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Does pig production improves cattle farm sustainability in the French massif central? A hierarchical constrained directional benefit-of-the-doubt approach

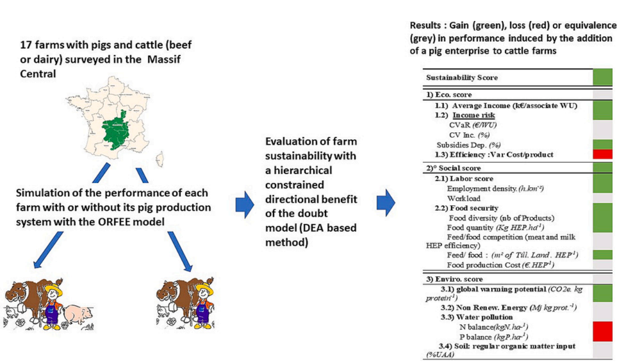
Claire Mosnier*, Sanae Boukhriss, Jean-Joseph Minviel

Université Clermont Auvergne, INRAE, VetAgro Sup, UMR 1213 Herbivores, Theix, Saint-Genès-Champanelle, 63122 France

HIGHLIGHTS

- Data from 17 mixed cattle-pig farms in the French Massif Central were used.
- Their farming system with or without pigs and sustainability indicators were simulated with the Orfee model.
- The directional benefit of doubt method was used to estimate the composite sustainability indicators.
- Pig farming systems significantly improve the overall sustainability and the social score of cattle farms.
- The addition of pork operations does not result in significantly differences in economic and environmental scores.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Pig production systems are currently in decline in the French Massif Central, while herbivore production systems, most of which are specialised, generate little income. The diversification of herbivore farms with pig production appears to be an interesting lever for improving farm sustainability.
OBJECTIVE: The objective of this study was to assess the impacts of adding pig production on the sustainability of beef and dairy farms and to assess the pros and cons of a DEA based multicriteria evaluation model.
METHODS: The Orfee bioeconomic model was used to simulate 17 beef or dairy farms with and without pigs. This pig production system consists of either a farrow-to-finish sow production system or a pig fattening production system only. The structural and technical parameters of these farms were established from a farm survey. Farm sustainability was assessed using 17 indicators. These indicators were hierarchically aggregated into a single sustainability composite indicator using an innovative method, the constrained directional benefit of the doubt (D-BoD) method.
RESULTS AND CONCLUSIONS: The results indicate that the addition of a pig production system has an overall positive impact on the sustainability of cattle farms. Mixed cattle-pig systems score significantly better on the social dimension as they generate more jobs and contribute more to food security. The overall economic performance is not significantly better than that of specialized systems for the price context from 2012 to 2022. The pig production system increases the average income per work unit for cattle farms but needs more purchased

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* Corresponding author.
E-mail address: claire.mosnier@inrae.fr (C. Mosnier).

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inputs to produce. This reduces but not offsets the risk reduction advantage of diversification and reduces production efficiency. Mixed farms do not score higher than specialized cattle farms on the environmental dimension. Mixed farms contribute less to global warming per kg of protein produced but have higher nitrogen and phosphorus surpluses. The constrained D-BoD method is a useful tool for endogenously aggregating indicators without having to arbitrarily set weights and thresholds to evaluate performance, but with certain limitations, such as the possibility that a farm may be judged efficient if it performs better on some indicators while being relatively weak on others.

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

1. Introduction

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

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

Several studies have analyzed the potential benefits of diversifying cattle farms. Brewin et al. (2014) simulated the net profit gains from integrating a beef and a pig production system in Canada compared to managing them separately. The economic gains came from the application of pig manure to fields producing forage for cattle. However, they did not explore sustainability indicators related to the environmental and social sustainability pillars. Some studies have been conducted to assess the benefits of diversifying livestock systems in the French Massif Central (Dumont et al., 2021; Mosnier et al., 2021a; Minviel and Benoit, 2022) but without considering pig production. Using organic farm data, Steinmetz et al. (2021) compared different farm performance indicators of organic mixed livestock farms. They found that systems with large monogastric production (pigs and poultry) had a poor agricultural nitrogen balance without gaining economic efficiency (measured by the ratio of added value to gross farm output). Mischler (2019) also found that mixed monogastric and ruminant systems had a higher nitrogen balance and energy consumption per ha but lower income variability than specialized or mixed ruminant farms. However, these studies did not distinguish between the different types of pig and ruminant production systems, while there is significant heterogeneity. Furthermore, they did not provide an overall assessment of the sustainability of mixed farms based on aggregations of indicators.

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

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

Although the analysis of real farms makes it possible to evaluate the farm functioning under real conditions for both mixed and specialized farm, modelling allows for the control of the effects of production system size and efficiency. It avoids biases in the comparison of different farms such as the Fox paradox (Karagiannis, 2012; Minviel and Veysset, 2021) that can occur when firms producing several goods produce a smaller proportion of the good for which they are less efficient than others. Modelling also allows the estimation of indicators that cannot be estimated directly with a farm survey. The farm model Orfee (Mosnier et al., 2017) is particularly suited to simulate mixed production systems as it takes into account several complementarities between different farm production systems, namely the value of organic fertilization, on-farm production of feed and litter for animals, possibility to use machines, building and labor for different productions (Mosnier et al., 2021a). We used Orfee to simulate the sustainability of 17 mixed pig-cattle farms surveyed in the French Massif Central., The same 17 farms were simulated with and without the pig production system in order to assess the changes in farm sustainability caused by the pig production system.

2. Method

2.1. Multi-criteria sustainability assessment

2.1.1. The evaluation tree

We have defined a hierarchical evaluation tree (Fig. 1) in which each sustainability pillar is characterized by different components, which are themselves assessed by a number of criteria measured by indicators. Only those indicators that were potentially impacted by pig production system and can be calculated by the Orfee model were selected. Consequently, indicators that might have been of interest such as return

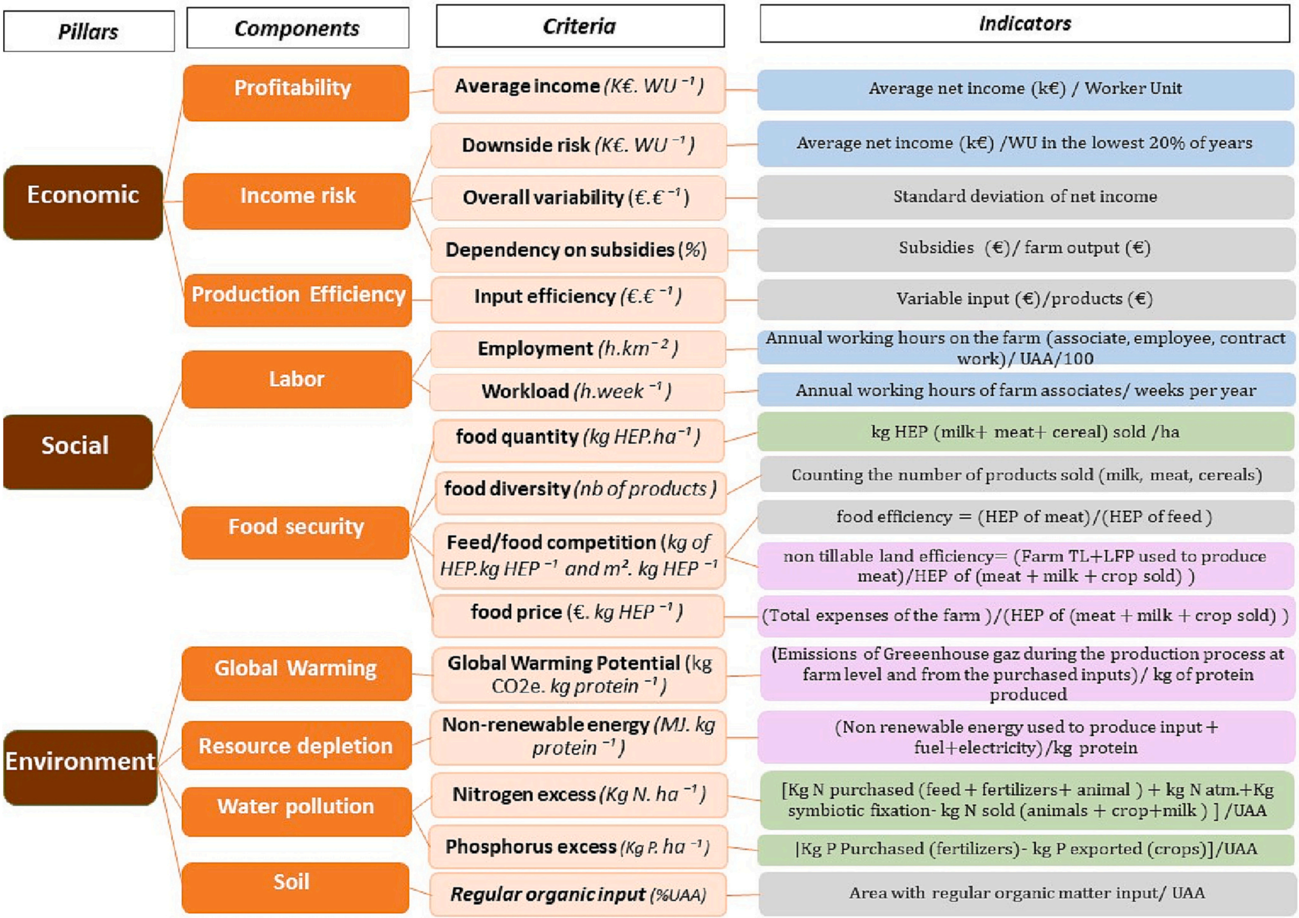

Fig. 1. Evaluation tree.

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

on capital and farm transferability, welfare, biodiversity, landscape quality and air quality were not included.

All the components studied are linked to the agricultural production process and could thus be included in the economic pillar. However, we have chosen to distinguish three pillars: 1) the economic pillar, which assesses the good management of the farm resources in order to generate an income for its managers, 2) the social pillar, which takes into account the services rendered by the farm to humans, and 3) the environmental pillar, which assesses the impacts of the production process on the environment. The economic pillar included three components: profitability, income risk and efficiency. The farm profitability component was assessed by the average net income per worker associate. Net income is calculated as the difference between farm outputs plus subsidies minus variable costs, fuel, water and electricity, maintenance and depreciation of machines and buildings, employee wages, cost of contract work and social taxes, land rental and financial costs. The income risk component was measured by (1) the conditional value at risk (CVaR) which is the average net income of the 20% of years with the lowest incomes and indicates downside risk, (2) the standard deviation of net income as a measure of overall variability and (3) the dependency on subsidies. We argue that since the share of subsidies in the outputs and income of cattle farmers is already very high, it is desirable to reduce their dependence on public subsidies.Public policies can indeed change as the objectives of successive governments evolve. The efficiency of the input used was measured as the ratio of variable input costs including feed, seed and energy that are transformed during the production process to sales of animal and crop products. A farm with a low ratio consumes less inputs to produce the same amount of outputs and is considered more sustainable. Capital such as labour, land and machinery is not included in this ratio because it can be used in several production cycles provided it is maintained in good condition.

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

For the environmental pillar, three components and five indicators were considered. The Global Warming Potential (GWP) quantified the emissions of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) at all stages of agricultural production and for all inputs (except machinery and buildings), from cradle to farm exit gate (Mosnier et al., 2017; Mosnier et al., 2021b) (Supplementary Material B). The functional unit chosen for this global indicator is one kg of protein (this includes proteins that are not edible by humans but used for other purposes as this indicator does not only concern food production). We have not opted for a functional unit per hectare because climate change is a global issue; the aim is to produce efficiently independently from the location where the emission is produced. The depletion of non-renewable resources was also calculated per kg of protein. This is the sum of the fuel and electricity consumed on the farm and the amount of non-renewable energy used to produce the purchased input. Livestock manure contains a significant amount of nutrients such as nitrogen and phosphorus, which at low concentrations, make the soil more fertile. However, in excess, they are responsible for water pollution. Too much nitrogen and phosphorus in the water causes eutrophication then algae blooms, often at the cost of other species. Since it is the excessive local concentration that induces pollution, the unit function is the hectare. This pollution was assessed by two per hectare indicators of excess nutrients: the nitrogen balance and the phosphorus balance. The nitrogen balance is the difference between N entries (N in purchased animals, fertilizers and feed, N fixed by leguminous crops and crop residues, atmospheric deposition) and N exits (N retained by animals, sold crops) at farm level (Simon and Le Corre, 1992). Phosphorus surplus was assessed with a simpler method since phosphorus cannot be absorbed in the atmosphere: it is the difference between the P content of applied fertilizers on the farm and crop exports. The quality of the soil depends on several factors including its organic matter content. The regular application of organic fertilizers can contribute to increase the organic matter of the soil (Diacono and Montemurro, 2011). The indicator used is the share of land that has received at least 5 t of organic matter every two years (equivalent to 24 tons of solid farmyard manure) to maintain organic matter content above 2% (Thiery et al., 2023).

2.1.2. *Sustainability score aggregated by the D-BoD model*

A composite indicator (CI) is a mathematical aggregation of a set of sub-indicators that measure multi-dimensional concepts but generally do not have common units of measurement (Nardo et al., 2005). The benefit of the doubt (BoD) addresses many of the methodological criticisms associated with composite indicators. In particular, insufficiently precise knowledge of the underlying structure of a farm's multi-performance, uncertainty or lack of a standard construction methodology and disagreement among experts on the importance of the underlying performance indicators used for each dimension (Cherchye et al., 2007). The weighting of sub-indicators has always been the most problematic methodological issue in the construction of composite indicators (Nardo et al., 2005). The BoD method does not require arbitrarily setting the weight of each indicator to be aggregated. Each farm evaluated has the benefit of the doubt in selecting its relative weights. The model endogenously selects the best possible weights for each evaluated farm to maximise its aggregate score. Recent developments in production systems research suggest the use of a directional benefit of the doubt model (D-BoD model) (Rogge et al., 2017). The D-BoD model combines the methodological advantages of the traditional BoD model with those of the directional distance function (Rogge et al., 2017; D'Inverno and De Witte, 2020). One of these advantages is that it satisfies the unit invariance property, i.e., the aggregate performance score is not affected by the scale of the performance indicators. For example, measuring an indicator in tons or kilos has no impact on the overall performance score. Another practical advantage of the D-BoD model is that it is flexible enough for performance evaluations in real-life decision-making situations by reflecting the evaluation attitude of the decision maker. The D-BoD model maximizes desirable indicators and minimizes undesirable indicators without transforming them, by specifying a direction vector, denoted g(.).

For a sample of N farms, a vector of s desirable indicators, and a vector of m undesirable indicators per farm, the dual[1] formulation of the D-BoD model (see Zanella et al., 2015; Rogge et al., 2017) is given by:

$$D_k\left(y_k^-, y_k^+, g_r^+, g_l^-\right) = \min_{w_{k,r}^+, u_{k,l}^-} \left(-\sum_{r=1}^{s} w_{k,r}^+ y_{k,r}^+ + \sum_{l=1}^{m} u_{k,l}^- y_{k,l}^- + \upsilon \right) \tag{1}$$

subject to

$$-\sum_{r=1}^{s} w_{k,r}^+ y_{j,r}^+ + \sum_{l=1}^{m} u_{k,l}^- y_{j,l}^- + \upsilon \geq 0 \; (j = 1, \ldots \text{k}, .., N) \tag{2}$$

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

$$w_{k,r}^+ \geq 0 \; (r = 1, \ldots, s) \tag{4}$$

$$u_{k,l}^- \geq 0 \; (l = 1, \ldots, m) \tag{5}$$

$$\upsilon \in \mathbb{R} \tag{6}$$

The objective function (1) minimizes the weighted sum of the desirable ($y_{k,r}^+$) and the undesirable ($y_{k,l}^-$) indicators, provided that no farm in the sample reaches a value lower than zero when computing a similar measure using the same weights as the farm under assessment (see constrain 2). The optimal value, $D_k\left(y_k^-, y_k^+, g_r^+, g_l^-\right)$, of the objective function corresponds to the maximal feasible expansion of desirable indicators and contraction of undesirable indicators that can be achieved simultaneously. The direction vector $\left(g_l^-, g_r^+\right) \in \mathbb{R}^{m+s}$ specifies the exact direction in which improvements can be sought. The direction vector is defined such that $g\left(g_l^-, g_r^+\right) = \left(-y_l^-, y_r^+\right)$, which is the direction along which desirable indicators are expanded and undesirable indicators contracted simultaneously. This definition of g() allows each farm to follow its own improvement path, and thus ensures a high level of flexibility; it also preserves the invariance of the D-BoD model units (Zanella et al., 2015). The variable υ comes from an equality constraint in the primal formulation of the D-BoD model that ensures the construction of an appropriate frontier to compute the composite indicators. It can also be seen as a factor that will be determined by the optimization process to ensure the non-negativity of the distance function. The second constraint (3) is a normalization condition, which ensures that the weights ($w_{k,r}^+$ and $u_{k,l}^-$) are relative. It is assumed that the weights should be not negative and subsequently non-negativity constraints (constraints 4 and 5) are imposed in the model. Before aggregating the indicators, they are interpreted to determine whether a higher value for an indicator reflects an improvement or, on the contrary, a deterioration in performance. In this way, it is possible to determine which indicators to maximise and which to minimize.

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

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

The previous program (eq. 1–6) and the additional weights constraints is solved for each farm of our sample using the R package “Composite Indicators Functions” (Compind), and the composite indicator for the kth farm (CI_k) is obtained as:

$$CI_k = 1/(1+D_k) \tag{7}$$

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

2.2. Simulation of farm functioning and performance with the model Orfee

2.2.1. Model overview

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

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

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

Price changes were calculated as a reference price calibrated to each farm reference, multiplied by the price change index (respectively the producer price index for agricultural products, IPPAP, and the purchase price index for agricultural inputs, IPAMPA, for products and inputs), and deflated annually by the consumer price index. These indices were calculated by the National Institute of Statistics and Economic Studies.

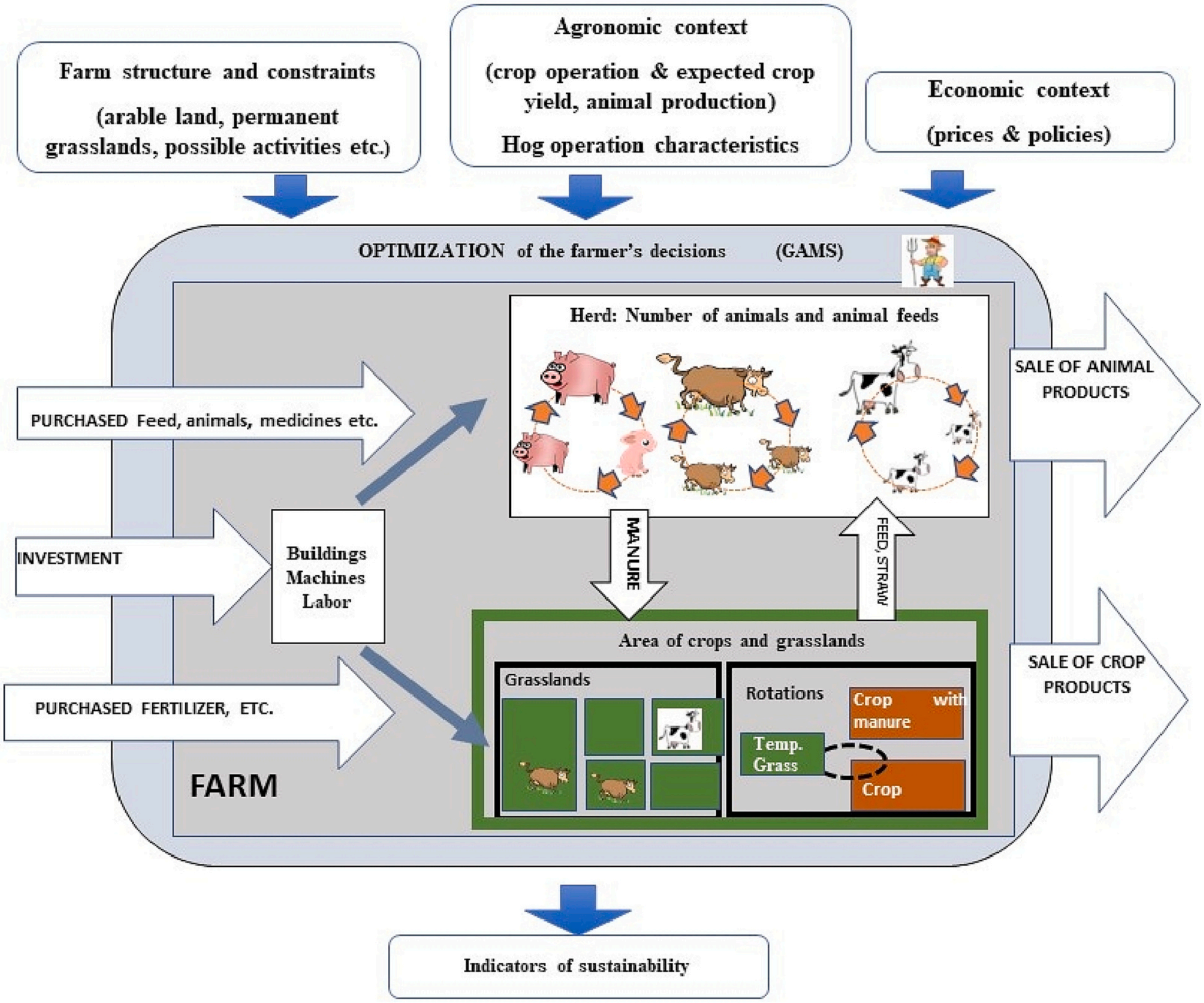

Fig. 2. Representation of the Orfee model.

The main national and European subsidies granted to cattle and crop production between 2012 and 2022 were taken into account (Mosnier et al., 2017). Optimization is carried out under a series of agronomic, structural and regulatory constraints.

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

The interactions between the different production of the farm (crops, cattle and pigs)- concern first of all the exchanges of materials between crops and animals. Plant products produced on the farm can be used for animal feed or bedding. Cattle mainly consume products from grasslands and fodder crops, supplemented by grains. Pigs consume mainly grains. The arable land can thus either be used to produce feed and litter for cattle and pigs or can be sold directly while permanent grasslands are exclusively used by cattle. Feed, excluding green or silage fodder can also be purchased. Pig feeding can be based solely on the purchase of complete industrial feed. Constraints in the model specify the types of feed that are possible for each farm and type of animal production. Animals provide in return organic matter and minerals to soils and plants. The composition of manure varies according to the type of bedding and the type of animal. Manures containing straw are richer in organic matter that will improve soil quality, while liquid manures contain more nitrogen that is rapidly available to plants (Supplementary data C, Table C6). Pig manures that are most often liquid, have higher nitrogen levels than cattle manures and are more balanced in N, P, K elements. The model requires that sufficient minerals be applied to balance crop export and other nitrogen transfers to the soil or to the atmosphere. However, mineral inputs are allowed to exceed plant exports for several reasons: 1) only a fraction of the minerals in manure can be used by plants in the short term, 2) organic fertilizers have an composition of N, P, K that is not perfectly balanced for plant needs, and 3) in the case where manure exports are not possible, the farmer has an interest in spreading all of his manure within regulatory limits.

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

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

2.3. Scenarios and farm surveys

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

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

The survey included structural data regarding the labor force, main land use, herd size, main beef production, milk production and pig production (Table 1). Dairy production systems and beef cow production systems were slightly larger than the average of specialized dairy or beef French farms in 2020: 84 and 80 vs *resp.* 60 dairy cows and 70 beef cows for French specialized farms (Agreste, 2020). The size of pig production system was lower than the national average but with a high heterogeneity between farms. Since the project was focusing on the pros and cons of pig production, rather detailed data was gathered on each farm to characterize pig production but limited technical data was available for crop and cattle production (Supplementary Material D) and consequently relied on the average technical coefficient of this area.

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 (1000 $L.cow^{-1}.year^{-1}$·) (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

Table 2
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

Orfee was used in this study to simulate the performance of the 17 farms studied under the 2012–2022 economic context. The same 17 farms were simulated with and without pig production system in order to assess the changes caused by the pig production system (Table 2). The opposite situation (pig only) was not tested because it raises questions about the alternative use of permanent grassland, currently grazed by cattle. For each simulation, the herd size, type of animal produced, and area of cash crops were set according to the farm data. Pig production and feeding were also set for each farm. Default data were used for cattle breeding and weights, crop yields and cultivation production systems. As no information was available for grassland management, cattle feeding, machinery and building capacity, these variables were endogenously optimized by the model. We considered that extra manure can be given away for free because the farmers interviewed had no problem giving it away but could not always sell it. The number of labour units considered for the mixed beef and pig farms was based on the farm surveys. For the scenario of the specializedcattle farm, the number of simulated annual working hours was generally lower. It was assumed that the reduction in the number of hours of salaried work and thus the cost of salaried workers was first reduced, assuming that a full-time job is always 35 h per week. The cost of salaried labour was defined on the basis of the minimum gross income imposed by legislation in France (10 €/hour over the period studied), multiplied by 1.2 to take into account the scarcity of agricultural employees on farms and the evolution of their wages, and multiplied by 1.4 to add the social charges paid by the employer on the employee's wages. When the reduction in working time exceeds the employee's working time, the number of associate workers has been reduced but rounded to the nearest half work unit to take into account the fact that the associates' working time is more flexible: from 30 h/week to 60 h/week, an associate is considered full-time.

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

3. Results

3.1. Economic sustainability

For the economic context studied (2012–2022), Table 3 shows that mixed systems have contrasting impacts on economic indicators leading to an overall economic performance not higher than that of specialized systems. The r variable costs to product ratio and the income per worker are the indicators with the highest weight in this composite score but it is the average income per associate worker unit and the conditional value at risk (CVaR) that are the most correlated with the composite economic score (Fig. 3).

The pig production system allows an average increase of 7 k€ in income per worker. This gain is more significant for beef cattle production which have a lower income per worker than dairy production systems (Table 3) and for pig fattening units. On average, the pig production system allows farms to reduce fertilizer costs by 8 k€ but the additional equipment needed to spread manure increases mechanization costs (external production system, maintenance, depreciation and fuel) by 7 k€ (Supplementary Material E2) and required additional manure storage capacity. In our sample, the increase in subsidies induced by the addition of the pig production system is on average 2 k€/farm but rises to nearly 10 k€ if the production system allows the addition of associate workers and meets the compensatory payment for mountain areas requirements. Pig production is not directly subsidized, however, can in some cases indirectly increase subsidies. The compensatory payment for mountain areas is capped at 75 ha, with a degressivity from 25 ha but this ceiling is increased if there are several associate workers on the farm.

The composite indicator of income risk is better for mixed farms (0.74) than for specialized cattle farms (0.67). The pig production system reduces dependence on subsidieswhich makes mixed farms less sensitive to changes in public policy, namely farms with beef cattle farms which have the highest share of subsidies in their income. However, the coefficient of variation of income is higher in mixed systems (27% for mixed systems vs. 25% for specialized ones), although this difference is only statistically significant in the case of dairy farms. Pig production generates significant economic flows in terms of sales (294 k€) but also in terms of expenditure, particularly for the purchase of animal feed (on average 142 k€). This increases the sensitivity of farms with pigs to market fluctuations. The pig fattening production system reduces the vulnerability of cattle farms by increasing the lowest income (CVaR), which reduces the risk of income falling below a critical threshold.

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

Table 3
Composite and individual sustainability indicators according to the presence of a pig production system *(mixed* vs. *spe.),* cattle *(dairy* vs *beef)* and pig production *(pig fattening* vs *sow to farrowing*) orientations.

	All		Dairy		Beef		Pig Fattening		farrow-to-finish sow	
Indicators	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
Eco. Score (W=33%)	0.81	**0.82**	**0.90**	0.87	**0.79**	0.76	**0.81**	0.80	0.82	**0.84**
Average income (k€/associate WU) (W=19%) 1.1)	**28.4*** **	20.9	**31.9** **	23.2	**25.9*** **	19.3	**26.8*** **	19.3	**31.2** *	23.8
Income risk (W=18%) 1.2)	**0.74*** **	0.67	**0.81** *	0.75	**0.68*** **	0.62	**0.72** **	0.67	**0.76** **	0.67
CVaR *(€/WU) (W=27%)*	**19.2**	17.1	**22.7** **	19.5	**16.8**	15.4	**19.4*** **	15.9	18.8	**19.3**
CV Inc. *(%) (W=40%)*	26.6	**24.5**	24.6	**18.1** **	**28.1**	29.0	25.5	**24.0**	28.7	**25.3**
Subsidies Dep. *(%) (W=33%)*	**13.8*** **	25.9	**9.8** **	17.9	**16.5*** **	31.4	**15.7*** **	25.2	**10.3** **	27.1
Efficiency (W=62%)Var Cost/product	58.6	**48.2*** **	56.9	**43.2*** **	59.8	**51.8** *	56.8	**49.0** **	61.9	**46.9** *
Social Score (W=35%)	**0.87** **	0.78	**0._83** **	0.71	**0.74*** **	0.62	**0.92*** **	0.72	**0.84** **	0.81
Labor score (W=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}) (W=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}) (W=72%)*	44.9	**42.2**	44.9	**42.7**	44.9	**41.8**	42.9	**39.6**	48.5	**46.8**
Food Security (W=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) (W=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}) (W= 9%)*	**154.2*** **	77.9	**139.5** **	61.7	**175.1*** **	101.0	**132.7*** **	70.6	**193.6** **	91.1
HEP efficiency (W=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}) (W=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}) (W=48%)*	**0.8*** **	2.2	**0.7** **	1.4	**0.9*** **	2.7	**0.8*** **	2.3	**0.7** **	1.9
Enviro. Score (W=34%)	**0.81**	0.78	**0.75**	0.73	**0.85**	0.81	**0.85** *	0.83	0.89	**0.96**
GWP (W=24%)GWP *(CO2e. kg protein^{-1})*	**21.8** **	43.0	**19.2** **	33.8	**23.5*** **	49.4	**25.1*** **	49.3	**15.6** **	31.5
Non Renew. Energy *(Mj kg prot.$^{-1}$)*	**97.4**	112.3	**110.7** **	159.0	88.1	**79.6**	**107.9** *	131.8	78.0	**76.5**
Water pollution (W=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}) (W=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}) (W=42%)*	44.2	**28.9*** **	56.9	**43.2** **	59.8	**51.8*** **	56.8	**49.0*** **	61.9	**46.9** **
Soil (W=31%)reg. Organic matter input *(%UAA)*	**66.0**	63.3	**60.0**	55.6	**70.2**	69.2	**64.5**	61.1	**68.7**	66.9

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

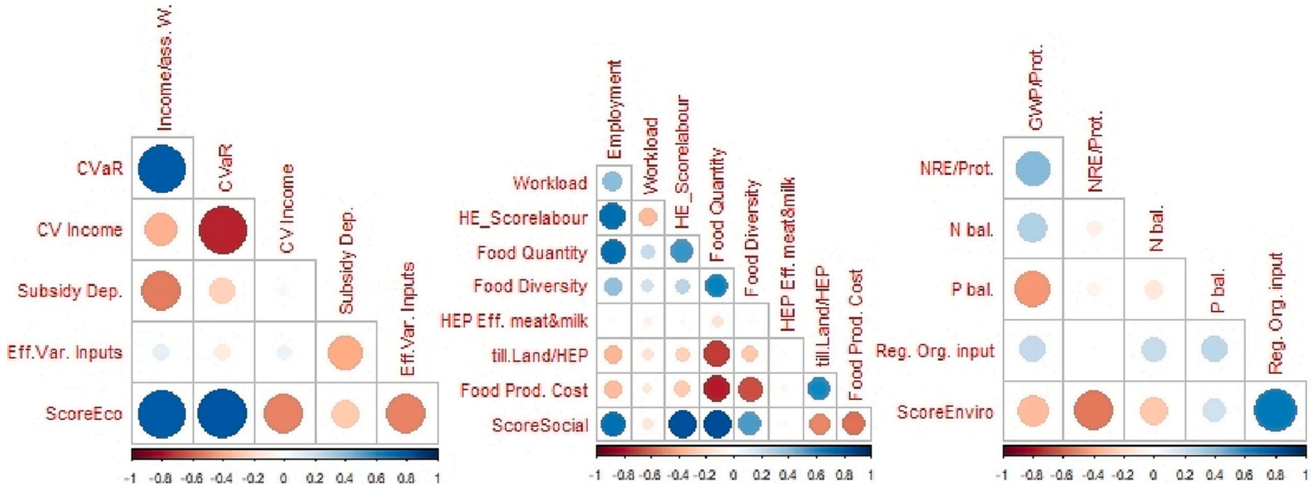

Fig. 3. Correlation matrix between composite indicators and single indicators.

Notes: red circle for negative correlation, blue circle for positive correlation.

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

ScoreSocio: aggregated social score with: workload, employment, HEP_Eff, Human Edible Protein efficiency of animal production, Food diversity measured by the number of food product produced on the farm, food quantity measure by the quantity of HEP produced per ha, TilLand_Hep Tillable land used per HEP, HEP_-ProdCost cost to produce 1 kg of HEP,

ScoreEnviro environmental score with: GWP_global warming potential per kg of protein, NRE non renewable energy consumed per kg of protein, N_bal nitrogen balance, P_bal: Phosphorus balance.

3.2. Social sustainability

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

The composite indicator of labor is significantly better for mixed farms. Mixed pig-cattle farms generate more on-farm employment than their specialized cattle counterparts. The employment density per unit area in mixed cattle-pig systems is about 0.5 $h.km^{-2}$ compared to 0.3 $h.km^{-2}$ in specialized cattle systems (Table 3). In the studied farms, the addition of a pig production system results in the addition of an average of one worker:0.6 employee and 0.4 associate. The working time per full time employee worker is assumed to be fixed (35 h of work per week for a full-time employee) but the workload of associate farmers vary since it is assumed that the number of associate workers is adjusted by steps of 0.5 WU. On average, associate workers work three hours more per week in mixed systems.

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

3.3. Environmental sustainability

The score of mixed farms is not higher on the environmental dimension (Table 3). The weights of the different indicators are balanced (Table 3). The indicators of regular organic input in soils and non-renewable energy consumed are the most correlated to the environmental score (Fig. 3).

Mixed farms have a lower global warming potential (GWP) per kg of protein than specialized cattle farms. This difference is explained by the absence of enteric methane emissions from pigs. The presence of pigs also reduces the application of mineral fertilizers. On average, mixed farms consume slightly less energy per kg of protein. Beef farms that use very few inputs do not have a lower consumption of non renewable energy per kg of protein with the addition of pigscontrary to dairy farms that require energy for milking and feed production.

The extra manure allows all farms to reduce the purchase of fertilizer and in some cases to give it to other farms, but the surplus in the nitrogen and phosphorus balance increases. The main reason for this is that only a fraction of the organic nitrogen in livestock manure is potentially taken up by crops during the year of application. The rate of mineralization for the first year is around 60% for pig slurry and 20% for cattle solid farmyard manure. Organic N is then slowly mineralized by microorganisms over the following years. The regular supply of organic matter increases the amount of humus mineralized each year (from 5 to 20 kg more depending on the soil and the crop COMIFER, 2013), but compared to a mineral fertilizer, more organic nitrogen must be provided for the same plant needs. The excess of P increases even more as manure is often too rich in P compared to N for plant needs.

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

3.4. Overall sustainability

The sustainability score is significantly higher for mixed farms (0.91) than for specialized cattle farms (0.85). This gain is particularly significant in the case of beef cattle farms and pig fattening production systems (Table 3). The weights of the different indicators are balanced (Table 3).

4. Discussion

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

To aggregate indicators, it is necessary to give weights to the different indicators but defining weights can be tricky. In traditional methods any choice of fixed weights is likely to be interpreted as arbitrary or unfair (De Witte and Rogge, 2011). The benefit of the doubt (BoD) method endogenously estimates the relative weights of each indicator for each farm. As a result, the weights of the indicators for which the farm outperforms are higher than the weights of the indicators for which the farm underperforms. This mechanism reduces the difference in scores between farms as pointed out by Ravanos and Karagiannis (2021) and allows farms that are better on one indicator to be classified as efficient even if their performance is relatively poor on other indicators (Ravanos and Karagiannis, 2021). Very high or very low weighting values may be undesirable as they induce compensation between indicators that is criticized under the assumption of high sustainability, which considers that a farm could not be considered sustainable if one criterion is too low. The R package used (Compind, D-BoD constrained) allows specifying a minimum weight to avoid this pitfall. Since it is not possible to specify the weight of each indicator separately in the d-BoD method, we used a hierarchical approach so that the minimum weight does not implicitly give more weight to components with more criteria. Compared to the D-BoD method without weighting and hierarchy (Fig. 4), the proposed framework reduces the score of specialized farms for the social pillar, for which they perform less well overall. The overall sustainability indicator estimated with the proposed framework is also significantly lower, increasing the gap between the sustainability indicators of mixed and specialized farms.

It was not possible to impose weight constraints close to the balanced weights, as this makes the model infeasible. However, increasing minimum weights limits one of the main advantages of the D-BoD method, namely the endogeneity of the weights.. High correlations between the weight of the indicators and their value are still observed in our analysis, with sometimes low weights when it was not possible to raise the weight constraint (Supplementary Material F). Some indicators that are generally better for mixed farms, such as the amount of protein produced per ha and labor employment, have higher weights than specialized farms (Fig. 5), however, the differences is generally low.

Other DEA based methods exist for controlling weights (Bagherikahvarin and De Smet, 2016; Oliveira et al., 2019; Henriques et al., 2020), but they do not allow to differentiate desirable indicators from undesirable ones. However, methods that aim to control for the weights of individual indicators do not necessarily control for their explanatory level on the composite indicator. Paruolo et al. (2013) found that the reported importance of individual indicators and their main effect on the composite indicators are very different. This is also the case here, with, for example, the weight of the variable costs to sales ratio being three times higher than that of average income, but ultimately proving to be less correlated with the composite economic indicator than average income. Normalisation and standardisation of the variables could avoid this dichotomy, but negative values make the model infeasible.

Another advantage of the BoD method is that there is no definition of what is a good or bad performance. In more traditional multi-criteria assessment methods, good or poor performance is often assessed as above or below the average performance of the farm or a reference

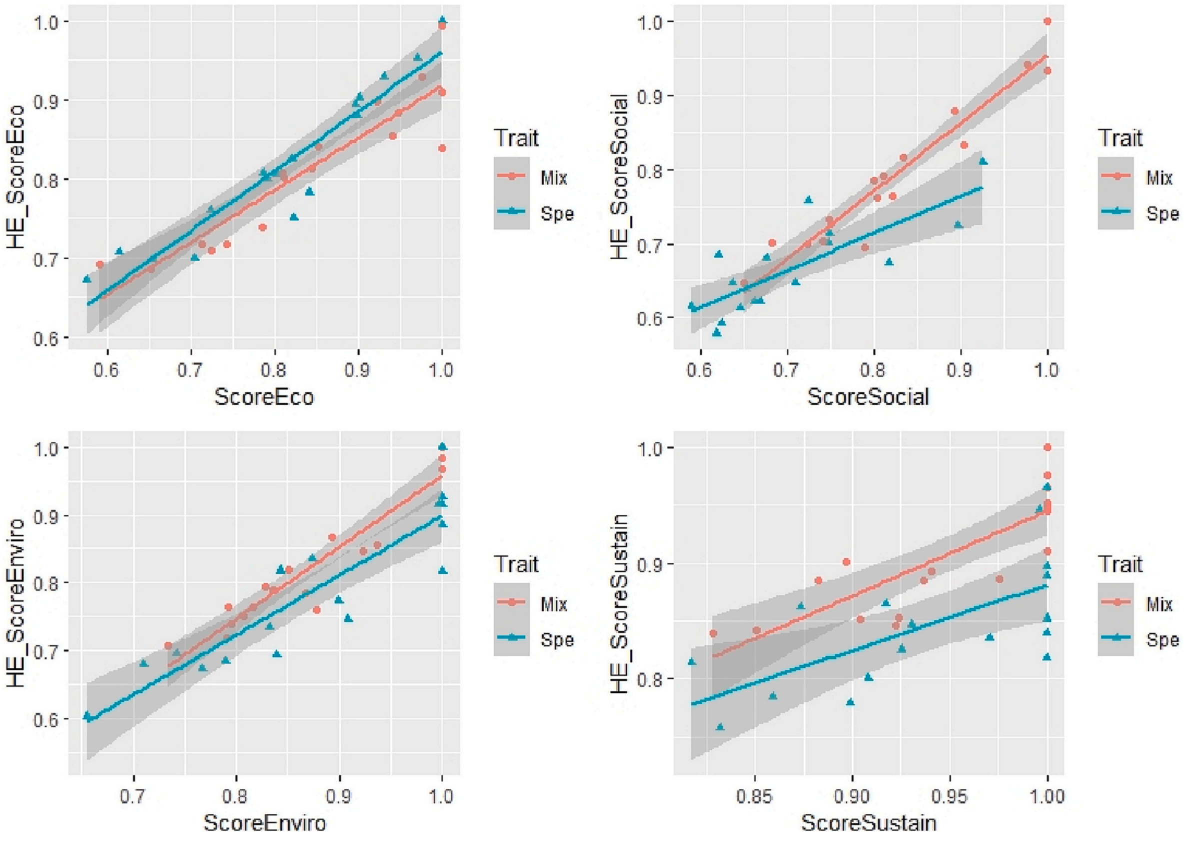

Fig. 4. D-BoD Score estimated with a minimum weight and a hierarchical organization ("HE_") versus D-BoD scores estimated without weight constraints.

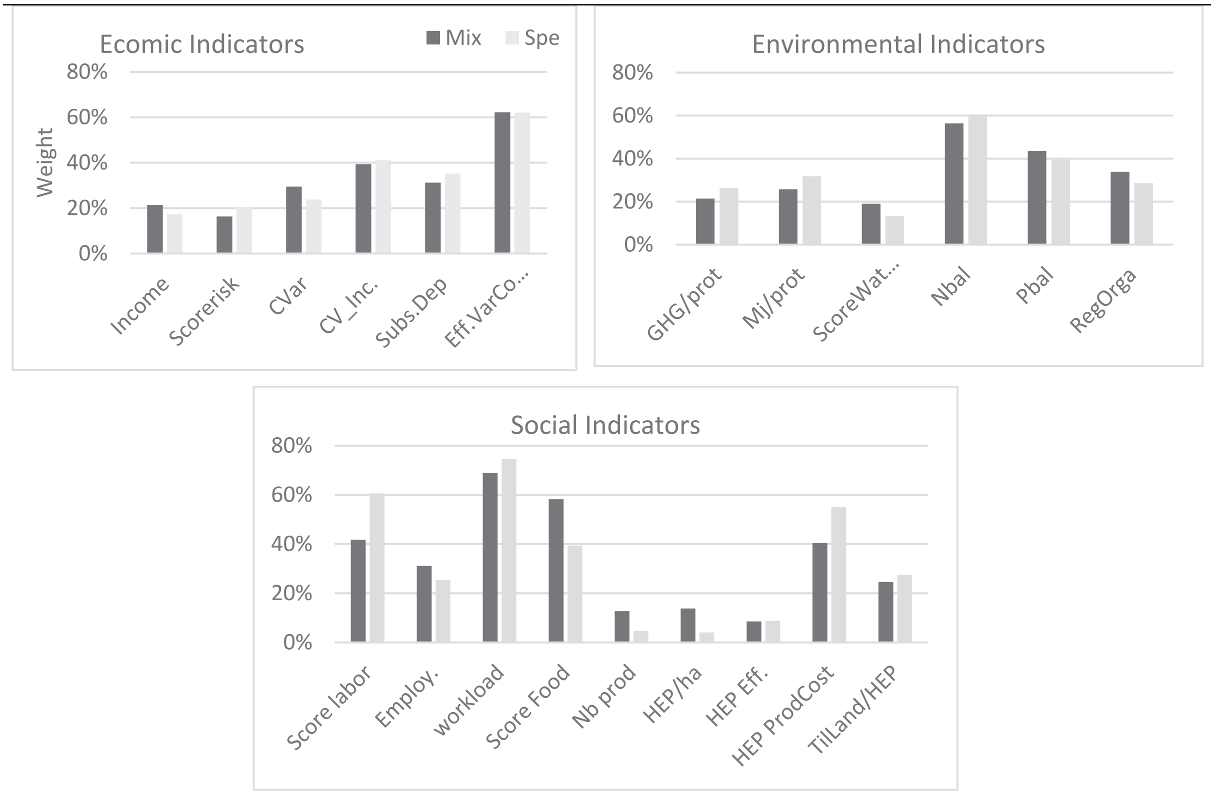

Fig. 5. Average weight of indicators with and without pig production system.

group rather than good or poor in absolute terms, which is close to what BoD methods do. However, some levels of performance of the indicators may be considered unacceptable, such as nitrogen and phosphorus surpluses that are too high relative to the level of water pollution in the area, or, for farmers, a change of system that would reduce their average income. In this case, one could imagine eliminating the farms with one of the results below a critical threshold and adding an indicator of the percentage of farms that have failed to estimate the risk associated with each system.

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

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

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

Interviews with mixed cattle-pig farmers conducted in 2019–2020 in the Massif Central revealed that increased income, income diversification and manure production are the main benefits of pig production for them (Aporthe, 2022). The results of our simulation partly corroborate the farmers’ perception but not totally. We found that the addition of a pig production system increases income per worker. This increase varies greatly depending on the efficiency of pig production, the price of pigs and the price of pig feed negotiated by farmers. In 2020, at national level, pig farms also had a dispersion of gross operating surplus per work unit (between the 10th and 90th percentile) 3.3 times higher than beef cattle production and 2.7 times higher than dairy production (Supplementary Material H, Agreste, 2021). As the gross margin per animal is low and the number of pigs sold is high, it is particularly important to fine tune the pig production system. Diversification does not always go hand in hand with the performance of each livestock activity due to the increasing complexity of systems (de Roest et al., 2018). Farmers with cattle and pig rearing activities should be well organised and advised to manage their system in an efficient and profitable way.

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

The third benefit cited concerned manure production. We simulated that the benefit of reduced mineral fertilizer purchases is offset by additional machinery costs. However, the benefits of organic fertilizers may be greater in the future. In 2022, the price of mineral fertilizers has increased by 80% since 2015 (Agreste, 2022). Although, fuel prices have also increased by 50% and feed prices by 25%, the savings in fertilizers offset the supplementary costs in our simulations. The benefit of pig manure on grassland may also have been underestimated in the simulations. Orfee takes into account the impact of regular addition of organic matter on soil fertility and humus mineralization in the soil. However, Orfee does not take into account the fact that organic matter in mountainous grasslands is less mineralized due to climatic conditions. In this context, the addition of a controlled amount of pig manure can provide a better C/N ratio for soil fertility and increase pasture production (Levasseur et al., 2021). The separation of urine and faeces (De Vries et al., 2013) can also lead to better fertilization. The cost of pig liquid manure could also be underestimated in some cases. The slope and shallowness of the soil in mountainous areas make it more difficult to comply with the future requirement to use spreaders that emit less ammonia. (De Vries et al., 2013).

5. Conclusion

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

The analysis conducted in this study shows that, for the context 2012-2022, the pig production system increased the overall sustainability of cattle farms, more particularly with beef cattle and pig fattening units. Average income per worker unit is increased and income risk decreased but the economic pilar doesn't score better due to the lower efficiency of pig production systems (variable costs to sales ratio). The mixed farms generated more employment, had a higher contribution to food production, lower greenhouse gas emissions per kg of protein produced. Although these results tend to favour mixed pig-cattle farms, it raises issues that need to be addressed in order foster the development of mixed systems, such as securing the pig production and improving fertilization. Keeping the size of the pig farm relatively small compared to the cattle farm can limit economic and environmental risk. Animal welfare and environmental quality for the neighbourhood are also elements that need to be further investigated in future studies.

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

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103692.

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