orfee model**

319 **2.3. Scenarios and farm surveys**

320 The objective of this study was to assess whether the addition of a pig production system improves the
 321 sustainability of cattle farm.

322 To do so, we used survey data from mixed pig-cattle farms in the French Massif Central obtained in the
 323 framework of the Aporthe project. Twenty-three semi-structured face-to-face interviews were conducted
 324 with the 1250 farms that had been pre-surveyed by mail, using the following criteria: (i) response to the
 325 postal survey (21%), (ii) the prospect of maintaining their pig farm, and (iii) the diversity of production
 326 orientations of pig farms and the main pig basins of the Massif Central., After eliminating farms with
 327 missing values, a sample of 17 mixed cattle-pig farms was selected for this study. 35% of the farms were
 328 involved in sow farrowing and 65% in fattening only pigs. 41% of the farms were involved in dairy
 329 cattle and 59% in beef cattle.

330 The survey included structural data regarding the labor force, main land use, herd size, main beef
 331 production, milk production and pig production (Table 1). Dairy production systems and beef cow
 332 production systems were slightly larger than the average of specialized dairy or beef French farms in
 333 2020: 84 and 80 vs *resp.* 60 dairy cows and 70 beef cows for French specialized farms (Agretse 2020).

334 The size of pig production system was lower than the national average (224 vs 493 livestock units) but
 335 with a high heterogeneity between farms. Since the project was focusing on the pros and cons of pig
 336 production, rather detailed data was gathered on each farm to characterize pig production but limited
 337 technical data was available for crop and cattle production (Supplementary Material D) and
 338 consequently relied on the average technical coefficient of this area.

339 **Table 1: Main characteristics of the farms surveyed**

	Mean	SD	Min	Max
Workers (WU)	2.6	1.5	1.0	7.0
Usable Agricultural Area (ha)	145	81	60	318
Grasslands (%UAA)	70%	18%	32%	100%
Forage crops (%UAA)	21%	12%	0%	45%
Cash crops (%UAA)	9%	10%	0%	29%
Number of beef cows (head) (N= 11)	80	33	50	150
% of beef finished (N= 11)	30%	37%	0%	100%
Number of dairy cows (head) (N=7)	84	41	30	150
Milk production (1000L.cow ⁻¹ .year ⁻¹) (N=7)	8.0	0.9	6.7	9.1
Stocking rate (LU Cattle/forage area)	1.2	0.3	0.8	1.9
Number of sows (N=7)	131	80	54	304
Number of piglet purchased (N=10)	2063	1839	600	7061

340

341 Orfee was used in this study to simulate the performance of the 17 farms studied in the 2012-2022
 342 economic context. The same 17 farms were simulated with and without pig production system in order
 343 to assess the changes caused by pig production system (table 3). The opposite situation (pig only) was
 344 not tested because it raises questions about the alternative use of permanent grassland, currently grazed
 345 by cattle. For each simulation, the herd size, type of animal produced, and area of cash crops were set
 346 according to the farm data. Pig production and feeding were also set for each farm. Default data were
 347 used for cattle breeding and weights, crop yields and cultivation production systems. As no information
 348 was available for grassland management, cattle feeding, machinery and building capacity, these
 349 variables were endogenously optimised by the model. We considered that extra manure can be given
 350 away for free because the farmers interviewed had no problem giving it away but could not always sell
 351 it. The number of labour units considered for the mixed beef and pig farm was based on the farm surveys.
 352 For the scenario of the specialised beef farm, the number of simulated annual working hours was
 353 generally lower. It was assumed that the reduction in the number of hours of salaried work and thus the
 354 cost of salaried workers was first reduced, assuming that a full-time job is always 35 hours per week.
 355 The cost of salaried labour was defined on the basis of the minimum gross income imposed by legislation
 356 in France (10 €/hour over the period studied), multiplied by 1.2 to take into account the scarcity of

357 agricultural employees on farms and the evolution of their wages, and multiplied by 1.4 to add the social
 358 charges paid by the employer on the employee's wages. When the reduction in working time exceeds
 359 the employee's working time, the number of associate workers has been reduced but rounded to the
 360 nearest work unit to take into account the fact that the associates' working time is more flexible: from
 361 30h/week to 60h/week, an associate is considered full-time.

362 **Table 3: Characteristics of the simulated scenarios for the 17 farms surveyed**

	Mixed cattle-pig	Specialized cattle
Pig production	According to farm survey	None
Number of cows, area of grasslands and cereals	According to farm survey	According to farm survey
Grassland management, crop management, animal diets	Optimized	Optimized
Worker unit	According to farm survey	Recalculated

363 A comparison with real data detailed economic simulated results are provided in Supplementary Data
 364 E.and F. They show that the technical-economic results of the sow and fattening workshop are very
 365 close to those observed in the farms for the year 2018. The technical results of the pig fatteners are also
 366 very close, however, the gross margin has more variance and the data are not available regarding the
 367 total cost of production, which makes the reliability of the estimate of the overall profitability of the pig
 368 fattening workshop more uncertain. The technical-economic results of the beef workshop and of the
 369 whole farm were not available in the farms, so the comparison was made with national data. It can be
 370 seen that the cattle farms are larger overall than those in the national INOSYS ruminant farm observation
 371 network, but that their technical and economic results are in the same order of magnitude.

372

373 **3 Results**

374 **3.1 Economic sustainability**

375 For the economic context studied (2012-2022), Table 4 shows that mixed systems have contrasting
 376 impacts on economic indicators leading to an overall economic performance not higher than that of
 377 specialised systems. The coefficient of variable costs over product and income per worker is the
 378 indicators with the highest weight in this composite score but it is average income per associate worker
 379 unit and minimum income (CVaR) that are most correlated with the composite economic sustainability
 380 score (Figure 3).

381 The pig production system allows an average increase of 7 k€ in income per worker. This gain is more
 382 significant for beef cattle production which have a lower income per worker than dairy production
 383 systems (table 4) and for pig fattening units. On average, the pig production system allows farms to
 384 reduce fertilizer expenses by 8 k€ but the additional equipment needed to spread manure increases
 385 mechanization expenses (external production system, maintenance, depreciation and fuel) by 7 k€
 386 (Supplementary Material E2) and required additional manure storage capacity. In our sample, the
 387 increase in subsidies allowed by the addition of the pig production system is on average 2 k€/farm but
 388 rises to nearly 10 k€ if the production system allows the addition of a partner and meets the
 389 compensatory payment for mountain areas requirements. Pig production is not directly subsidized.
 390 However, the addition of a pig production system can in some cases indirectly increase subsidies. The
 391 compensatory payment for mountain areas is capped at 75 ha, with a degressivity from 25 ha but this
 392 ceiling can be increased if there are several partners on the farm as is often the case with the addition of
 393 pig production system.

394 The composite indicator of income risk is better for mixed farms (0.74) than for specialized cattle farms
 395 (0.67) The pig production system stabilize income because of the reduced dependence on subsidies. The
 396 lower share of subsidies in their income, makes them less sensitive to changes in public policy. Beef
 397 cattle farms with a higher share of subsidies in their income benefited more from this reduction.
 398 However, the coefficient of variation of income is higher in mixed systems (27% for mixed systems vs.
 399 25% for specialized ones), although this difference is only statistically significant in the case of the dairy
 400 farm. Pig production generates significant economic flows in terms of sales (294 k€) but also in terms
 401 of expenses, particularly for feed purchases (on average 142 k€). This increases the sensitivity of farms
 402 with pigs to market fluctuations. The pig fattening production system reduces the vulnerability of cattle
 403 farms by increasing the lowest income (CVaR), which reduces the risk of income falling below a critical
 404 threshold.

405 In mixed farms, variable input costs represented 59% of the value of output compared to 48% of the
 406 value of output in specialised cattle systems, demonstrating better input efficiency in specialised cattle
 407 systems that are more self-sufficient in variable inputs. These differences are more pronounced for the
 408 dairy-pig farms (57% vs 43%) than for the beef-pig farms (60% vs 52%) due to a lower output
 409 production in the beef cattle system.

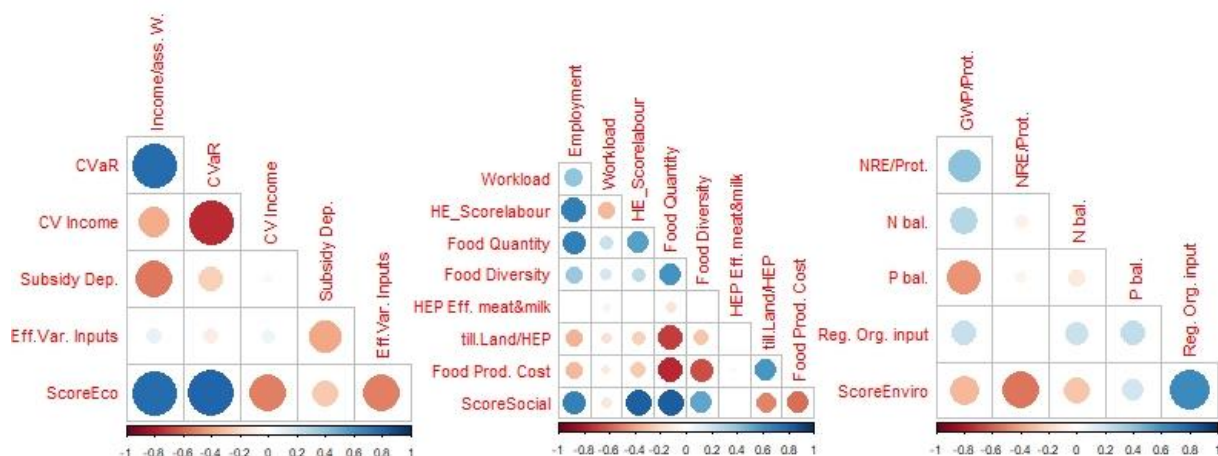
410

411 **Table 4: Composite and individual sustainability indicators according to the presence of a pig**
 412 **production system (*mixed vs. spe.*), cattle (*dairy vs beef*) and pig production (*pig fattening vs sow to***
 413 ***farrowing*) orientations**

Indicators*	Weight*	All		Dairy		Beef		Pig Fattening		farrow-to-finish sow	
		Mixed	Spe	Mixed	Spe	Mixed	Spe	Mixed	Spe	Mixed	Spe
Nb of Obs.		17	17	7	7	10	10	11	11	6	6
Sustainability Score		0.91***	0.85	0.92	0.88	0.90***	0.83	0.89***	0.83	0.93*	0.88

1)Eco. score	33%	0.81	0.82	0.90	0.87	0.79	0.76	0.81	0.80	0.82	0.84
<i>1.1) Average Income (k€/associate WU)</i>	19%	28.4***	20.9	31.9**	23.2	25.9***	19.3	26.8***	19.3	31.2*	23.8
1.2) Income risk	18%	0.74***	0.67	0.81*	0.75	0.68***	0.62	0.72**	0.67	0.76**	0.67
CVaR (€/WU)	27%	19.2	17.1	22.7**	19.5	16.8	15.4	19.4***	15.9	18.8	19.3
CV Inc. (%)	40%	26.6	24.5	24.6	18.1**	28.1	29.0	25.5	24.0	28.7	25.3
Subsidies Dep. (%)	33%	13.8***	25.9	9.8**	17.9	16.5***	31.4	15.7***	25.2	10.3**	27.1
1.3) Efficiency :Var Cost/product	62%	58.6	48.2***	56.9	43.2***	59.8	51.8*	56.8	49.0**	61.9	46.9*
2)° Social score	35%	0.87**	0.78	0.83**	0.71	0.74***	0.62	0.92***	0.72	0.84**	0.81
2.1) Labor score	51%	0.74***	0.68	0.81**	0.73	0.68***	0.64	0.72***	0.69	0.76*	0.66
Employment(h.km ⁻²)	28%	0.5***	0.3	0.6**	0.4	0.4***	0.2	0.4***	0.3	0.6**	0.3
Workload (h.week ⁻¹ assWU ⁻¹)	72%	44.9	42.2	44.9	42.7	44.9	41.8	42.9	39.6	48.5	46.8
2.2) Food security	49%	0.79***	0.61	0.83**	0.66	0.76***	0.58	0.76***	0.62	0.83**	0.60
Diversity (Number of products)	9%	2.9***	1.9	3.1***	2.1	2.7***	1.8	3.0***	2.1	3.0**	2
Quantity(Kg HEP.ha ⁻¹)	9%	154.2***	77.9	139.5**	61.7	175.1***	101.0	132.7***	70.6	193.6**	91.1
HEP efficiency	9%	0.82	1.10*	0.95	1.60**	0.73	0.75*	0.87	1.21	0.73	0.89
Tillable Land (m ² HEP ⁻¹)	26%	56.4***	100.7	52.6**	81.5	59.0***	114.1	62.7***	107.6	44.9**	87.9
Production Cost (€/HEP ⁻¹)	48%	0.8***	2.2	0.7**	1.4	0.9***	2.7	0.8***	2.3	0.7**	1.9
3) Enviro. score	34%	0.81	0.78	0.75	0.73	0.85	0.81	0.85*	0.83	0.89	0.96
3.1) GWP (CO2e. kg protein⁻¹)	24%	21.8**	43.0	19.2**	33.8	23.5***	49.4	25.1***	49.3	15.6**	31.5
3.2) Non Renew. Energy (Mj kg prot.⁻¹)	29%	97.4	112.3	110.7**	159.0	88.1	79.6	107.9*	131.8	78.0	76.5
3.3) Water pollution	16%	0.68	0.51	0.73	0.48**	0.65	0.53***	0.69	0.55***	0.66	0.43
N balance(kgN.ha ⁻¹)	58%	30.1	25.3***	27.2	20.8**	32.2	28.5***	31.6	28.0***	27.4	20.5**
P balance (kgP.ha ⁻¹)	42%	44.2	28.9***	56.9	43.2**	59.8	51.8***	56.8	49.0***	61.9	46.9**
3.4) reg. organic matter input (%UAA)	31%	66.0	63.3	60.0	55.6	70.2	69.2	64.5	61.1	68.7	66.9

414 Notes: Weights are endogenously defined by the D-BoD model for each farm. In bold values are more sustainable with *, **,
415 *** indicating a significance at 10%, 5% and 1% with the non parametric Wilcoxon signed rank test. WU: worker unit, HEP:
416 Human Edible Protein, CVaR: Conditional Value at Risk (average of the 20% of the lowest income), CV coefficient of variation
417 of income, Subsidies Dep.: subsidy dependency, GWP global warming potential, N nitrogen and P Phosphorus balance, reg.
418 organic matter input: % of area with regular organic matter input
419



420
421 **Figure 3: Correlation matrix between composite indicators and single indicators**

422 Notes: from large red square for negative correlation to large blue circle for positive correlation

423 *ScoreEco*: aggregated economic score with net income per associate worker unit, *Cvar* : the conditional value at risk of net
424 income, *CV Income*: standard deviation of net income, *SubsidyDep*: dependency on subsidies, *Eff_VarCost*: input efficiency
425 (variable costs on product),

426 *ScoreSocio: aggregated social score with workload, employment, HEP_Eff, Human Edible Protein efficiency of animal*
427 *production, Food diversity measured by the number of food product produced on the farm, food quantity measure by the*
428 *quantity of HEP produced per ha, TilLand_Hep Tillable land used per HEP, HEP_ProdCost cost to produce 1 kg of HEP,*
429 *ScoreEnviro environmental score with GWP_global warming potential per kg of protein, NRE non renewable energy consumed*
430 *per kg of protein, N_bal nitrogen balance, P_bal: Phosphorus balance,*

431 **3.2 Social sustainability**

432 Mixed farms score significantly better on the social dimension of sustainability (0.87 vs 0.78) (Table 4).
433 The composite indicators of labor and food security have balanced average weights. The highest
434 correlations with the social score are the employment density, food quantity and food production cost
435 (Figure 3).

436 The composite indicator of labor is significantly better for mixed farms. Mixed pig-cattle farms generate
437 more on-farm employment than their specialized cattle counterparts. The employment density per unit
438 area in mixed cattle-pig systems is about 0.5 h.km⁻² compared to 0.3 h.km⁻² in specialised cattle systems
439 (Table 4). In the studied farms, the addition of a pig production system implies the addition of an average
440 of one worker:0.6 employee and 0.4 associate. The working time per full time employee worker is
441 assumed to be fixed (35 hours of work per week for a full-time employee) but the workload of associate
442 farmers can vary since it is assumed that the number of associate workers is adjusted by steps of 0.5
443 WU. On average, the worker-associates work three hours more per week due to the addition of the hog
444 production system.

445 Concerning the contribution of the farm to human food, mixed farms performs also significantly better
446 (0.79 vs 0.61). The mixed systems produce more Human Edible Protein (HEP) per unit area, including
447 the areas necessary for the production of cereals imported to feed the pigs. They also produce more
448 diversified feed. The area of arable land used to produce HEP is on average half as large in mixed
449 systems, with a larger difference in mixed beef/pig systems. These positive aspects concerning the
450 contribution to human food are less evident concerning the competition between feed and food. Overall,
451 dairy production is the most efficient in converting HEP, followed by pig and beef production.
452 Therefore, the efficiency of HEP conversion of total animal products is improved in mixed beef farms
453 but not in mixed dairy farms. Mixed farms have a lower average cost of producing HEP, which could
454 provide the consumer with cheaper food if the organization and the strategy of the sector allows it. The
455 cost of HEP in pig production is lower than the cost of HEP in cattle production and the complementarity
456 of pigs and grazing animals slightly reduces the cost of production associated with cattle and crops.

457

458 **3.3 Environmental sustainability**

459 The score of mixed farms is not higher on the environmental dimension for mixed farm (Table 4). The
460 weights of the different indicators are balanced (Table 4). The indicator of regulator organic input in
461 soils and non-renewable energy consumed are the most correlated to the sustainability score (Figure 3).

462

463 Mixed farms have a lower global warming potential (GWP) per kg of protein than specialised cattle
464 farms. This difference is explained by the absence of enteric methane emissions from pigs. The presence
465 of pigs also reduces the application of mineral fertilizers. On average, mixed farms consume slightly
466 less energy per kg of protein. Beef farms that use very few inputs do not benefit from the addition of the
467 pig production system, while dairy farms that require energy for milking and feed production consume
468 on average less non-renewable energy per kg of protein produced when there is a pig production system.
469 the extra manure allows all farms to reduce the purchase of fertilizer and in some cases to give it to other
470 farms, the surpluses in the nitrogen and phosphorus balance increase. The main reason for this is that
471 only a fraction of the organic nitrogen in livestock manure is potentially taken up by the growing crop
472 during the year the manure was applied. The rate of mineralization for the first year is around 60% for
473 pig slurry and 20% for cattle solid farmyard manure. Organic N is then slowly mineralized by micro-
474 organisms over the following years. The regular supply of organic matter increases the amount of humus
475 mineralized each year (from 5 to 20 kg more depending on the soil and the crop compared to a soil
476 without regular manure addition, COMIFER, 2013), but compared to a mineral fertilizer, more organic
477 nitrogen must be provided for the same plant needs. The excess of P increases even more as manure is
478 often too rich in P compared to N for the needs of the plants.

479 The production of more organic fertilizer on mixed farms allows more organic matter to be added to the
480 land. However, since it is the share of land that receives at least the equivalent of 24t of manure every 2
481 years (or 10t if it is grasslands) that is counted, applying more than 24t on a given crop does not improve
482 the indicator, thus mixed cropping does not significantly improve this indicator.

483

484 **3.4 Overall Sustainability**

485 The sustainability score is significantly higher for mixed farms (0.91) than for specialized cattle farms
486 (0.85). This gain is particularly significant in the case of beef cattle farms and for the pig fattening
487 production systems (Table 4). The weights of the different indicators are balanced (Table 4).

488

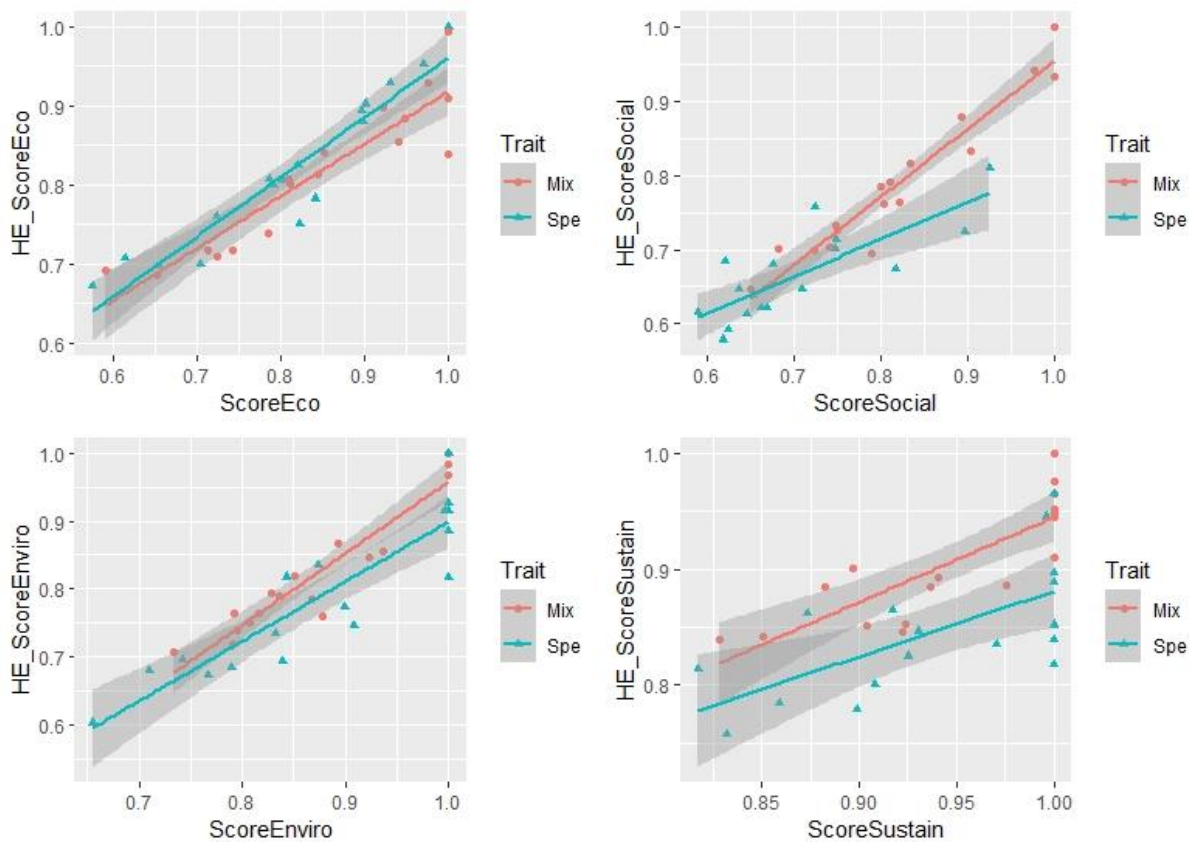
489 **4 Discussion**

490 **4.1 Relevance of the directional benefit of the doubt method to build composite indicator**

491 To aggregate indicators, it is necessary to give weights to the different indicators, Defining weights can
492 be tricky when weights have a significant impact on the value of the composite indicator. In traditional
493 method any choice of fixed weights is likely to be interpreted as arbitrary or unfair (de Witte and Rogge,
494 2011). The benefit of the doubt (BoD) method endogenously estimates the relative weights of each

495 indicator for each farm. As a result, the weights of the indicators for which the farm outperforms are
 496 higher than the weights of the indicators for which the farm underperforms. This mechanism reduces
 497 the difference in scores between farms as pointed out by Ravanos & Karagiannis (2021) and allows
 498 farms that are better on one indicator to be classified as efficient even if their performance is relatively
 499 poor on other indicators (Ravanos & Karagiannis 2021). Very high or very low weighting values may
 500 be undesirable as they induce compensation between indicators that is criticised under the assumption
 501 of high sustainability, as a farm could not be considered sustainable if one criterion is too low. The R
 502 package used (Compind, D-BoD constrained) allows specifying a minimum weight to avoid this pitfall.
 503 Since it is not possible to specify the weight of each indicator separately in the d-BoD method, we used
 504 a hierarchical approach so that the minimum weight does not implicitly give more weight to components
 505 with more criteria. Compared to the d-BoD method without weighting and hierarchy (Figure 4), the
 506 proposed framework reduces the score of specialized farms for the social pillar, where they perform less
 507 well overall. The overall sustainability indicator estimated with weights limiting offsets is also
 508 significantly lower, inducing more gap between the sustainability indicators of mixed and specialized
 509 farms.

510

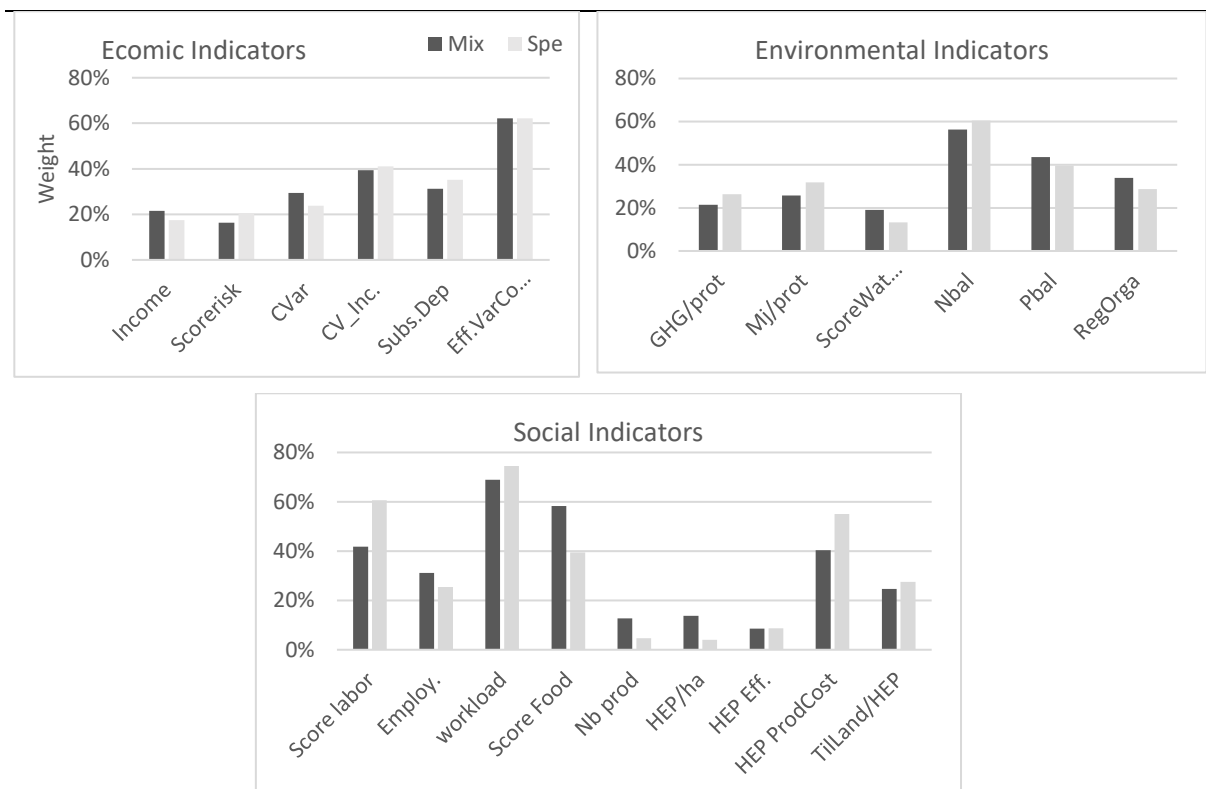


511

512 Figure 4: D-BoD Score estimated with a minimum weight and a hierarchical organization ("HE_")
 513 versus D-BoD scores estimated without weight constraints

514 However, it was not possible to impose weight constraints close to the balanced weights, as this makes
 515 the model infeasible. High correlations between the weight of the indicators and their value are still
 516 observed in our analysis, with sometimes low weights when it was not possible to raise the weight
 517 constraint (Supplementary Material F). Some indicators that are generally better for mixed farms, such
 518 as the amount of protein produced per ha and labor employment, have higher weights than specialised
 519 farms (figure 5), however, the differences is generally low.

520



521 Figure 5: Average weight of indicators with and without pig production system

522 Other DEA based methods exist to control the weights (Bagherikahvarin & De Smet 2016, Oliveira et
 523 al., 2019, Henriques et al., 2020), but they do not allow to differentiate desirable indicators from
 524 undesirable ones. However, when controlled weights are desired, this option can be interesting although
 525 it reduces one of the main advantages of the BoD method which is the endogeneity of the weights.
 526 Furthermore, methods that aim to control for the weights of individual indicators do not necessarily
 527 control for their explanatory level on the composite indicator. Paruolo et al (2013) found that the
 528 reported importance of individual indicators and their main effect on the composite indicators are very
 529 different. This is also the case here, with, for example, the weight of variable costs on the product being
 530 three times higher than that of average income per worker, but ultimately proving to be less correlated
 531 with the composite economic indicator than average income. Standard normal variables could avoid this
 532 dichotomy, but care must be taken to ensure that the variables do not have negative values to keep the
 533 model feasible.

534 Another advantage of the BoD method is that there is no definition of what is a good or bad performance.
535 In more traditional multi-criteria assessment methods, good or poor performance is often assessed as
536 above or below the average performance of the farm or a reference group rather than good or poor in
537 absolute terms, which is close to what BoD methods do. However, some levels of performance of the
538 indicators may be considered unacceptable, such as nitrogen and phosphorus surpluses that are too high
539 relative to the level of water pollution in the area, or, for farmers, a change of system that would reduce
540 their average income. In this case, one could imagine eliminating the farms with one of the results below
541 a critical threshold and adding an indicator of the percentage of farms that have failed to estimate the
542 risk associated with each system.

543 The BoD model can consider that a difference between two farms is discriminating whereas this
544 difference can be considered as not significant. For example, the simulated excess nitrogen balance is
545 below 50 kg/ha in all cases by the model and is significantly correlated with the composite
546 environmental indicators. Nevertheless, a nitrogen surplus below 60 kg/ha is considered as a correct
547 performance in the French High Environmental Value certification; therefore, the importance given to
548 the differences between the nitrogen balances may be too high. In this case, if accurate knowledge is
549 available to value the performance and if the sample is not too large, other methodology such as
550 PROMETHEE method (Brans et al., 1986). or CONTRA (Bockstaller *et al.* 2017)

551 Finally, the D-BoD method can be used in “Participatory Impact Assessment (PIA)” to evaluate the
552 performance of agricultural projects or public services. In fact, it can be applied to impact indicators
553 identified and measured by local populations, such as social indicators that are currently not well
554 addressed in quantitative models such as welfare indicators for instance, but can be addressed with
555 participatory methods. The PIA approach recognizes that local people are able to identify and measure
556 their own impact indicators (Catley, 1999). In the same vein, another appealing feature of the D-BoD
557 model is that it is enough flexible to incorporate stakeholder opinion (De Witte and Rogge, 2011)

558 **4.2 Main benefits of mixed pig cattle farms cited by farmers versus simulated**

559 Interviews with mixed cattle-pig farmers conducted in 2019-2020 in the Massif Central revealed that
560 increased income, income diversification and production manure are the main benefits of pig production
561 for them (Aporthe, 2022). The results of our simulation partly corroborate the farmers' perception but
562 not totally. We found that the addition of a pig production system increases income per worker. This
563 increase in income varies greatly depending on the efficiency of pig production, the price of pigs and
564 the price of pig feed negotiated by farmers. In 2020, at national level, pig farms also had a dispersion of
565 gross operating surplus per work unit (between the 10th and 90th percentile) 3.3 times higher than beef
566 cattle production and 2.7 times higher than dairy production (Agreste, 2021). As the gross margin per
567 animal is low and the number of pigs sold is high, it is particularly important to fine tune the pig

568 production system. Diversification does not always go hand in hand with the performance of each
569 livestock activity due to the increasing complexity of systems (de Roest *et al.*, 2018). Farmers with cattle
570 and pig rearing activities should be well organised and advised to manage their system in an efficient
571 and profitable way.

572 The second benefit cited by survey respondents is income diversification. Income diversification is
573 expected to reduce the risk exposure of the farm and increase its resilience. However, we simulated that
574 pig production reduce income risk globally but doesn't reduce income variability measure by the
575 coefficient of variation. This counter-intuitive result is attributed to the high weight of input purchases
576 and pig sales in the margin of the pig production system, which makes this production system more
577 sensitive to market risks than cattle production. In our simulation, the inter-annual variability of the
578 income of the cattle farms was underestimated since the climatic risk on forage production was not taken
579 into account. Nevertheless, the interannual variability of pig production recorded at national level is
580 much higher than that of cattle production (Supplementary Material G, Agreste 2021). As pointed out
581 by Mosnier *et al.*, (2021a), the variability of income of a farm with two production systems is lower than
582 the weighted sum of the variability of income of each production system taken separately if the risks of
583 each activity are not completely correlated. However, a mixed farm with a riskier activity has a more
584 variable income than a farm specialising in a low risk activity, at least in the short term. The use of more
585 local grain, by-products or food waste for pig feed, stabilisation of the pig market or minimum subsidies
586 could secure the pig margin. The estimated variability also depends on the time interval considered.
587 Mischler (2019) found that the coefficient of variation of mixed monogastric-ruminant farms was lower
588 than that of farms with only ruminants. This can be explained by the period he considered (2000-2016)
589 which includes the year 2001 characterised by a major crisis in the beef market. In a context of increasing
590 uncertainty about the future, mixed cattle and pig farms could gain interest in the future.

591 The third benefit cited concerned manure production. The average simulated results are mixed as the
592 benefit of reduced mineral fertilizer purchases is offset by additional machinery costs. However, the
593 benefits of organic fertilizers may be greater in the future. In 2022, the price of mineral fertilizers has
594 increased by 80% since 2015 (Agreste, 2022). Although, fuel prices have also increased by 50% and
595 feed prices by 25%, the savings in fertilizers offset the supplementary costs in our simulations. The
596 benefit of pig manure on grassland may also have been underestimated in the simulations. Orfee takes
597 into account the impact of regular addition of organic matter on soil fertility and humus mineralisation
598 in the soil. However, Orfee does not take into account the fact that organic matter in mountainous
599 grasslands is less well mineralised due to climatic conditions. In this context, the addition of a controlled
600 amount of pig manure can provide a better C/N ratio for soil fertility and increase pasture production
601 (Levasseur *et al.*, 2021). The separation of urine and faeces (De Vries *et al.*, 2013) can also lead to
602 better fertilisation. In the future, the The cost of pig liquid manure could also having underestimated in
603 some cases. In the future, the slope and often shallow depth of the soil of mountainous areas can

604 complicate the compliance with the future mandatory use of spreaders that emit less ammonia
605 (Levasseur *et al.*, 2021).

606 **5 Conclusion**

607 The objectives of this study were to estimate whether the addition of a pig production system improves
608 or worsens the sustainability of cattle farms and test the directional benefit of the doubt method, which
609 to our knowledge has never been used in agriculture. We combined different methods: survey data to
610 take into account the structural and technical heterogeneity of the farms, bioeconomic simulations in
611 order to redesign the farming systems with and without pig production systems and to calculate
612 numerous sustainability indicators, and econometric estimation to build composite indicators of
613 sustainability. The analysis is based on 17 pig-beef cattle or dairy cattle real farms located in the Massif
614 Central, a mountainous region located in the centre of France.

615 The analysis conducted in this study shows that, for the context 2012- 2022, the pig production system
616 increased the overall sustainability of cattle farms, more particularly with cattle farms and pig fattening
617 units. Average income per worker unit is increased but the economic pillar doesn't score better. The
618 mixed farms generated more employment, had a higher contribution to food production, lower
619 greenhouse gas emissions per kg of protein produced but more excess nitrogen and phosphorus per
620 hectare. Although these results tend to favour mixed pig-cattle farms, it raises issues that need to be
621 addressed in order foster the development of mixed systems, such as securing the pig production and
622 improving fertilization. Another possibility to limit the economic and environmental risks is to keep the
623 size of the pig farm relatively small compared to the cattle farm. Animal welfare and environmental
624 quality for the neighbourhood are also elements that need to be further investigated in future studies.

625 The D-BoD method appears to be a useful tool for endogenous aggregation of indicators, particularly
626 effective and easy to implement for large samples of farms. The D-BoD method does not require
627 arbitrary weighting of each indicator. However, the possibility to have varying weights for different
628 farms allows compensations between the different indicators and tends to reduce the difference in
629 sustainability score between farms. The possibility of imposing a minimum weight limits this
630 compensation. Another advantage of the D-BoD methodology is that it is not necessary to define
631 thresholds at which the indicator value becomes favorable or unfavorable, but therefore unacceptable
632 values or differences between indicator values that could be considered negligible could not be specified
633 directly in the model.

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641

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777 Supplementary Material

778 **Supplementary Material A: Feed-food competition parameters**

779

780 The quantity of human edible protein in animal product (HEP) depends on the liveweight of animals,
781 the quantity of protein per kg of liveweight and the share of human edible protein per kg of animal
782 protein (SHEPA) (table A1) (Laisse et al., 2018). SHEPA depends on carcass yield, which varies
783 according to breed and category of animals (Table A2). Giblets and human edible byproducts which are
784 also produced when slaughtering beef are included in the meat production estimate. In the case where
785 animals are not sold directly to be slaughtered, but to other farms where they will be finished, they were
786 treated as if they had been slaughtered. Regardless of the animal, 1 kg of bovine or pork human edible

787 meat is composed of 158 g of Gross Protein (GP) and contains 10.9 Mj of Gross Energy (GE) (Laisse
788 et al., 2018). For cow's milk produced, it was assumed that it is 98% human edible which gives an
789 identical share of human edible protein of 0.98. The average GP content of 32 g.l⁻¹ of milk is assumed.
790 For plant products,

791 **Table A1: Method for calculating human edible protein and energy contained in meat, milk and**
792 **cereals sold.**

Animal or vegetable product	Calculation method
Meat, (including giblets and human edible) by-product milk,	HEP produced = animal product * GP * SHEPA
Crops sold and feed	HEP produced or consumed = feed or crops sold * GP * SHEPV

793 *Notes: HEP: Human Edible Protein, Animal product in kg of live-weight (kg of meat sold minus*
794 *the kg of meat purchased) and kg of milk. Feed and crops in kg of Dry Matter (DM), GP gross*
795 *protein in kg of protein of crop DM or human edible animal live-weight SHEPA (%): Share of*
796 *HEP in animal products, SHEPV(%): Share of HEP in vegetable products.*
797
798

799 **Table A2: Carcass yield , gross protein content (GP), and Share of Human Edible Protein (SHEPA)**
800 **and Energy (SHEEA) values for each category and breed of cattle in the study**

Animal category	Breed	GP (kg of protein.kg ⁻¹ of live-weight);	Carcass yield (kg of Carcass. kg ⁻¹ of live-weight*100)	SHEPA (Kg of HEP. kg ⁻¹ of protein)
Pork		0.158	76.5	0.87
Swine		0.158	65.0	0.87
Cow	Holstein	0.158	45.5	0.520
	Montbéliarde	0.158	47.0	0.530
	Salers or Aubrac	0.158	51.0	0.560
	Charolaise	0.158	52.5	0.570
	Limousine	0.158	54.5	0.585
Heifer m.o	≥15 Holstein	0.158	47.0	0.530
	Limousine	0.158	55.5	0.590
Young bull ≥15 m.o.	Charolais	0.158	58.0	0.610
Bull ≥24 m.o.	Salers or Aubrac	0.158	54.0	0.580
	Charolais	0.158	57.0	0.600
	Limousin	0.158	58.0	0.610

801 *Notes: m.o. month old*
802 *Sources: ^a Laisse et al 2018, ^b*

803
804 Table A3 gives the content in protein and the shares of human edible protein (SHEPV) (in % of gross
805 protein) of all feed products and the land necessary to grow these feed.

806 **Table A3: Share of human edible protein (SHEPV) and energy (SHEEV), gross protein (GP) and**
807 **gross energy (GE) contained in each plant-based raw material used in animal feed and land**
808 **competition of these crops.**

Crops sold and feed	SHEPV %^a	Gross protein (g.kg⁻¹ DM)^b	Land competition (m².kg⁻¹ DM)^c
Wheat	66	126	1.33
Barley	61	112	1.48
Moist grain maize	15	92	1.04
Oats	84	108	2.08
Triticale	66	115	1.84
Rape	0	202	3.12
Soya meal from Brazil	60	526	1.51
Rapeseed meal	0	336	1.21
Dehydrated beet pulp	0	89	0.55
Pressed beet pulp	0	120	0.15
Beet molasses	0	142	0.26
Whole cow's milk powder for calves	30	254	1.38
Corn silage	10	78	0.89
Sorghum silage	57	59	1.17
Weanling concentrate	33	165	1.12
Cow concentrate	21	226	1.03
Finishing concentrate	29	193	1.2
Veal concentrate	30	197	1.06

809 *Sources: ^a Laisse et al 2018, ^b Inra 2018. ^c ECOALIM (Wilfart et al., 2016) and AGRIBALYSE ®*
810 *(Colomb et al., 2015) excepted for grass for which an average production of 7 ton of DM.ha⁻¹ was*
811 *assumed; DM: Dry Matter.*

812

813

Supplementary Material B: Global warming potential calculation.

814
815

816 The Global Warming Potential (GWP) indicator included GHG emissions and carbon storage. GHG
817 considered the emissions of methane (CH₄), nitrous oxide (N₂O) and carbon dioxide (CO₂) at all stages
818 of agricultural production and for all inputs, from cradle to farm exit gate (Mosnier *et al.*, 2017). The
819 three gases are aggregated by their GWP into a single indicator expressed in CO₂-equivalent (CO₂e)
820 with CO₂ =1; CH₄ = 28; N₂O= 265 (Myhre *et al.*, 2013).

821 Indirect CO₂ equivalent emissions from purchased inputs (feed and litter produced off-farm, non-
822 organic fertilizers, purchased animals) were estimated using by life cycle assessment (Agribalyse®
823 (Koch and Salou, 2014)). Emissions related to the construction of buildings, the purchase of seeds, the
824 use of pesticides and sprayers and machinery were not taken into account. Direct CO₂ emissions from
825 fuel combustion were estimated using the Dia'terre® method (ADEME, 2010) v. 4.51. Carbon storage
826 in soils was considered in a simple way, based on Soussana *et al.*, (2010). We assumed that permanent
827 grasslands store 570 kg C/ha/year, temporary grassland kept for 5 years has a net carbon storage of 360
828 (950 kg C/ha/year is lost in the two years following grassland destruction). Annual crops are a net source
829 of C losing 160 kg C/ha/year. Real storage is more complex since it depends on land use history, initial
830 carbon stock status, soil, climate, agricultural practices, botanical composition and grassland age
831 (Pellerin *et al.*, 2020).

832 Enteric methane (CH₄) emissions were estimated using equations of Sauviant *et al.*, (2011) and Sauviant
833 and Nozière (2016) that considered the quantity and quality of feed, digestive interactions and animal
834 size. Enteric methane (CH₄) emissions are the product of the quantity of organic matter (OM) ingested,
835 its digestibility (OMdc) and the emission factor (EF) of the digestible OM (DOM) (**Erreur ! Source du
836 renvoi introuvable.**1). EF, expressed in g CH₄/kg DOM, is a second-degree polynomial function (Eq.
837 2) that includes dry matter intake (DMI) per kg of animal liveweight (DMI%LW) and the quantity of
838 concentrate feed in an animal's diet (CO%DMI). DOM ingested by an animal was calculated as mean
839 DOM in the diet, with three corrective parameters to capture digestive interactions (Sauviant and
840 Nozière, 2016): (i) the difference between DMI%LW and the reference value (i.e. DMI of a given forage
841 by standard castrated sheep, which was used to measure forage digestibility and energy content (INRA,
842 2007)), (ii) the quantity of concentrate fed (CO), and (iii) the rumen protein balance, which equals crude
843 protein intake (CP) minus non-ammonia crude protein flowing out of the duodenum (
844). In general, EF decreases as DMI%LW increases and when CO%DMI exceeds 30%.

845 Enteric methane emissions = OM × OMdc × EF (Eq. 1)

846

$$EF = 45.42 - 6.66 \times \text{DMI}\%LW + 0.75 \text{DMI}\%LW^2 + 19.65 \text{CO}/\text{DMI} - 35.0 (\text{CO}/\text{DMI})^2 - 2.69 \text{DMI}\%LW \times (\text{CO}/\text{DMI}) \quad (\text{Eq. 2})$$

849

$$\text{OMdc} = \text{DOM} - 2.74 \times (\text{DMI}\%LW - \text{DMI}\%LW_{\text{ref}}) - 6.5 / (1 + (0.35 \text{DMI} / \text{CO}))^3 + 0.26 + 0.06 (-84.5 + 0.61 \text{CP}) \quad (\text{Eq. 3})$$

852 To estimate CH₄ emissions from animal manure, the IPCC (2006) Tier 2 method (Equation 10.23) was
 853 used. Following Eugène *et al.*, (2012), the quantity of volatile solids excreted daily was estimated from
 854 the non-digestible organic matter ingested by animals (**Erreur ! Source du renvoi introuvable.**). The
 855 urine fraction of volatile solids was assumed to be negligible, as urine contains much less OM than
 856 faeces (IPCC, 2006).

857

$$\text{Methane from manure} = (\text{OM}-\text{DOM}) \times d_{\text{ms}} \times \text{Bo}_{\text{ms}} \times 0.67 \times \text{MCF}_{\text{ms}} / 100 \quad (\text{Eq. 4})$$

860

861 with the time spent in manure management system ms and MCF a methane conversion factor for a given
 862 ms (Table 10.17, IPCC 2006): 0.13 for liquid slurry with natural crust, 0.20 for pit storage below animals
 863 and 0.03 for solid storage. Variable BO is set to 0.2027 m³ CH₄/kg OM for liquid manure and 0.2042
 864 for other types of manure.

865 Nitrous oxide (N₂O) emissions included direct emissions from manure management and managed soils
 866 (Tier 1; IPCC, 2006), with emission factors set at 0.01 kg N-N₂O/kg nitrogen (N). N₂O emissions from
 867 manure management were calculated according to the Tier 2 equation (IPCC, 2006) and were
 868 proportional to the quantity of N excreted by cattle. N excretion was calculated monthly as the N
 869 contained in feed ingested by cattle minus the N contained in beef and milk. This excretion was allocated
 870 to manure management systems as a function of the time spent in a given barn or plot. Indirect N₂O
 871 emissions from N volatilization and leaching (NO₃) were also included. N leaching was estimated from
 872 a farm's N balance (Simon and Le Corre, 1992), which equalled N inputs (i.e. N in purchased animals,
 873 fertilizers and feed; N fixed by legume crops; N in crop residues and atmospheric N deposition) minus
 874 N outputs (i.e. N in animals, animal products and crops sold). 1% of the nitrogen volatilized during
 875 fertilizer application as NH₃ and NO (20% of N fertilizer content) was assumed to be transformed into
 876 N₂O (IPCC, 2006).

877 **Table B1.** Summary of emissions or resource use estimated, their sources and their estimation methods
 878 and references

Emission or resource use	Sources of emissions	Estimation method and references
Carbon dioxide (CO ₂)	inputs purchased for farm production systems (i.e. feed, fuel and fertilizers)	Agribalyse® life cycle assessment database (Koch and Salou, 2014)
	from fuel combustion (Direct CO ₂ emissions)	Dia'terre® method v. 4.51 (ADEME, 2010)
Methane (CH ₄) (biogenic)	Enteric fermentation	Equations of Sauvant et al., (2011) and Sauvant and Nozière (2016) that considered the quantity and quality of feed, digestive interactions and animal size
	Animal manure	Tier 2 equation (IPCC, 2006), but with the quantity of volatile solids excreted daily estimated from the non-digestible organic matter ingested by cattle
Nitrous oxide (N ₂ O)	Manure management (direct)	Tier 2 equation (IPCC, 2006), were proportional to the quantity of nitrogen (N) excreted by cattle
	Managed soils (direct)	Tier 1 equation (IPCC, 2006), with the emissions factor set at 0.01 kg N-N ₂ O/kg N
	Indirect emissions	Conversion factor of NH ₃ et NO set at 0.01 kg N-N ₂ O/kg (IPCC, 2006),
Nitrate (NO ₃) leaching	Indirect N ₂ O emissions from N volatilization and NO ₃ leaching	N leaching was estimated from a farm's N balance (Simon and Le Corre, 1992), which equalled N inputs (i.e. N in purchased animals, fertilizers and feed; N fixed by legume crops; N in crop residues and atmospheric N deposition) minus N outputs (i.e. N in animals, animal products and crops sold).
Non-renewable energy use (MJ)	Direct use (i.e. oil (35 MJ/L) and electricity (3.6 MJ/kWh in France) used for on-farm production systems) and indirect use (i.e. to produce feed and fertilizer inputs, estimated by life cycle assessment)	Agribalyse® life cycle assessment database (Koch and Salou, 2014)

879

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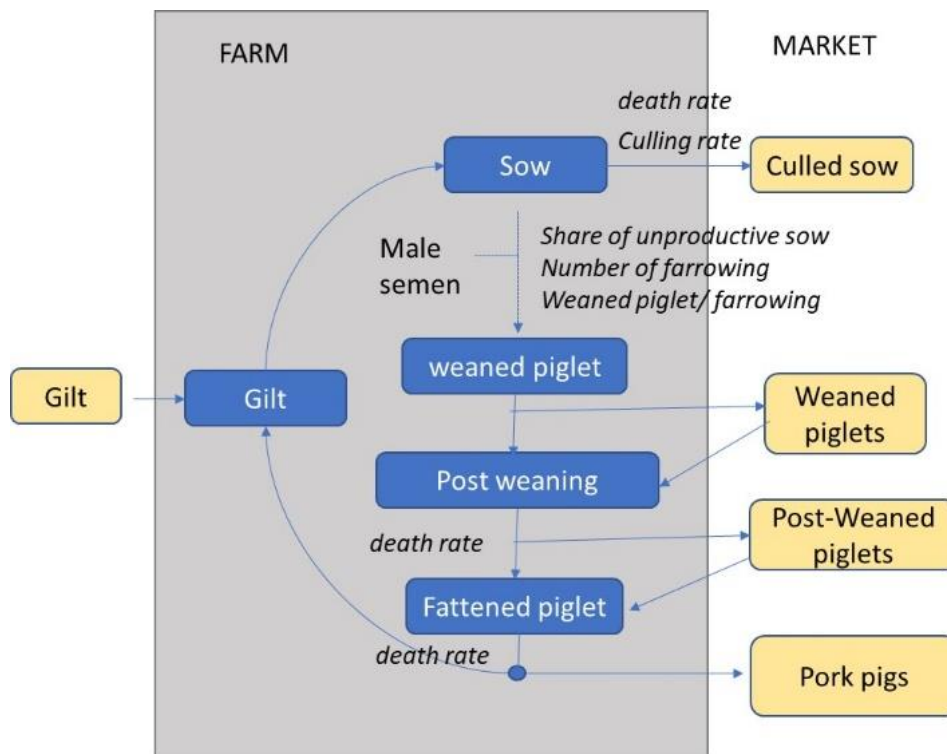
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907 **Supplementary Material C: The pig module and other related modules in**
 908 **Orfee**

909 The pig module first simulates the demography of the herd. The number of animals belonging to
 910 different types of pigs depends on the aging process of the animals, their mortality, their reproduction
 911 and the choices of the type and number of animals produced, bought and sold. The feeding of pigs is
 912 represented in a simplified way. The total feed and straw requirements of the herd are calculated based
 913 on the average consumption per pig type defined as input to the model. These requirements can be met
 914 either by purchasing complete feed or by making feed on the farm. Pig manure depends on the number
 915 of pigs and the type of bedding. Labor time is estimated according to the herd size and the average labor
 916 time per pig defined in the model input. The infrastructure: type and size of buildings are parameterized
 917 in the model input. The equations and parameters used are detailed in the following.

918 **1. Flows between the different pig categories**

919 Flows of animals between categories i are presented in the figure C1.



920
 921 *Figure C1: Representation of the different types of pigs and flows between them*

922 The number of weaned piglets ($Head_{wp}$) depends on the number of sows ($Head_s$) that are not
 923 unproductive ($unps$), farrowing per sow per year (fs) and weaned piglets per farrowing (wpf). Piglets
 924 are weaned after around 4 weeks of suckling. Their mortality during the suckling phase is included in

925 the parameter “number of weaned piglets per sow” (wpf). which is a transition phase before fattening.
 926 The post weaning phase lasts around 2 months.

928

$$927 \quad [Eq1.1] \quad \text{PigHead}_{wp} = \text{PigHead}_s \times fs \times wpf \times (1 - \text{unps})$$

929 These weaned piglets modulated by the number of weaned piglets bought or sold ($BHead_{wp}$, $SHead_{wp}$)
 930 become post-weaning piglet ($Head_{pwp}$)

$$931 \quad [Eq1.2] \quad \text{PigHead}_{pwp} = \text{PigHead}_{sp} + B\text{PigHead}_{wp} - S\text{PigHead}_{wp}$$

932 The post-weaned piglets that have survived ($1 - d_{wp}$) modulated by the post weaned piglets bought or sold
 933 ($BHead_{pwp}$, $SHead_{pwp}$) enter the fattening process for about 3 to 4 months.

$$934 \quad [Eq1.3] \quad \text{PigHead}_{fp} = \text{PigHead}_{pwp} \times (1 - d_{wp}) + B\text{PigHead}_{pwp} - S\text{PigHead}_{pwp}$$

935 A share of sow is sold ($SHead_s$) to renew culled sows ($cull_s$) which had lower performance of animals
 936 due to ageing process, low genetic or maternal potential or health problems. This number of sold cow
 937 is defined as a proportion of culled sows minus the sows that have died (ds).

$$938 \quad [Eq1.4] \quad S\text{PigHead}_s = \text{PigHead}_s \times cull_s - \text{PigHead}_s \times ds$$

939 At equilibrium the number of gilt ($Head_g$) should be equal to the number of culled sows (included dead
 940 sows) in order to maintain the number of sows.

$$941 \quad [Eq1.5] \quad \text{PigHead}_g = \text{PigHead}_s \times cull_s$$

942 The fattened pigs ($Head_{fp}$) that have survived the fattening process ($1 - d_{fp}$) are sold as pork pigs ready to
 943 be slaughtered ($SHead_{fp}$). Gilt for the renewal of the mother sow herd ($PigHead_g$) equals the number of
 944 fattened pigs (fp) not dead or sold plus the gilt purchased ($Head_{pg}$).

$$945 \quad [Eq1.6] \quad \text{PigHead}_g = \text{PigHead}_{fp} \times (1 - d_{fp}) - S\text{PigHead}_{fp} + B\text{PigHead}_g$$

946 In this simulation the type of pig sold and the herd size are not optimized. Consequently, additional
 947 constraints have been added to set the number of sows, purchased gilt and piglets to their values $h0$ in
 948 the farm studied.

$$949 \quad [Eq1.7] \quad \text{PigHead}_s = h0_s ;$$

$$950 \quad [Eq1.8] \quad B\text{PigHead}_i = hp0_i ,$$

951 We apply a similar constraint to fix the share $r0$ of each type of piglet sold according to each each
 952 farm characteristic:

$$953 \quad [Eq1.9] \quad S\text{PigHead}_i = r0_i \times (S\text{PigHead}_{wp} + S\text{PigHead}_{pwp} + S\text{PigHead}_{fp})$$

954 for $i =$ weaned pig (wp), post weaned pig (pwp) and fattened pig (fp)

955 The parameters used are summarized in table A1.

956 **Table C1: Technical characteristics of pig demography on the surveyed farms**

	Sow Production (N=7)				piglets (all farm)		
	Mean.	Min.	Max		Mean.	Min.	Max
culling rate ($culls$)	42%	37%	48%	% pork pig sold (rO_{pp})	90%	35%	100
Mortality of sow (ds)	4%	0%	10%	nb piglet purchased (Nobs. =10) ($phO_{wp} + phO_{pwp}$)	1026	560	1577
unproductive sow (% sow) ($unps$)	13%	11%	18%	Mortality of post weaned piglet (d_{pwp})	3%	1%	7%
number of farrowings / sow /year (fs)	2.4	2.3	2.6	Mortality of post weaned fattened pig (d_{fp})	3%	0%	7%
weaned piglet/farrowing (wps)	11.4	10.6	12.4	Age at slaughter (days)	198	172	301

957 Source: Aporthe Survey (Balouzat et al., 2020)

958 2. Pig feeding

959 The quantity of feed ($feed$) consumed per pig that have survived is defined based on farm survey for
 960 each animal category i . A constraint in the model specifies that the quantity of feed purchased or
 961 processed on the farm must reach the the pig herd requirement required quantity of feed. This feed
 962 could be either industrial feed ($QIndFeed$) or feed processed on farm ($QFarmFeed$).

$$963 \quad [Eq2.1] \quad PigHead_i \times (1-d_i) \times feed_i = QIndFeed_i + QfarmFeed_i$$

964 To get closer to farm current practice or possibilities, bounds ($minFF$ and $maxFF$) on the share of feed
 965 processed on the farm were added.

$$966 \quad [Eq2.2] \quad minFF \times \sum_i (QIndFeed_i + QFarmFeed_i) \leq \sum_i QFarmFeed_i \leq$$

$$967 \quad maxFF \times \sum_i (QIndFeed_i + QFarmFeed_i)$$

968 **Table C2: Pig feed on the surveyed farms**

	Mean	Min.	Max
Kg feed / sow ($feeds$)	1243	1167	1321
Kg feed./ weaned piglet to finished pig ($feed_{wfp} + feed_{pft}$)	267	193	321
Pig feed price (€/t)	230	190	250
Share of on-farm processed feed (N= 5 farms)	100%	87%	100%

969 Source: Aporthe Survey (Balouzat et al., 2020)

970 Calculating the composition of farm processed feed for pig ($compoPigFF$) is necessary to assess the
 971 quantity of each farm feed f required ($QPigFarmFeed$). If pig production is organic ($orgpig$), the
 972 composition of processed farm feed will include only organic ingredients.

973 [Eq2.3]
$$QPigFarmFeed_f = \sum_i QFarmFeed_i \times [compoPigFF_{i,f} \times (1-orgpig) +$$

974
$$compoOrgPigFF_{i,f} \times orgpig]$$

975

976 In order to be able to calculate feed food competition indicators and LCA on the purchased inputs,
 977 additional equations were added in order to estimate the quantity of each organic (*orgpig*) or
 978 conventional feed ingredient based on the composition of industrial feed (*CompoIndFeed*).

979 [Eq2.4]
$$QPigIndFeed_f = \sum_i QIndFeed_i \times [CompoIndFeed_{i,f} \times (1-orgpig) +$$

980
$$compoIndFeed_{i,f} \times orgpig]$$

981

982 **Table C3: Composition of farm processed feed and industrial feed**

	Farm processed feed (<i>CompoFF</i>) ¹			Industrial feed (<i>CompoIndFeed</i>) ²		
	Sow and gilt	Post weaned piglet	Fattening piglet	Sow and gilt	Post weaned piglet	Fattening piglet
Wheat	21%	45%	40%	37%	57%	75%
Barley	51%	10%	0%	29%	18%	9%
Grain corn	5%	20%	40%	0%	0%	0%
Soybean meal	5%	7%	5%	8%	21%	9%
Rapeseed meal	14%	14%	12%	7%	0%	0%
Sunflower meal				0%	4%	7%
Soybean grain				10%		
Dehydrated Beet pulp				9%		

983 *Source: ¹expert from the IFIP (pig institute), 2018; ²IFIP, Mémento de l'éleveur de porc (2013)*

984 The quantity of farm feed could be either produced on the farm (*QCrop*) or purchased (*QBFeed*). Feed
 985 produced on the should also meet the feed requirement of the other herd (cattle, sheep). The surplus is
 986 sold on the market (*QSCrop*). During storage and handling of feeds and distribution to animals, there
 987 are losses (*feedloss*). These losses are more important for forage (15% for silage, 7% for hay) than for
 988 concentrate feeds (1%).

989 [Eq2.5]
$$(\sum_f QDietCattle_f + QPigFarmFeed_f) \times (1 + feedloss_f) \leq QCrop_f +$$

990
$$QBFeed_f - QSCrop_f$$

991 3. Manure production

992 Pigs are fully raised indoor. Some specific barns are defined for each category of pigs. Several barns are
 993 possible, with or without straw bedding. The type and capacity of each barn is defined exogenously by
 994 model user.

995 Animals that are raised in barns b with straw bedding induce an annual consumption of straw for litter
 996 ($QSTRAW$) which depends on the straw requirement per type of animals and barn ($reqstraw$), number
 997 of animals in each animal category i , and the time spent by each type of animal in straw bedded barns.
 998 The time spent depends on the age at weaning ($agewean = 28$ days), post-weaning ($agepostwean = 49$
 999 days) and the age fattened pigs are sows ($agefatt = \text{recorded farm value}$).

$$\begin{aligned}
 [Eq3.1] \quad QSTRAW &= \sum_{b=b_{mat}} PigHead_s \times nbfarrow \times agewean \times reqstraw_{s,b} + \\
 &\sum_{b=b_{preg}} PigHead_s \times (365 - nbfarrow \times agewean) \times reqstraw_{s,b} + \sum_{b=b_{pw}} PigHead_{pw} \times \\
 &(agepostwean - agewean) \times reqstraw_{pw,b} + \sum_{b=b_{pf}} PigHead_{pf} \times (agefatt - agepostwean) \times \\
 &reqstraw_{pf,b}
 \end{aligned}$$

1004 The quantity of manure v produced ($v = \text{liquid pig manure or compact pig manure}$) is defined
 1005 according the number of days (α) spent by each animal category (i) in the barn type (b).

1006

$$[Eq3.2] \quad PigManure_v = \sum_{i,b} PigHead_i \times \alpha_{i,b,v} \times manure_{i,b,v}$$

1008 **Table C4: Manure production in kg/ day per type of animal and according the manure**
 1009 **management system**

	Liquid manure*	Compact manure **
Pregnant sow	18.9	15 manure+1.1straw
Lactating sow	25.6	16.4+2
Post weaning piglet	1.7	1.78+0.12
Fattening piglet	4.16	3.69+0.3
Density (kg/m ³)*	0.95	0.65

1010

1011 * Institut Technique du Porc, (2005)

1012 ** Levasseur 1998 TECHNI vol 21: liquid manure before washing + quantity of straw bedding

1013 *** manure production : <https://occitanie.chambre-agriculture.fr/publications/toutes-les-publications/la-publication-en-detail/actualites/guide-des-produits-organiques-utilisables-en-languedoc-roussillon-tome-2/> (access July 2022)

1014 Straw requirement : Chambre régionale d'agriculture de Bretagne et pays de Loire, Inra et IFIP (2012)

1016

1017 4. Crop fertilisation

1018 In this study the area ($HACult$) allocated to each crop activity (c) is forced to be equal to the area declared
 1019 by the farmer. However, The management modalities of the grasslands were not specified in the surveys
 1020 and the number and type of mowing is optimized under the constraint that the sum of management
 1021 modalities equals the total declared grassland area ($ha0_{gr}$).

$$[Eq4.1] \quad \sum_{c \in \text{grasslands}} HACult_c = ha0_{gr}$$

1022

1023 **Table C5: Crop area of the surveyed farms**

	mean	SD	min	max
UAA	145	60	81	318
Grasslands	95	37	47	208
Barley	12	-	16	64
Wheat	20	-	20	63
Triticale	1	-	3	10
Corn silage	13	-	18	63
Corn grain	2	-	7	30
Mix legume/cereals	0	-	1	2
Alfalfa	1	-	6	25

1024

1025 The amount $QFert$ of each fertilizer applied on each crop activity should meet crop activity needs. The
 1026 needs in minerals ($reqfert$) are calculated for each crop depending on the type of crop c , its yield, the
 1027 previous crops and the type of soils (Mosnier *et al.*, 2017). These requirements could be fulfilled by
 1028 different types of fertilizers ($fert$) either organic or mineral characterized by its content of minerals
 1029 $compofert$ and the percentage of each mineral available for the plant through the mineralization
 1030 process ($minerfert$) given in table A5 and A6.

1031 [Eq4.2]
$$HACult_c \times reqfert_{c,min} = \sum_{fert} QFert_{fert,c} \times compofert_{fert,min} \times minerfert_{fert,min}$$

1032 **Table C6: Composition of organic fertilizers**

	N (kg/t)	P ₂ O ₅ (kg/t)	K ₂ O (kg/t)	DryMatter (%)	Organic matter(%)
Pig Liquid manure*	3.5	2.1	2.5	3	2
Pig compact manure	9.1	7.2	12.9	25	23
Bovine Liquid manure	1.3	1.5	3.6	4	3
Bovine compact manure	5.9	2.8	9.5	22	21

1033 Source: Arvalis, 2023 [https://www.arvalis.fr/infos-techniques/integrer-les-valeurs-fertilisantes-des-produits-](https://www.arvalis.fr/infos-techniques/integrer-les-valeurs-fertilisantes-des-produits-organiques-dans-le-plan-de-fumure#ancre_3)
 1034 [organiques-dans-le-plan-de-fumure#ancre_3](https://www.arvalis.fr/infos-techniques/integrer-les-valeurs-fertilisantes-des-produits-organiques-dans-le-plan-de-fumure#ancre_3)

1035 **Table C7: Parameters considered for the mineralisation of organic fertilizers**

	N				P ₂ O ₅	K ₂ O
	Oilseed	Maize	grasslands	others		
Pig Liquid manure	60%	70%	60%	60%	95%	100%
Pig compact manure	30%	30%	40%	20%	95%	100%
Bovine compact manure	20%	25%	10%	10%	80%	100%

1036 source : Arvalis, 2023

1037 The quantity of each fertilizer $QFert$ applied on each crop should be equal to the quantity bought
 1038 ($BQFert$) and produced ($PQFert$) minus the quantity sold ($SQFert$). Constraints are added to limit the
 1039 opportunities to sell or buy each type of organic fertilizer based on the market opportunities of the
 1040 farm under study.

1041 [Eq4.3]
$$\sum_c QFert_{fert,c} = BQFert_{fert} - SQFert_{fert} + PQFert_{fert}$$

1042 Additional constraints concern regulatory issues. For instance, it is forbidden to spread more than 170
 1043 kg of N/ha/year.

1044 [Eq4.4]
$$\sum_{c,fert} Qfert_{fert,c} \times compofert_{fert,"N"} \leq 170 * uaa$$

1045

1046 **5. Facilities, electricity and energy used by pigs**

1047 The manure should be stored on the farm before being spread on field. A constraint specifies that the
 1048 manure storage capacity (in m³) adapted to each type of manure should be large enough to store the
 1049 manure produced (the quantity is measured in ton and divided by its density). Solid manure related to
 1050 straw bedding can be stored in the field while manure will have to be stored in pits. Density
 1051 parameters are provided in table A4.

1052 [Eq5.1]
$$\sum_s ManStor_s \times tpestor_{s,v} \leq PigManure_v / density_v$$

1053 The building capacity (BUILD) of each type used to house the different types of animals can be
 1054 optimized by the model. In this study, it has been fixed according to farm declaration.

1055 **Table C8: Type of pig building and pig building capacity of the surveyed farms**

	Nb of observation	Mean	Min	Max	Standard deviation
Sows on grates	6	34	16	72	20
Pregnancy type1	6	34	16	72	20
Pregnancy type2	6	30	-	214	55
Post weaning on grates	14	298	-	1200	298
post weaning on straw	1	240			58
Pig fattening on grates	13	635	300	1950	430
Pig fattening on straw	1	183			

1056

1057 The quantity of electricity consumed by the pig herd (*QPigElec*) depends on herd size and on the type
 1058 of pig production system (with or without sow and pig fattening) based on published surveyed (A9):

1059 [Eq5.2]
$$QPigElec = \begin{cases} Head_{pf} \times elec_{pigfatt} & - \rightarrow \text{if number of sow} = 0 \\ Head_s \times elec_{sow} & - \rightarrow \text{if number sows and pig fattened} > 0 \\ Head_s \times elec_{sow} & - \rightarrow \text{if number sows} > 0 \text{ and pig fattened} = 0 \\ & 1.5 \times \sum_i QFarmFeed_i \end{cases}$$

1060 The quantity of fuel consumed by the pig herd (*QPigFuel*) is defined on the same way:

$$1061 \quad [Eq5.3] \quad Q_{PigFuel} = \begin{cases} \text{Head}_{pf} \times \text{fuel}_{pigfatt} & - \rightarrow \text{if number of sow} = 0 \\ \text{Head}_s \times \text{fuelsow} & - \rightarrow \text{if number sows and pig fattened} > 0 \\ \text{Head}_s \times \text{fuelsow} & - \rightarrow \text{if number sows} > 0 \text{ and pig fattened} = 0 \end{cases}$$

1062 **Table C9: Consumption and cost of electricity and fuel according to the pig production system**

		Sow farrowing to pig finishing	Sow	Pig fattening
Electricity	consumption	983 kwh/year/sow	403 kwh/year/sow	25 kwh/year/piglet
	Cost 2007	44 €/year/sow	26 €/year/sow	1.5 €/year/piglet
Fuel	Consumption*	14 €/year/sow	4.5 €/L/year/sow	0.2 €/year/sow

1063 *Source: Ademe 2007, * price of fuel in 2007: 0.8€/L*

1064

1065 **6. Pig Labor**

1066 The time necessary for the management of the pig herd is calculated per sow if the farm has sows and
1067 per fattened pig in the opposite case since the reference for the labor of the sow to the fattening pig
1068 unit (lab_s) and (lab_{pf}) is calculated as follows

$$1069 \quad [Eq6.1] \quad Lab_{Pig} = \begin{cases} lab_s \times PigHead_s & \text{if } Head_s > 0 \\ lab_{pf} \times PigHead_{pf} & \text{if } Head_s = 0 \end{cases}$$

1070 *With $Lab_s = 20.72h/sow$, $lab_{pf} = 0.52h/fattened\ pig$ (Renaud, 2010²)*

1071

1072 **7. Revenues and costs**

1073 The pig revenue depends on the number of pig sold ($SPigHead$) of each type I and of their price
1074 ($pigprice$) and their weight ($pigweight$) in the case the price is defined per kg of carcass. The cost of
1075 pig purchasing is deducted from the revenue. In this study; prices and liveweight of sold pork are
1076 defined according to survey results (Table A2) excepted from sow and gilt. These latter that represent
1077 a small percentage of receipts and costs have been defined based on expert knowledge. Prices vary
1078 according to the economic context of the year ζ considered.

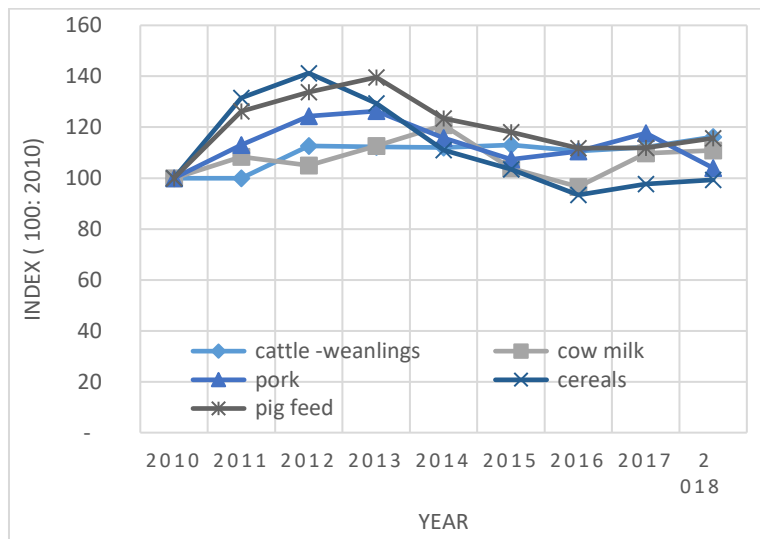
² Renaud, H. (2010). Le temps de travail en élevage porcin: facteurs de variation et voies d'amélioration. *Mémoire d'Ingénieur, Ecole d'ingénieurs de Purpan, 89e promotion.*

1079 $[Eq7.1] \quad \text{€PigSales}_\zeta = \sum_i \text{SPigHead}_i \times \text{pigprice}_{i,\zeta} \times \text{pigweight}_i - \sum_i \text{BPigHead}_i \times$
 1080 $\text{pigprice}_{i,\zeta} \times \text{pigweight}_i$

1081 **Table C10: 2018 prices of pigs sold and purchased**

		Mean.	Min.	Max
Pork (farm surveys) N = 17	Age at slaughter (days)	198	172	301
	liveweight of pork slaughtered (kg)	131	103	200
	Carcass weight of pork slaughtered (kg)	100	79	153
	price of pork (€/kg carcass)	1.44	1.33	1.5
Piglet purchased N=11	liveweight	11	7	25
	Price (€/piglet)*	39	25	42
Piglet sold N= 4	liveweight	23	19	30
	Price (€/piglet)*	46	42	60
Culled sows sold**	liveweight	250		
	Price (€/sow)	147		
Gilt purchased**	liveweight	110		
	Price (€/gilt)	251		

1082 Source: Aporth Survey (Balouzat et al., 2020)
 1083 *few surveys had this information and the default value used was 42€/piglet according to experts
 1084 **values not available in surveys, values were given by experts
 1085
 1086



1087
 1088 **Figure C2: Index of pig prices (IPPAP)**

1089
 1090 Veterinary expenses are proportional to the volume of pig sold (SHead x CarcWeight). These costs are
 1091 higher for farms having a sow to finishing unit ($vetSF = 0.057$) than a pig finishing unit only
 1092 ($vetPF=0.035$).

1093 [Eq7.2]
$$\text{€PigVetExp}_\zeta = \begin{cases} \sum_i \text{SHead}_i \times \text{CarcWeight}_i \times \text{vetSF}_\zeta & \text{if Head}_s > 0 \\ \sum_i \text{SHead}_i \times \text{CarcWeight}_i \times \text{vetPF}_\zeta & \text{if Head}_s = 0 \end{cases}$$

1094

1095 Operating expenses of pig production covers artificial insemination ($ai=32$) and miscellaneous costs
1096 per kg of carcass produced ($misc=0.05$).

1097 [Eq7.3]
$$\text{€PigMiscExp}_\zeta = \text{Head}_s \times ai_s + misc \times \sum_i (\text{Head}_i - \text{PHead}_i) \times \text{CarcWeight}_i$$

1098

1099 If farmers use more feed for their herds they will have less receipts from crop sales (€CropSale). This
1100 crop sales include crops that cannot be consumed by animals (nf) and potential animal feed (f).

1101 [Eq7.3]
$$\text{€CropSales}_\zeta = \sum_{nf} \text{QCrop}_{nf} \times \text{priScrop}_{nf,\zeta} + \sum_f \text{QSCrop}_f \times \text{priScrop}_{f,\zeta}$$

1102

1103 Using more farm feed reduces feed purchase. Industrial feed expenses depend on the quantity of
1104 industrial feed and its price ($feedprice$).

1105 [Eq7.4]
$$\text{€FeedExp}_\zeta = \sum_f \text{QBCrop}_f \times \text{priBcrop}_{f,\zeta} + \sum_f \text{QPigIndFeed}_f \times \text{feedprice}_{f,\zeta}$$

1106

1107 **Table C11: Price of the main raw feed (excepted pig industrial feed) in 2018**

prices	
Soft wheat	170
Maize grain	167
barley	146
triticale	160
straw	65
Rapeseed meal	239
Soybean meal	399

1108 Note: It is assumed that the price of non industrial purchased crop is 20% higher than the price of sold crop.

1109

1110

1111 Two types of costs are computed for manure storage facilities and buildings to house animals:
1112 depreciation costs which correspond to the investment costs divided by the life span of the facilities
1113 and maintenance costs which correspond to the repairs necessary to maintain the facilities in good
1114 functioning state. The depreciation costs of the different barns depend on the initial investment cost
1115 (€BUILD) which in turn depends on building capacity of each type of building b . The life span
1116 (deprlength) of the buildings is assumed to be 20 years.

1117 [Eq7.5]
$$\text{€DepBuild}_\zeta = \sum_b \text{€BUILD}_b / \text{DeprLenght}_b$$

1118 This capacity is either optimized by the model to fit current herd size (*BUILD*) or defined exogenously
 1119 (*build_size*). In the case of pig production, building capacity is defined exogenously for each type of
 1120 building.

1121 [Eq7.6] $\text{€BUILD}_{b,\zeta} \geq \text{BUILD}_b \times \text{pricebuild}_{b,\zeta}$

1122 [Eq7.7] $\text{€BUILD}_{b,\zeta} \geq \text{build_size}_b \times \text{pricebuild}_{b,\zeta}$

1123 **Table C12: Investment cost (pricebuild) according to the type of barn (€/place) for year 2018**

	On grates	With straw
Sows		
Lactating	3792	
Pregnancy 1	1225	1071
Pregnancy 2	1465	
Post weaning	296	167
Pig fattening 1	302	354
Pig fattening 2		377

1124 Source: Ifip, Revue technique (2019)

1125

1126 The maintenance cost is assumed to be proportional (*maintcost* =9.5€/place) to the building capacity
 1127 *BUILD*.

1128 [Eq7.8] $\text{€MaintBuild}_{b,\zeta} = \sum_b \text{BUILD}_b \times \text{maintcost}_b$

1129 The upgrading or construction of manure storage in accordance with environmental regulations is
 1130 generally subsidized up to 25% (*subb*). The purchase cost of a slurry pit is set at 55€/m³ and that of a
 1131 manure pit at 76€ per m³. The capacity is calculated based on the assumption that the pit is emptied
 1132 every 4 months. The amortization is calculated over 25 years.

1133 [Eq7.9] $\text{€DepManStor}_\zeta = \sum_s \text{ManStor}_s \times (1-\text{subb}_s) \times \text{pricebuild}_{s,\zeta} / \text{DeprLenght}_s$

1134 The time spent on each type of machine capable of carrying out a spreading production system (*opmach*)
 1135 n a machine belonging to the farm (*HrFarmMach*) or a machine belonging to an external company
 1136 (*HrMachEnt*) must be sufficient to spread the amount of organic fertilizer (*QFertorg*).

1137 [Eq7.10] $\sum_{c,\text{orgfert}} \text{QFert}_{\text{orgfert},c} \times \text{manSpreading}_{\text{orgfert},\text{op}} = \sum_{\text{mach}} (\text{HrFarmMach}_{\text{mach}} +$
 1138 $\text{HrMachEnt}_{\text{mach}}) \times \text{opmach}_{\text{mach},\text{op}} \times \text{spreadCapacity}_{\text{mach}}$

1139
 1140 A binary variable *BINmach* takes the value of 1 if at least one hour of this machine *HrFarmMach* is
 1141 used:

1142 [Eq7.11] $\text{HrFarmMach}_{\text{FarmMach}} \leq \text{BINmach}_{\text{FarmMach}} \times 10000$

1143

1144 The depreciation cost of each machine *€DepMach* is proportional to its time of use *HrFarmMach* or,
 1145 if this time of use is low, is fixed for each machine *mindepmach*

1146 [Eq7.12] $\text{€DepMach}_{\text{FarmMach},\zeta} \geq \text{BINmach}_{\text{FarmMach}} \times \text{mindepmach}_{\text{FarmMach},\zeta}$

1147

1148 [Eq7.13] $\text{€DepMach}_{\text{FarmMach},\zeta} \geq \text{HrFarmMach}_{\text{FarmMach}} \times \text{hrDepmach}_{\text{FarmMach},\zeta}$

1149

1150 The maintenance cost of each machine €MaintMach is proportional to its time of use HrFarmMach

1151 or, if this time of use is low, is fixed for each machine minMaintmach

1152

1153 [Eq7.14] $\text{€MaintMach}_{\text{FarmMach},\zeta} \geq \text{BINmach}_{\text{FarmMach}} \times \text{minMaintMach}_{\text{FarmMach},\zeta}$

1154

1155 [Eq7.15] $\text{€MaintMach}_{\text{FarmMach},\zeta} \geq \text{HrFarmMach}_{\text{FarmMach}} \times \text{hrMaintmach}_{\text{FarmMach},\zeta}$

1156

1157 **Table C13: machine cost and spreading capacity**

characteristics	Investment	depreciation		Maintenance cost		Speed and capacity	
	Price (k€)	€/hr	Min k€/year	Min €/year**	€/ha	Ha/hr	m3/hr
<u>Liquid manure spreader</u>							
12-13m ³ with nozzles 12m boom;	43.8	21	5.31	1.59	4.8	2	30*
<u>Compact manure spreader</u>							
7t <u>horizontal hedgepig</u>	15.8	10	1.91	0.57	4	2	21
10t <u>horizontal hedgepig</u>	18.6	11	2.25	0.68	4	2	30
12t <u>vertical hedgepig</u>	35.4	28	4.04	1.21	6	3	36
<u>Mineral spreader</u>							
15m Cuve :10-12hl	3.5	7	0.35	0.11	0.9	1	
20m Cuve:12*-18	4.9	11	0.49	1.48	1.5	3	
30m Cuve 20hl	7.4	13	0.75	2.25	3.0	5	
Tractor	58k€		5.77	2.29	5***		

1158 Source:Entr'Aide 2016 , *Assuming 15m³/ha or 15t/ha and 2 ha/ hour, **, ***in €/hour

1159 **Supplementary Material D: Technical data collected**

1160 **Table D.1 Technical characteristics of pig demography on the surveyed farms**

	Sow Production (N=7)				piglets (all farm)		
	Mean.	Min.	Max		Mean.	Min.	Max
culling rate ($cull_s$)	42%	37%	48%	% pork pig sold (rO_{pp})	90%	35%	100
Mortality of sow (ds)	4%	0%	10%	nb piglet purchased (Nobs. =10) ($phO_{wp} + phO_{pwp}$)	1026	560	1577
unproductive sow (% sow) ($unps$)	13%	11%	18%	Mortality of post weaned piglet (d_{pwp})	3%	1%	7%
number of farrowings / sow /year (fs)	2.4	2.3	2.6	Mortality of post weaned fattened pig (d_{fp})	3%	0%	7%
weaned piglet/farrowing (wps)	11.4	10.6	12.4	Age at slaughter (days)	198	172	301

1161 *Source: Aporthe Survey (Balouzat et al., 2020)*

1162 **Table D.2: Pig feed on the surveyed farms**

	Mean	Min.	Max
Kg feed / sow ($feed_s$)	1243	1167	1321
Kg feed./ weaned piglet to finished pig ($feed_{wfp} + feed_{pf}$)	267	193	321
Pig feed price (€/t)	230	190	250
Share of on-farm processed feed (N= 5 farms)	100%	87%	100%

1163 *Source: Aporthe Survey (Balouzat et al., 2020)*

1164 **Table D.3: 2018 prices of pigs sold and purchased**

	Mean.	Min.	Max
Pork (farm surveys) N = 17			
Age at slaughter (days)	198	172	301
liveweight of pork slaughtered (kg)	131	103	200
Carcass weight of pork slaughtered (kg)	100	79	153
price of pork (€/kg carcass)	1.44	1.33	1.5

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1167 **Table D.4: Characteristics of beef herd on the surveyed farms**

	mean	min	max
Suckler beef cows (head)	91	50	150
% of male sold before fattening	77%	0%	100%
% of female sold before fattening	66%	0%	100%

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1170 **Table D.5: Characteristics of dairy herd on the surveyed farms**

	mean	min	max
Dairy cows (head)	85	30	150
Milk production (1000L.farm ⁻¹)	649	280	1 500
Share of male calves sold at 2 weeks old	100	100	100

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1172 **Table D.6: Area of the surveyed farms**

	mean	min	max
UAA	145	318	81
Grasslands	95	208	47
Barley	12	64	16
Wheat	20	63	20
Triticale	1	10	3
Corn silage	13	63	18
Corn grain	2	30	7
Mix legume/cereals	0	2	1
Alfalfa	1	25	6

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1175 **Supplementary Material E: comparison of simulated results with real data**

1176 **Table E.1: Comparison of results with available economic indicators for the sow breeding-**
 1177 **production systems (6 farms ;2018)**

	Ap_2 (beef)			AP_4 (beef)			AP_5 (dairy)			AP_7 (beef)			AP_13 (beef fattening)			AP_14 (dairy)			Mean Δ
	Sim	Obs.	Δ	Sim	Obs.	Δ	Sim	Obs.	Δ	Sim	Obs.	Δ	Sim	Obs.	Δ	Sim	Obs.	Δ	
Piglet sold fattened (% piglet sold)	100	100	0%	94	100	-6%	100	100	0%	87	87	0%	35	35	0%	71	71	0%	-1%
Sows (head)	54	54	0%	121	121	0%	122	121	0%	97	96	1%	320	320	0%	104	104	0%	0%
Piglet sold (head)	1004	1026	-2%	2695	2682	0%	2742	2739	0%	1945	1884	3%	7986	8492	-6%	2669	2665	0%	-1%
Live weight produced (kg/sow)	1968	1927	2%	2469	2466	0%	2688	2663	1%	2208	2140	3%	1280	1216	5%	2130	2124	0%	2%
Global Consumption Index (feed/Lw gain)	3.01	3.02	0%	2.99	3.03	-1%	2.77	2.81	-2%	3.22	3.25	-1%	3.03	2.99	2%	2.93	2.93	0%	0%
Feed cost (€/kg lw)	0.72	0.73	-1%	0.75	0.76	-1%	0.62	0.63	-2%	0.80	0.81	-1%	0.56	0.66	-15%	0.69	0.70	-2%	-4%
Price (€/kg Carc.)	1.48	1.50	-2%	1.39	1.40	0%	1.33	1.35	-1%	1.49	1.49	0%	1.45	1.33	9%	1.81	1.69	7%	2%
Product (€/sow)	2232	2242	0%	2708	2727	-1%	2814	2741	3%	2519	2483	1%	1497	1591	-6%	3133	3118	0%	0%
Goss margin (€/sow)	705	616	14%	667	705	-5%	972	973	0%	636	619	3%	644	667	-3%	1437	1368	5%	2%
Total cost (€/carc.)	1.59	1.63	-2%	1.61	1.60	1%	1.30	1.35	-3%	1.58	1.49	6%	1.10	1.28	-14%	1.61	1.71	-6%	-3%

1178 *Note observed data come from GTE accountability of the farms simulated*

1179 **Table E.2: Comparison of results with available economic indicators for the pig fattening**
 1180 **production systems (5 farms for 2018)**

	ap_6 (Dairy)			Ap_8 (Dairy)			ap_12 (Beef)			Ap15 (beef fattening)			ap 16 (Dairy)			Mean Diff
	Sim	Obs.	Δ	Sim	Obs.	Δ	Sim	Obs.	Δ	Sim	Obs.	Δ	Sim	Obs.	Δ	
Piglet sold fattened (% piglet sold)	99	99	0%	100	100	0%	100	100	0%	93	93	0%	100	100	0%	0%
piglet purchased	1524	1524	0%	1780	1780	0%	1577	1577	0%	1252	1252	0%	7061	7061	0%	0%
Piglet sold (head)	1422	1423	0%	1687	1687	0%	1557	1557	0%	1201	1201	0%	6589	6821	-3%	-1%
Live weight produced (kg/piglet purchased)	107	108	-1%	111	111	0%	123	123	0%	106	111	-4%	116	116	0%	-1%
Global Consumption Index (feed/Lw gain)	2.74	2.73	0%	2.44	2.75	-11%	2.63	2.64	0%	2.68	2.87	-7%	2.63	2.68	-2%	-4%
Feed cost (€/kg lw)	0.69	0.70	-2%	0.51	0.57	-11%	0.63	0.64	-2%		0.66		*	0.57		-5%
Price (€/kg Carc.)	1.35	1.35	0%	1.31	1.31	0%	1.47	1.48	0%	1.46	1.45	1%	1.38	1.38	0%	0%
Product (€/piglet)	111	112	-1%	111	111	0%	139	139	0%	129	127	2%	122	122	0%	0%
Goss margin (€/piglet)	5	6	-14%	13	14	-5%	21	27	-23%	11	18	-38%	1.09	1.48	-27%	-21%

1181 *Note observed data come from GTE accountability of the farms simulated*

1182 **Table E.3: Comparison of simulated results and average results of the French farm network**
 1183 **INOSYS for beef cattle farms** (farm accountability of the simulated farm is not available for cattle)

	<i>Beef farm with suckler cows</i>						beef fattening without suckler cows					
	specilized			with a granivore unit			specilized			with a granivore unit		
	Sim.	INOSYS	Δ	Sim.	INOSYS		Sim.	INOSYS		Sim.	INOSYS	Δ
Number of Farms	6.00	98.00		7.00	11.00		3.00	53.00		3.00	12.00	
Worker units	1.10	1.68	-35%	1.76	2.07	-15%	3	1.94	52%	4.36	2.10	108%
Number of suckler cows (head)	68	105	-35%	73	68	7%	123	115	8%	123	80	54%
Herbivorous livestock units (LU)	92	162	-43%	97	107	-9%	216	203	6%	216	150	44%
Usable Arable Area (ha)	103	153	-33%	104	133	-22%	245	156	57%	245	130	89%
Forage area (% UAA)	86%	91%	-5%	86%	66%	29%	64%	85%	-25%	64%	66%	-3%
. Inluc. Corn silage [%]	1%	3%	-75%	1%	5%	-87%	16%	11%	49%	16%	16%	-3%
cattle stocking rate (LU /ha for. area)	1.10	1.18	-7%	1.13	1.43	-21%	1	1.58	-9%	1.45	1.80	-20%
Beef production [kg liveweight /LU]	311	301	3%	313	299	5%	345	379	-9%	345	395	-13%
number of weaned calves per cow [%]	92	88	4%	92	91	1%	2	86	-98%	2	84	-98%
cow renewal rate [%]	22%	23%	-7%	22%	25%	-14%	24%	26%	-8%	24%	25%	-4%
LU/calving	1.38	1.50	-8%	1.38	1.50	-8%	1.9	1.8	5%	1.9	1.8	3%
forage stock / LU [t Dry matter]	2.00	2.38	-16%	2.0	2.7	-27%	2.0	2.7	-25%	2.0	2.8	-26%
concentrate and by products [kg/LU]	483	639	-24%	532.30	607.33	-12%	1108	858.60	29%	1090.76	812.33	34%
Gorss product [€/UAA]	1219	1411	-14%	2762.70	1880.00	47%	1394	1802.00	-23%	2503.00	2635.00	-5%
gross beef product without subsidies [€/LU]	675	758	-11%	675.00	775.00	-13%	700	902.00	-22%	700.00	937.00	-25%
beef variable costs [€/LU]	218	318	-31%				322	356.00	-10%	1206.30		
forage variable costs [€/ ha of forage area]	66	73	-10%	57.22	98.67	-42%	123	120.00	2%	104.53	146.33	-29%
Gross operating surplus [k€/ associate workers]	56	45	24%	57.99	47.27	23%	48	54.00	-11%	32.72	55.70	-41%
operating results [k€/ associate workers]	19	14	36%	18.74	21.33	-12%	28	24.00	17%	32.52	22.85	42%

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1185 **Table E.4: Comparison of simulated results and average results of the French farm network**
 1186 **INOSYS for the specialized dairy farms** (farm accountability of the simulated farm is not available
 1187 for cattle)

	Sim.	INOSYS	Δ
Number of Farms	7	103	
Worker units	2.8	2.3	22%

Number of dairy cows	84	84	0%
Number of suckler cows (head)	8	-	
Herbivorous livestock units (LU)	136	131	4%
Usable Arable Area (ha)	142	118	20%
Forage area (% UAA)	82%	74%	12%
cattle stocking rate (LU /ha for. area)	1.2	1.5	-21%
milk production	7300	7671	4%
concentrate and by products [kg/1000 L milk]	209	206	2%
Gross product [€/UAA]	2317	2864	-22%
Operating results[k€ /associate workers]	25	30	-16%

1188 <https://idele.fr/observatoire->
1189 [inosys?tx_ideleinosys_inosys%5Baction%5D=synthese&tx_ideleinosys_inosys%5Bcontroller%5D=Inosys&cHash=882ea4a](https://idele.fr/observatoire-)
1190 [3123808ab552c55d36ee67303](https://idele.fr/observatoire-)
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1193 **Supplementary Material F: Simulated results**

1194 *Table F.1: Simulated economic results (k€)*

Valeurs	Beef fattening		Sow		Dairy fattening		Sow	
	Mix	Spe	Mix	Spe	Mix	Spe	Mix	Spe
Number of farms	6	6	4	4	5	5	2	2
TOTAL OUTPUT	335	203	543	200	601	334	659	273
Subsidies	60	59	56	51	53	51	59	57
SaleBeefanimals	110	110	86	86	11	11	0	0
Purch.beefAnimals	3	3	5	5	0	0	0	0
Purch.Dairyanimals	0	0	0	0	3	3	3	3
Saledairyanimals	0	0	0	0	28	28	25	25
Salecowmilk	0	0	0	0	213	213	182	182
SalePiganimals	173	0	338	0	372	0	385	0
Purch.PigAnimals	42	0	1	0	107	0	0	0
Sales&ConsumptionCrops	37	36	70	68	34	34	10	11
OPERATINGCOSTS	151	66	295	72	293	110	308	78
Purch.Feed	69	9	216	13	196	28	232	25
FarmFeed	28	9	8	7	13	13	10	11
Purch.Straw	6	6	4	3	8	7	4	4
fertilizer(k€)	5	6	4	11	4	10	0	4
VeterinaryCost	14	10	19	7	19	10	21	8
OtherAnimalCost	12	7	20	5	29	18	31	17
LandRental	15	15	14	14	15	15	10	10
Employee & Social Costs	25	15	40	11	51	24	46	21
fuel	7	7	10	8	13	12	10	8
Water&Elec	4	3	9	3	4	3	8	3
Machinery Cost	46	42	53	48	62	54	55	50
Building Cost	33	17	60	13	84	57	76	35
Financial Costs	10	7	14	7	18	13	16	9
OPERATIONAL RESULT	51	38	58	34	74	58	140	67

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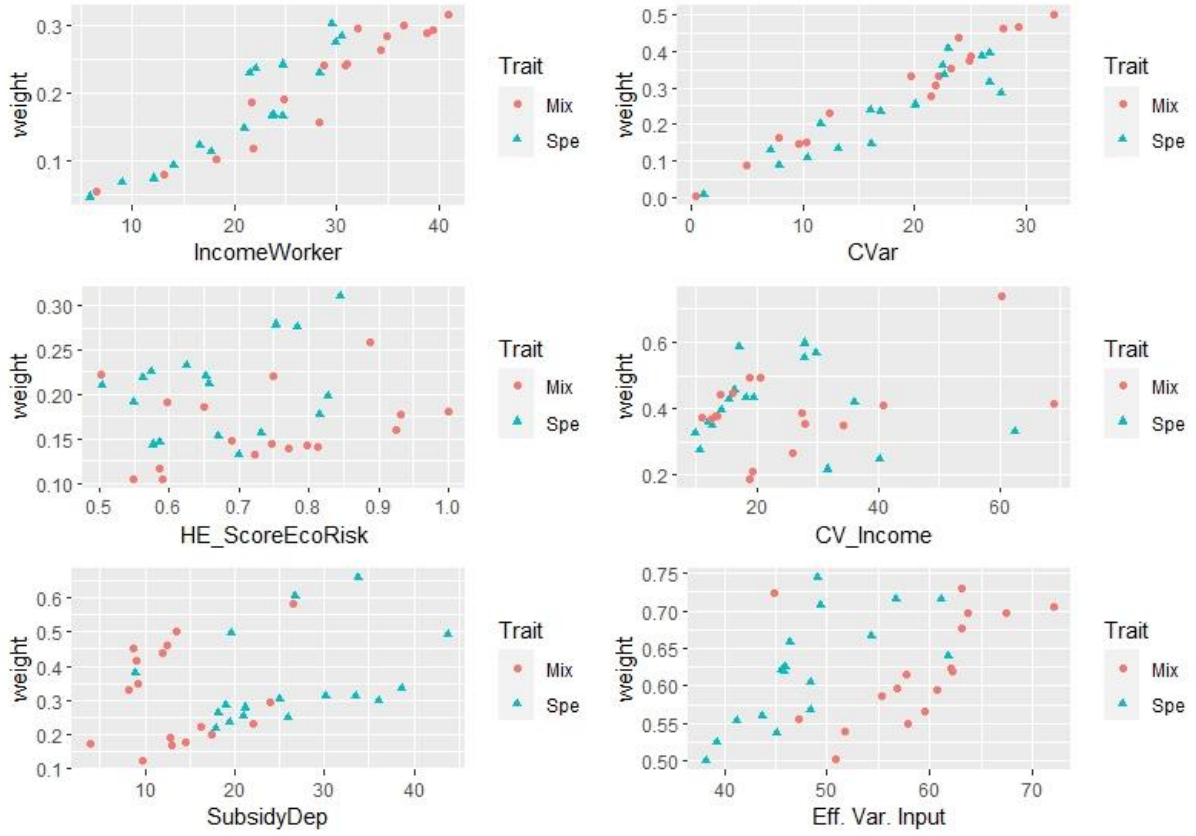
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1206 **Supplementary Material G: Weights of indicators according to their absolute**
1207 **values**

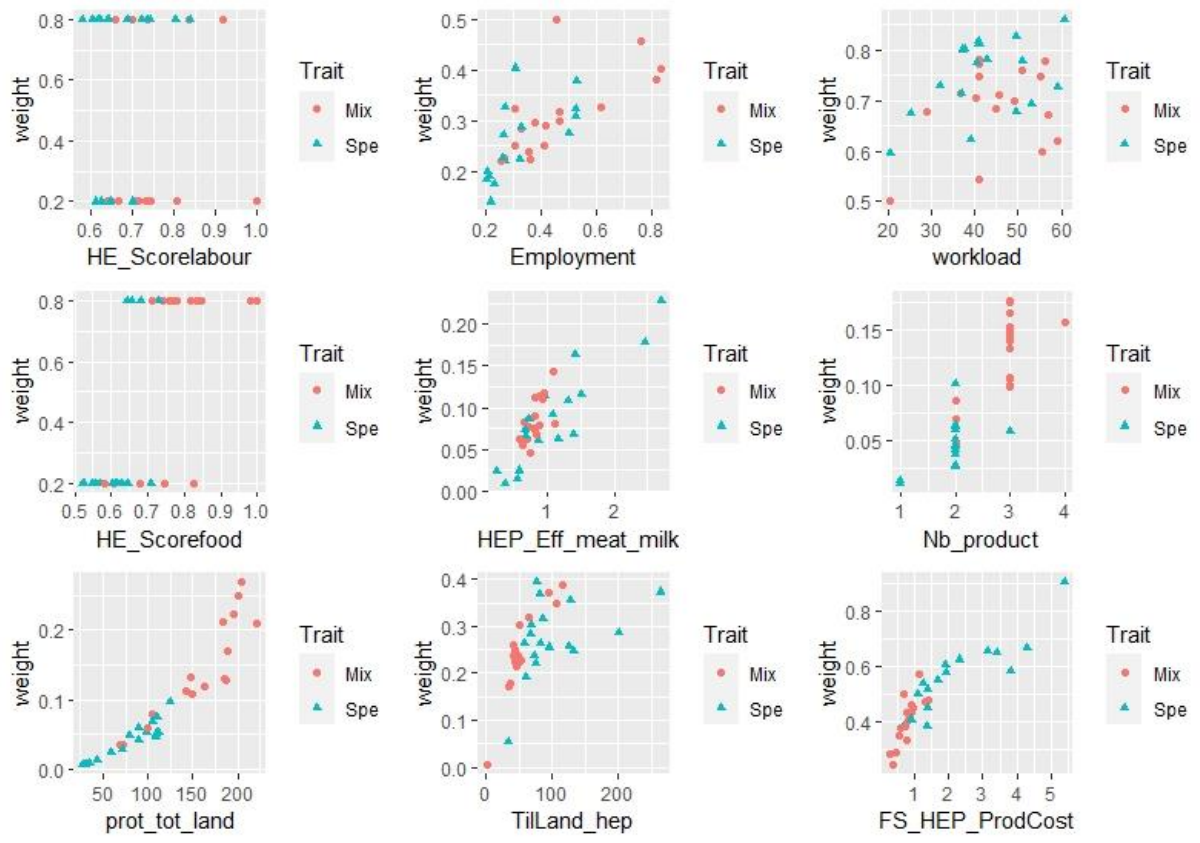
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1210 **Figure G_1: Weights of economic indicators according to their absolute values in mixed and**
1211 **specialized farming systems. Source : own simulation**

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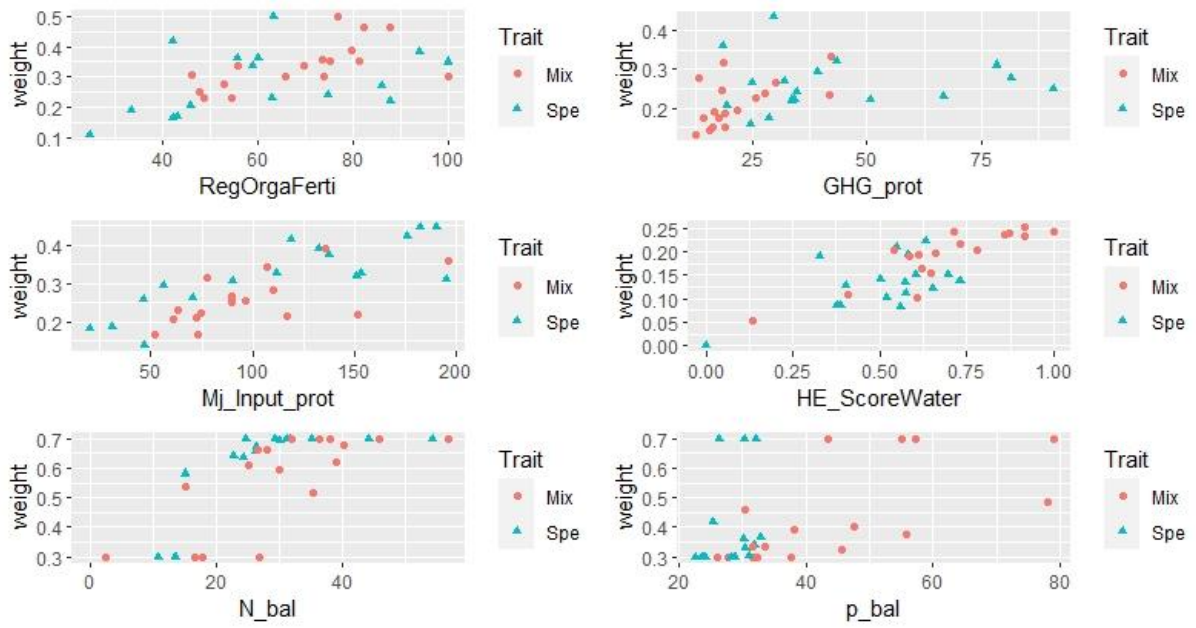


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1214 **Figure G_2: Weights of social indicators according to their absolute values in mixed and**
 1215 **specialized farming systems** *Source : own simulation*

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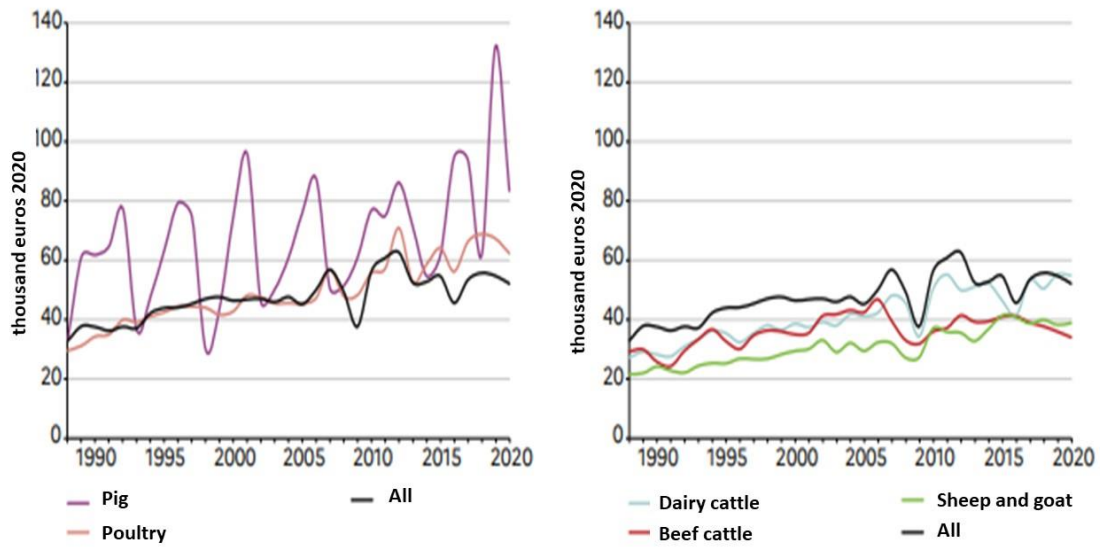


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1219 **Figure G_3: Weights of environmental indicators according to their absolute values in mixed and**
 1220 **specialized farming systems** *Source : own simulation*

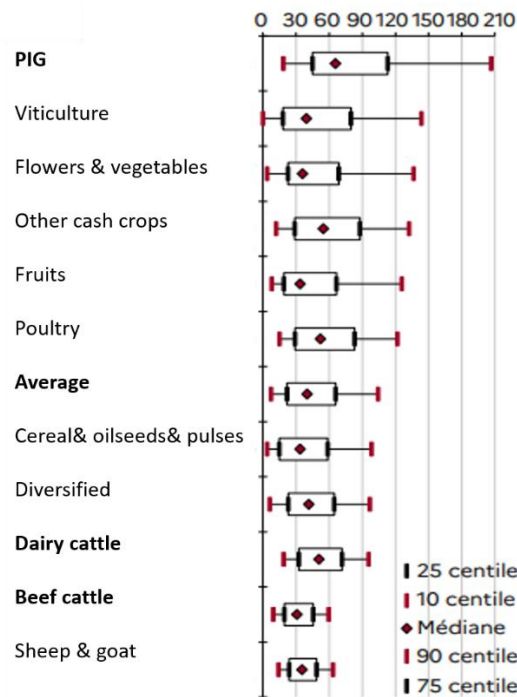
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1222 **Appendix H: Variability of Gross operating surplus according to production systems**



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1224 **Figure H1: Interannual evolution of the gross operating surplus in France according to the**
 1225 **production orientation of the farms.** On the left figure in purple line: pig production; On the left figure
 1226 in red line: beef production, in light blue line: dairy production. *Source : SSP-Agreste-Rica Results 2020*



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1228 **Figure H2: Dispersion of the gross operating surplus (in k€) in 2020 in France according to the**
 1229 **production orientation of the farms.** *Source : SSP-Agreste-Rica Results 2020*

1230 Agreste, 2021, Commission des comptes de l'agriculture de la Nation. *Les dossiers, décembre 2021 (5)*,
1231 105p. available at : [https://agreste.agriculture.gouv.fr/agreste-
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1232 web/download/publication/publie/Dos2105/Dossier2021-
1233 5_CCAN%20D%C3%A9finitif_d%C3%A9c2021%20V2.pdf) (last access June 2023).

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