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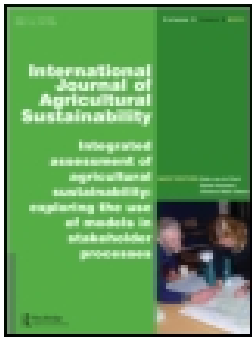
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# Does mixing livestock farming enterprises improve farm and product sustainability?

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## ABSTRACT

Mixed farming systems are gaining interest both as a risk management strategy and to apply agroecological principles. This study set out to assess the sustainability of mixed systems compared to their specialized counterparts. The Orfee bioeconomic farm model was used to simulate three mixed farms: beef and dairy, beef and sheep, and cash crop and beef, under 1990–2017 prices and policies in France. Several sustainability criteria were computed at two scales (i) aggregated farm level, to assess whether mixed farms with several integrated enterprises performed better than if these enterprises were managed in specialized farms, and (ii) unit of product or labour to assess whether a product was produced more sustainably and a worker obtained higher and more stable income in a mixed farm. We found that mixed farms had less work peaks, lower global warming potentials and nitrogen balances, lower total production costs, higher and more stable net incomes than if their enterprises were managed in two specialized farms. However, profitability and income variability of the mixed farms were not better than the best performing specialized farm. The consumption of concentrate feed decreased in the mixed livestock farms but increased in the beef-crop farm that degraded feed-food competition.



## KEYWORDS

Crop-livestock farm;  
multi-species livestock farm;  
bioeconomic model;  
agroecology; economies of  
scope

## 1. Introduction

In developed countries, farming systems are becoming more and more specialized in animal or plant production (Bowman & Zilberman, 2013). This farm specialization has seen an increasing use of pesticides, which contaminate food and the environment (Carvalho, 2006), of synthetic fertilizers and of animal feed supplementation, which breaches nutrient cycles (Lassaletta et al., 2014; Le Noë et al., 2018). Mixed farming systems that can be defined as a farm with several agricultural enterprises are gaining interest among researchers for the application of agroecological principles with integrated management of the different enterprises (Altieri, 1999; Dumont et al., 2013). This integrated management implies that some interactions between enterprises are implemented in order to take advantage of their complementarities. According to Dumont et al.

(2020), diversity of system components and interactions among these components can increase productivity, resource-use efficiency and farm resilience. Crop-livestock systems can reduce mineral fertilizer input by using on-farm organic fertilizer. They can improve soil fertility (Zavattaro et al., 2017) and decrease pesticide consumption by diversifying crop rotation with forage crops (Lechenet et al., 2017). Mixing several ruminant species can make better use of grazed pastures because of their complementary grazing behaviour and reduced parasite pressure (d’Alexis et al., 2014). This can generate economies of scope by reducing the variable production cost of each product compared to their production in separate farms (de Roest et al., 2018). Mixing several enterprises is also a risk management strategy used by farmers (Mishra et al., 2004) to improve their resilience. According to the portfolio theory, a system

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combining productions with different risk patterns exhibits less variance than the weighted average variance of its constituents (Paut et al., 2019). Thus, mixed systems have multiple potential benefits. However, these benefits or detriments are poorly quantified. Some studies have quantified some of the potential economic and/or environmental benefits of integrated crop-livestock systems based either on simulations (Sneessens et al., 2016) or on real farm survey data (Minviel & Veysset, 2021; Veysset et al., 2014; Villano et al., 2010). Fewer studies have investigated the environmental, social and economic benefits of integrating several livestock enterprises and Martin et al. (2020) conclude that further research was needed to better assess the complementarity of livestock species at farm scale.

The objective of this study was to compare the benefits or detriments of different types of mixed farming systems (crop-livestock farming system and mixed livestock farming systems) relative to their specialized counterparts, and to quantify them. Several sustainability criteria were more closely analysed: workload and work peaks, consumption of feed by animals potentially directly consumable by humans, Global Warming Potential (GWP), nitrogen balance, total production cost, average income, overall variability of income and downside risk (Conditional Value at Risk). According to the Fox's paradox (Karagiannis, 2012), the overall performance of a farm may depend on the share of the most or least efficient enterprise in the total farm business; it is possible for a multi-product enterprise to produce each product more efficiently than another, but when all products are considered together, this enterprise may no longer be the most efficient. The criteria were thus computed at two scales, (i) aggregated farm level to assess whether farms with several combined enterprises performed better than if these enterprises were managed in two specialized farms, and (ii) unit of product or worker to assess whether a product was produced more sustainably and a worker had higher and more stable income in a mixed farm.

This analysis was performed by modelling. Although the analysis of real farms makes it possible to evaluate the farm functioning under real conditions, the effects of soil and climate conditions, farm structure, management methods and the many hazards to which the farm is subjected are intertwined and difficult to disentangle. Moreover, the data available on real farm are partial which can make difficult the analysis of some processes occurring on the farm.

Compared with real farm data analysis, modelling offers the possibility to disentangle the effects crop successions, grazing practices, or equipment used on farm performance in mixed versus specialized production systems, other things being equal, and to estimate indicators that would be difficult to measure on real farms. The modelling also allows us to control the effects of the farms' size as well as the respective size and efficiency of each enterprise in mixed farms, which can be the cause of Fox's paradox (Karagiannis, 2012) that can lead to biases in comparing different farms. Mathematical programming farm models also called bioeconomic farm models simulate both economic and biophysical processes (Janssen & van Ittersum, 2007). Of these, mechanistic models that use available knowledge of production processes are well suited to simulate and evaluate how the introduction of an alternative technology or a change in the production context might modify the configuration and performance of the farm. The farm-level optimization algorithm used in these models simulates new combinations of activities that maximize a given objective function and are consistent with specified biological, technical, structural, and regulatory constraints. The farm model Orfee (Mosnier et al., 2017) is particularly suited to the configuration of mixed production systems since it takes into account several complementarities between the different farm enterprises. These complementarities are parameterized according to current knowledge regarding the value of organic fertilization, impacts of one crop on the following ones, on-farm production of feed and litter for animals, value of grazed grass in mixed grazed pasture, possibility to use machines, building and labour for different productions. It also benefits from references from a large database of commercial farms (INOSYS: Charroin et al., 2005). The model allocates resources to the different productions considering these complementarities which enable to assess the impacts of specialized vs mixed systems on different components of sustainability at farm level. Orfee was previously applied to several systems in France (Diakité et al., 2019; Mosnier et al., 2019; Mosnier et al., 2020) and is well adapted to simulate French mixed livestock farming systems.

The context of this study was France and more specifically the Auvergne-Rhône-Alpes region (Centre of France). In 2010, 39% of professional ruminant farms in the region had several agricultural enterprises (Rapey et al., 2018). Mixed dairy and beef cattle farms represented 19% of the region's ruminant

farms and were mainly found in mountain areas. The other diversified ruminant systems (9% mixed crop-meat, 7% mixed crop-milk and 4% mixed beef cattle-sheep for meat beef) were very present in the plains and in the foothills (Rapey et al., 2018). In this study, three typical mixed farming systems were simulated: beef cattle and sheep-for-meat, beef cattle and dairy cattle and beef cattle and cash crops and compared to farms with similar characteristics (utilized agricultural area, yield potential, herd production) but specialized in one enterprise.

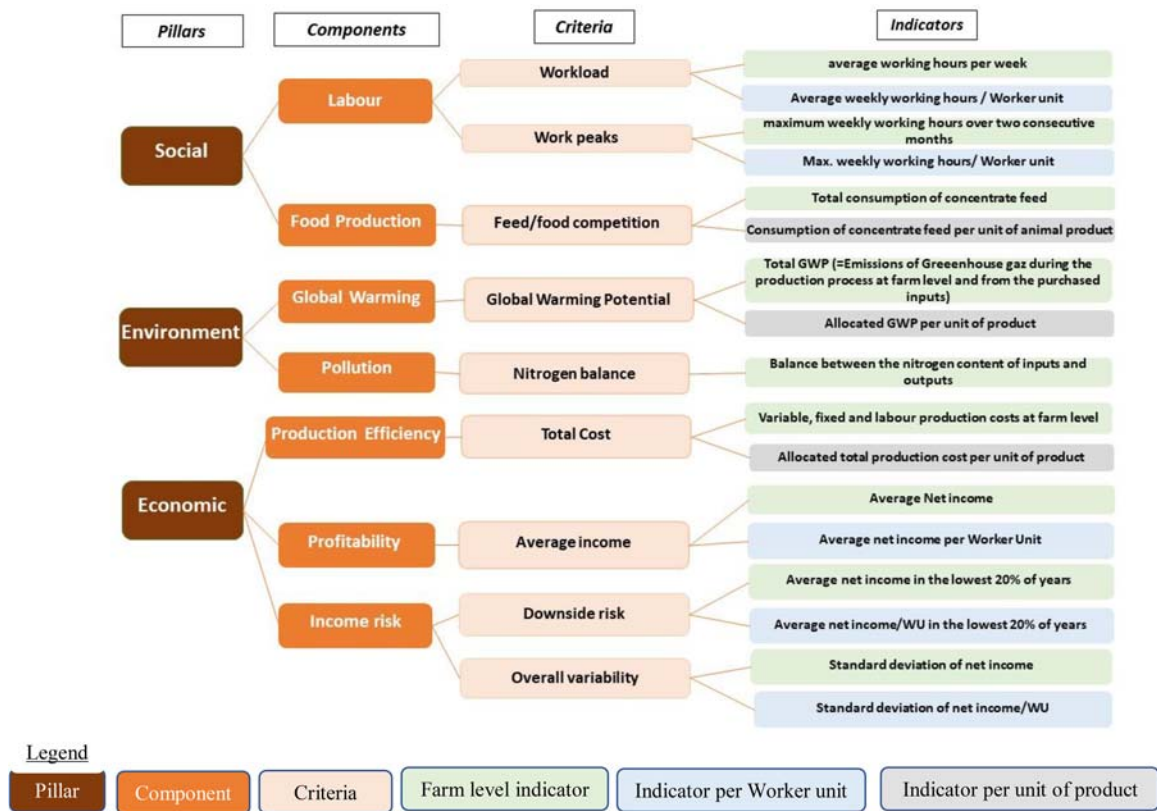
## 2. Materials and methods

### 2.1. Sustainability assessment

The purpose of the evaluation was to test the effectiveness of mixed farm in improving overall sustainability at farm level, and per unit of product or worker. We defined an evaluation tree in which each of the pillars was characterized by different components, which were in turn assessed by a number of criteria that were measured by indicators (Figure 1). The components, criteria and indicators were chosen with the following specifications: (1) providing information on the three pillars of sustainability, (2) potentially impacted by diversification, (3) calculable by the Orfee model. Therefore, the sustainability analysis was not exhaustive. Regarding the social pillar, two components were considered. The first component was labour which was appraised by two criteria: (1) the average weekly workload measured by the number of hours required to care for animals, carry out the field works and manage the farm, divided by the number of weeks in the year and (2) peak workloads, calculated as the highest average of weekly hours over two consecutive months. The second component was food production. Ruminants are criticized for low conversion efficiency of natural resources into edible food (Gerber et al., 2015) but they have the capacity to make use of resources (roughage and products that are produced as a consequence of the production of biofuels, human food, etc.) that cannot be consumed by humans. Concentrate feed can often be directly consumed by humans although in different proportions depending on the nature of the concentrate (Wilkinson, 2011). To keep this indicator simple, the total quantity of concentrate feed consumed by animals (cereals, soybean and rapeseed meals) was used as a proxy of feed food competition.

Regarding the environmental pillar, the Global Warming Potential (GWP) quantified the emissions of methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>) at all stages of agricultural production and for all inputs, from cradle to farm exit gate (Mosnier et al., 2017). The three gases were aggregated by their GWP into a single indicator expressed in CO<sub>2</sub>-equivalent (CO<sub>2</sub>e) with CO<sub>2</sub>=1; CH<sub>4</sub>=28; N<sub>2</sub>O=265 (Myhre et al., 2013). CO<sub>2</sub>e of input purchased were computed based on life cycle assessment (Agribalyse<sup>®</sup>, Koch & Salou, 2014). Direct CO<sub>2</sub> emissions from the burning of fuels were estimated using the Dia'terre<sup>®</sup> method (ADEME, 2010) version 4.51. Emissions arising from the construction of buildings, purchase of seeds, pesticides and spray use and machinery were ignored. CH<sub>4</sub> emissions arise from enteric fermentation and excreta of animals. The enteric methane was calculated according to Sauvant et al. (2011) and Sauvant and Nozière (2016) in order to take into account the quantity and quality of feed, digestive interactions and animal size. To estimate methane from excreta, we used the Intergovernmental Panel on Climate Change (IPCC, 2006) Tier 2 method. N<sub>2</sub>O emissions encompassed direct emissions from manure management (Tier 2; IPCC, 2006) and managed soils (Tier 1; IPCC, 2006), and indirect N<sub>2</sub>O emissions. Indirect N<sub>2</sub>O emissions arise from nitrogen volatilization and leaching (NO<sub>3</sub>). N leaching was estimated based on the nitrogen balance calculated on a farm scale (Simon & Le Corre, 1992) 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). The nitrogen balance was also considered as an indicator of potential pollution.

Regarding the economic pillar, the first component concerned input efficiency and was measured by total production cost. The total production costs included variable costs (purchase of feed and litter, veterinary costs, crop treatments, mineral fertilizers, etc.), fixed costs (fuel, maintenance, rental price of land, taxes, depreciation, and financial costs) and labour cost (workload in hours multiplied by one and a half times the minimum hourly wage in France). The second component was income which was divided into two criteria: profitability and income risk to appraise the farm's potential to provide high and stable income for the farmers. The economic performances of the modelled production systems were assessed over a 18-years period (1990–2017), that is



**Figure 1.** Evaluation tree.

to say 18 different prices and subsidies contexts (see infra 2.4.1.). Profitability was measured by average net income over the period and was defined as animal and crop receipts plus subsidies minus variable and fixed costs. Income risk was measured by (1) the conditional value at risk (CVaR) which corresponds to the average net income in the lowest 20% of years and indicates downside risk (Bell et al., 2021) and (2) the standard deviation of net income as a measure of the overall variability.

The functional unit is a measure of the function of the studied system and provides a reference to which the inputs and outputs can be related. Three functional units were considered: (1) farm level for all indicators, (2) worker unit (WU) for income and workload indicators assuming that the benefits of the farms and total workload were shared among the associate farmers and (3) product unit for production costs, concentrate and GWP. A different functional unit per enterprise was chosen: kilogram of liveweight of animal produced for the beef enterprise and the sheep enterprise, kilogram of milk for the dairy

enterprise, and, for cash crops the average economic value of one ton of cash crop. The production costs (except for taxes, financial costs and other costs) and GWP were allocated to each crop product (e.g. straw and grain) according to an economic allocation for cash crop products and to a mass allocation for forage products (Appendix 1). The production costs were allocated to each animal according to their simulated feed and litter consumptions. Building and equipment costs were allocated to each animal according to the share of the building and equipment used by them.

## 2.2. Estimation of the benefits of mixed systems relative to specialized farms

To assess whether farms with several integrated enterprises performed better than if those enterprises were managed in specialised farms,  $\Delta X_{ij}$ , was calculated as the relative difference for each aggregated farm level indicator  $X$ , between the mixed farm ( $F_{ij}$ ) that jointly managed the enterprises  $i$  and  $j$  in

proportion  $\omega_i$  and  $\omega_j$ , and the weighted sum ( $\omega_i, \omega_j$ ) of farms  $F_i$  and  $F_j$  that managed each enterprise separately (Equation (1)) with  $\omega_i + \omega_j = 1$ .

$$\Delta X_{ij} = 1 - \frac{\omega_i X_{F_i} + \omega_j X_{F_j}}{X_{F_{ij}}} \quad (1)$$

Equation (1) enabled us to measure the economy of scope obtained.  $\Delta X$  is negative when it is less costly to produce two or more outputs jointly within one firm than to produce them separately. The indicator defined in Equation (1) is also in line with the diversification gain  $\Delta\sigma_{ij}$  calculated by (Paut et al., 2019) (Equation (2)) with  $\sigma$  the standard deviation and  $\rho$  the coefficient of correlation, assuming that mixing activities has no impacts on input-output coefficients of each activity.

$$\Delta\sigma_{ij} = 1 - \frac{\sigma_{ij}}{\omega_i\sigma_i + \omega_j\sigma_j} \quad \text{with } \sigma_{ij} = \sqrt{\omega_i^2\sigma_i^2 + \omega_j^2\sigma_j^2 + 2\omega_i\omega_j\sigma_i\sigma_j\rho_{ij}} \quad (2)$$

The second type of indicator aimed at assessing whether one unit of product was more sustainably produced when integrated into a mixed farm or if one worker unit had higher benefits to work in a mixed farm. The indicator  $\Delta Y_{i/ij}$  was calculated as the relative difference for the sustainability criterion  $Y$  between the mixed farm  $ij$  and the specialized farm  $i$  (Equation (3)).

$$\Delta Y_{i/ij} = 1 - \frac{Y_{F_i}}{Y_{F_{ij}}} \quad (3)$$

### 2.3. Scenarios and case studies

The mixed systems were defined on three INOSYS farm types. The INOSYS Breeding Network references (Charroin et al., 2005) are built with real farm data from a large network of commercial farms, and with expert knowledge input. They mirror the coherent running of a well-run farm for a given system and context. The first farm was a mixed beef and dairy farm (Farm-type BL22, Référentiel Cantal, 2016) in the Planèze of Saint-Flour in southern Auvergne mountain areas. The 125 livestock unit (LU) herd consisted of 45% beef LUs from which were sold 8- to 11-month-old weanlings and culled cows and 55% dairy LUs. It had relatively remote and fragmented grassland plots, so that only a limited area could be grazed by dairy cows. Grassland (108 ha) had an average potential of 4.6 tons of dry matter (DM) per

hectare for the first hay cut. It also produced 5 ha of cereals with an average yield of 4.5 t ha<sup>-1</sup>. The second farm was a large mixed farm with beef and sheep (farm type 'Mixtes Ovins dominants - BV', Référentiel Auvergne, 2015) located in the Bourbonnais area in northern Auvergne, a less favoured area. The 170 livestock units comprised 32% beef LUs from which were sold weanlings and culled cows, and 68% sheep LUs from which were sold lambs, culled ewes and rams. Animals were fed from 190 ha of grasslands and 10 ha of cereals (yield 4 t ha<sup>-1</sup>). The third farm (farm type 31060, Référentiel Charolais, 2012) was also a large farm located in northern Auvergne, which mixed 102 ha of cash crop production, 178 ha of forage crops (including some corn silage) with a herd of 257 LUs from which were sold young bulls and heifers, female weanlings and culled cows. Cereals had a yield potential of 6.3 t ha<sup>-1</sup>.

For the mixed farm scenarios (*Beef and Dairy*:  $F_{b+d}$ , *Beef and Sheep*:  $F_{b+s}$  and *Beef and Crops*:  $F_{b+c}$ ), the farm herd sizes and usable area were fixed according to the INOSYS farm type references (Table 1). For the specialized farm scenarios, the number of beef cows, dairy cows or ewes were set to keep the same number of LUs per hectare of forage area i.e. the same stocking rate compared to the mixed system. Imposing similar stocking rates prevented the optimization process from increasing or reducing the production intensity per ha according to the profitability of each enterprise. This could have hidden the effects of complementarity between enterprises. Cash crops acreages remained unchanged for the mixed livestock scenarios. For the beef-crop farm, the specialized beef farm scenario had no cash crop (but could grow corn silage) and the cash crops were proportionally increased in the specialized crops scenario.

The three farm types were used to parametrize crop yields and crop fertilization, field areas (permanent grassland, cash crop areas), animal production (herd size, monthly growth rates, milk production per cow, grazing periods), reproduction performance (e.g. prolificacy and mortality rates, distribution of calving, weaning, cull rate) and prices for each scenario. In each configuration, grassland management (number of cuts and type of harvest), corn silage area, fertilization, animal diets, feed purchase and machinery were optimized according to the model parameters and constraints detailed in next section.

**Table 1.** Farm structure considered for each scenario.

	Beef-Dairy farm			Beef-Sheep farm			Beef-Crops farm		
	F <sub>b</sub>	F <sub>d</sub>	F <sub>b+d</sub>	F <sub>b</sub>	F <sub>s</sub>	F <sub>b+s</sub>	F <sub>b</sub>	F <sub>c</sub>	F <sub>b+c</sub>
Agricultural area (ha)		113			200			-280	
Forage area		108			190		280	0	178
Straw cereals		-5			10		0	184	67
Rapeseed		-0			-0		0	96	35
Animals									
Total herd size (LU)		128			170		404	0	257
Beef Cows (head)	89	0	49	125	0	40	215	0	137
Dairy Cows (head)	0	100	45		-0			0	
Ewe (head)		-0		0	1287	880		0	
Beef production (kgLw.LU <sup>-1</sup> )		-303			-332			-370	
Milk production (1000L.DC <sup>-1</sup> )		-6.4							
Sheep production (KgCarc.Ewe <sup>-1</sup> )					-25				
Max annual hour.WU <sup>-1</sup>		-2350			-3000			3000	

Notes: F<sub>b</sub>, F<sub>d</sub>, F<sub>s</sub>, F<sub>c</sub>: resp. farm specialized in beef, dairy, sheep and cash crops; LU: livestock unit, kg LW: kilogram liveweight, DC: dairy cow, kgcarc: kilogram of carcasse.

## 2.4. Model description

### 2.4.1. Model overview

This study used the bioeconomic optimization model Orfee (Figure 2), a simulation model designed to explore livestock systems associated with grassland and cash crop production in France (Mosnier et al., 2017). The model was implemented using the mathematical modelling platform of the General Algebraic Modeling System<sup>®</sup> (GAMS Development Corporation, Washington, DC) (McCarl et al., 2004) and used the mixed integer programming solver CPLEX.

Orfee was used in this study to optimize production decisions including pasture management, animal feeding, fertilization, and machinery for fixed herd size and cash crop areas and to estimate the different indicators described in section 2.1 and 2.2. The simulated decisions were optimized to maximize the average farm profit for the economic context of the period 1990–2017 under agronomic, structural, regulatory and economic constraints. It simulates the annual production of a farm at equilibrium, which means that crop production, animals, machinery and labour are the same from year to year under average climate conditions. Profits which was defined as animal and crop receipts plus subsidies minus variable, fixed and labour costs (wages and opportunity costs for associate workers), and taxes were calculated for different economic context characterized by the annual prices and subsidies that occurred over the period 1990–2017. Prices were indeed the main cause of income variability for French beef farms (Mosnier et al., 2010) and crop farms (Agreste, 2018), and a major cause of variability for French sheep farms (Benoit et al., 2020); public

supports are the main source of income for beef and sheep producers in France (Veysset et al., 2015). Price variations between years were calculated as a reference price calibrated according to the farm type reference, multiplied by the index of price variation (respectively the index of producer prices of agricultural products, PPAPI, and the index of purchase prices of the means of agricultural production, PPMAPI, for the products and inputs), and deflated annually by the consumer price index. These indices were computed by the French national institute of statistics and economic studies.<sup>1</sup> The main national and European subsidies granted to bovine, ovine and crop productions between 1990 and 2017 were taken into account (Mosnier et al., 2017). Risk reduction was not modelled as an objective but was analysed from simulation outputs.

### 2.4.2. Interactions and complementarities between the different farm enterprises

**2.4.2.1. Agronomic interactions and complementarities.** Crop-livestock interactions were first modelled through crop rotation constraints. Fertilization requirements were set up according to COMIFER (2013). The destruction of grasslands will supply around 50 kgN ha<sup>-1</sup> to the following crop. In the short run, organic manure has a direct fertilization effect, with 10–20% of nitrogen content, 80% of phosphorus content and all the potassium content usable directly by plants. In the long run, organic manure increases the mineralization of organic matter into nitrogen available for plants (≈10 kgN/ha/year). In addition, harvesting straw used for animal litter reduces nitrogen requirements for crops by 10 kg/



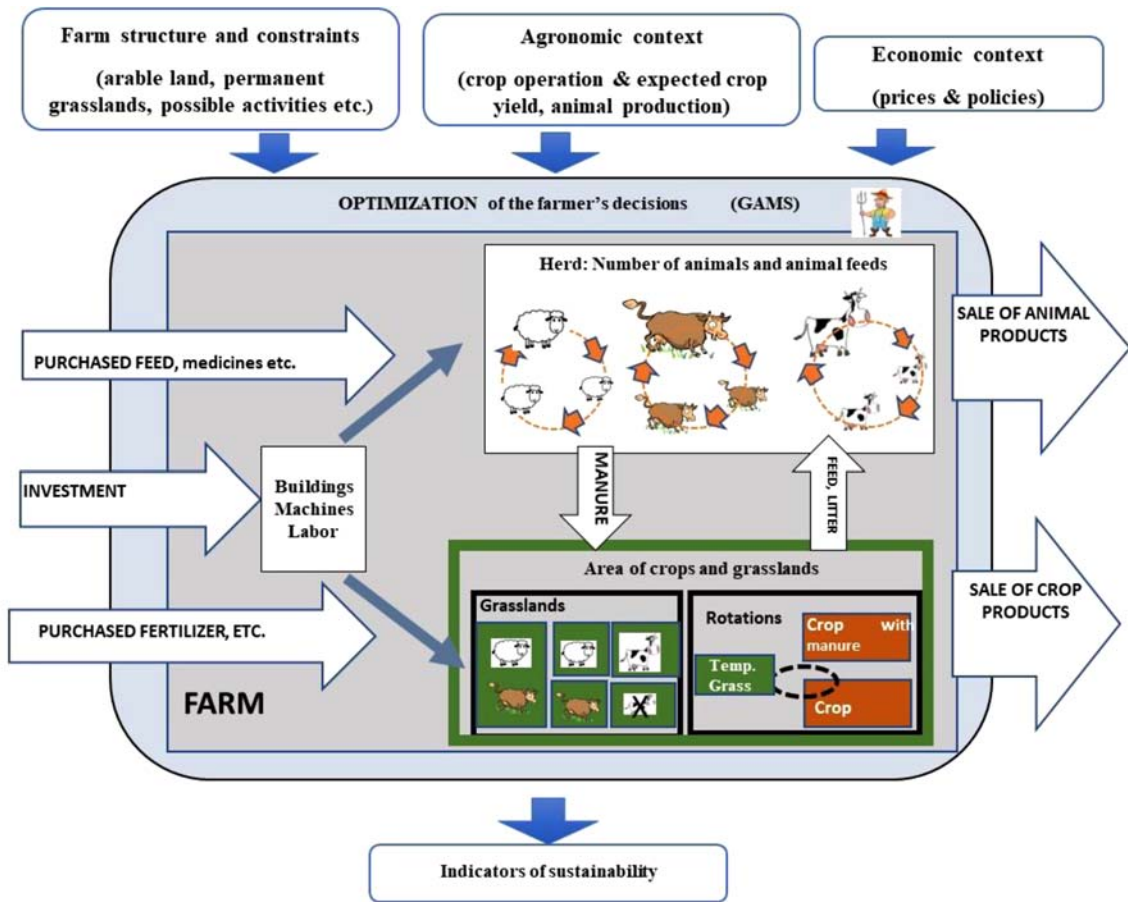


Figure 2. Representation of the Orfee Model.

ha/year (on the short run, less nitrogen is required by microorganisms to degrade straw).

Animal diets and grassland management were optimized on a monthly basis. Diets had to meet the animals' requirements relative to energy and digestible protein in the intestine allowed by energy and nitrogen and match their intake capacity (Inra, 2007) with a minimum fill value of the diet of 80% of the animal intake capacity. The diet also had to be balanced in energy and protein and starch must not exceed 22% of the dry matter ingested, except during the fattening phase (35%) to ensure a proper rumen function. Grassland management (haymaking, silage, grazing, etc.) was constrained by farm structure. In highly fragmented parcels, dairy cows that had to be milked twice a day often had no access to remote pastures; a constraint on the area that could be grazed by dairy cows was thus included (Diakité et al., 2019). Regarding sheep production, as sheep

are lighter than beef cattle, the risk of trampling is reduced. We considered that a fraction of sheep could stay outdoors and graze the grass carryover during winter without degrading the pasture provided their stocking rate was low (0.15 LU/ha forage area). Beef and sheep have different intake preferences with sheep being more selective than cattle. Co-grazing can modify the sward botanical composition. Based on Cuchillo-Hilario et al. (2018), we assumed that the pasture quality was 5% lower for sheep-only systems than for mixed sheep and beef and beef-only systems. This assumption is relatively conservative, taking into account the variability in the results of Cuchillo-Hilario et al. (2018).

**2.4.2.2. Complementarities for mechanization.** Several crop operations are necessary for each cropping activity (seeding, treatment, manure spreading, harvesting, etc.). Either own on-farm machinery

could be used or in some cases external operators (generally cereal harvesting, silage and silage baling were done with machinery in co-ownership or by external operators). In average, three types of machinery were available for a given crop operation. They differed in their cost, speed and fuel consumption. Machinery cost was proportional to its use, but minimum depreciation costs were imposed as long as the machine was owned<sup>2</sup> to reflect that even if the equipment was little used it would not last for ever. Consequently, the cost of the machine can be diluted if it is used more intensively.

**2.4.2.3. Labour complementarities considered between activities.** Labour requirements encompassed crop operation, herd management and global farm monitoring (18% of labour requirement for crop and herd management). Labour associated with crop activities was proportional to the time calculated to carry out the different crop operations with the owned machinery selected. The time to manage the different herds included the time to monitor births and new-borns during their first days of life, milk dairy cows, feed animals, clean and replenish litter, and otherwise handle animals (vaccinations, seasonal operations and other). We calibrated the workload per associate worker unit to match the number of worker unit of the case study: at most 3000 h.year<sup>-1</sup> for the beef-sheep and beef-crop farms and 2500 h.year<sup>-1</sup> for the beef-dairy farm, with peak workloads not exceeding 30% of the average monthly workload.

### 3. Main results

#### 3.1. Social indicators

##### 3.1.1. Labour

The number of working hours was slightly modified by the combination of the two enterprises (Table 2). It increased in the mixed beef-crop farm (2%) and in the mixed beef-dairy farm (1%) but slightly decreased in the beef-sheep farm. The sizes of some machines were indeed adjusted by the model according to need. For instance, the plough had two units in the specialized beef farm, five units in the mixed farm and six units in the specialized cash crop farm. Ploughs with fewer units had lower depreciation cost but higher labour requirement. Mixing activities smoothed peak workloads (Figure 3). Assuming that no temporary worker was hired during those peaks,

mixing different activities enabled to reduce the number of Workers Units. This reduction was the highest for the situations where both specialized enterprises had high but different work seasonality. A 5% and 6% reduction of required WU were respectively simulated for the beef-sheep farm and the beef-crop farm but with a higher workload per WU (Table 3).

##### 3.1.2. Feed-Food competition

The combination of two livestock enterprises enabled an average 16% reduction in the consumption of concentrate feed (Table 3). The lower consumption of concentrate by the sheep in the mixed beef-sheep farm was mainly explained by the better quality of the grazed grass in the presence of the cattle. In the mixed beef-dairy farm, more grazing area was accessible per dairy cow compared to the specialized dairy farm and more grazed grass was available for beef cattle in early summer due to a higher proportion of grassland harvested for silage early in the season in the mixed farm (Table 2). Conversely, the consumption of concentrate feed increased in the beef-crop farms (14%), since it became cheaper to consume more on-farm produced cereals but less corn and grass silages. Contrary to the mixed livestock farms, the crop livestock farm did not reduce feed-food competition.

#### 3.2. Environment

The nitrogen balance measured the difference between nitrogen inputs and nitrogen outputs (Table 3). The balance was improved by 5% in the mixed livestock farms due to lower purchases of concentrates and a slight decrease in fertilizer purchases. The improvement was stronger (70%) for the beef crop farm due to the important reduction of fertilizer purchases (Table 2).

For the mixed livestock farms, the reductions of the total GWP ranged between 1% and 2% due to the reduction in purchases of concentrate feed, partly offset by higher enteric emissions (lower in diets rich in concentrate feed). In most cases, the integration of another enterprise also reduced GWP per unit of product, most of all for the sheep (4%) and dairy (3%) enterprises, which enjoyed improved pasture quality or a greater proportion of accessible pasture. The GWP reduction was highest for the beef-crop farm (8%) and benefited more particularly for the crop enterprise (38%), in which fertilizer use was reduced.

**Table 2.** Technical and economic indicators simulated.

		Beef-Dairy farm				Beef-Sheep farm				Beef-Crops farm			
		F <sub>b</sub>	F <sub>d</sub>	F <sub>b+d</sub>	$\Delta X_{bd}$	F <sub>b</sub>	F <sub>s</sub>	F <sub>b+s</sub>	$\Delta X_{bs}$	F <sub>b</sub>	F <sub>c</sub>	F <sub>b+c</sub>	$\Delta X_{bc}$
Labour	<b>w<sub>i</sub></b>	0.45	0.55	1.00		0.32	0.68	1.00		0.6	0.4	1.0	
	Working hours	3298	5925	4796	1%	3595	5744	5030	-1%	7999	1129	5601	2%
	Worker Unit	1.3	2.4	1.9	1%	1.2	2.3	1.8	-5%	2.7	0.8	1.9	-6%
	Grazed grass (DM)	278	169	240	9%	493	573	549	0%	914		559	-4%
Feed	Hay. grass (DM)	115	89	114	12%	279	199	215	-4%	354		277	19%
	Silage grass (DM)	170	316	235	-6%					191		113	-8%
	Corn silage (DM)									190		67	-81%
	Feed Self Sufficiency (% DM consumed)	91%	78%	86%	2%	89%	84%	90%	4%	71%		90%	50%
Machine and building	Number	11	11	11	0%	11	11	11	0%	9	6	12	34%
	Machine (k€)	16.6	16.9	15.7	-7%	15.0	15.4	14.5	-5%	20.3	16.2	21.7	13%
	Building (k€)	11.0	18.0	14.7	-1%	11.3	10.0	10.2	-2%	4.1		2.6	0%
Fertilization	Forage area (k€)	6.2	8.2	7.2	-1%	5.5	6.3	6.0	-1%	0.0		1.1	-99%
	Cash crop area (k€)	0.6	0.6	0.6	0%	0.4	0.4	0.4	5%		51.6	11.7	-60%
Economics	Sales (€)	102	271	195	0%	158	178	172	0%	342	329	339	0%
	Fixed costs (k€)	86	127	109	0%	105	114	111	0%	152	140	156	5%
	Variable costs (k€)	43	84	61	-8%	64	67	63	-6%	163	143	135	-15%
	Labour costs (k€)	40	71	58	1%	43	69	60	-1%	96	14	67	2%

Notes: F<sub>b</sub>, F<sub>d</sub>, F<sub>s</sub>, F<sub>c</sub> resp. farm specialized in beef, dairy, sheep and cash crops. w<sub>i</sub> weight of enterprise i in the mixed farm.  $\Delta X_{ij} = 1 - \frac{\omega_i \chi_{Fi} + \omega_j \chi_{Fj}}{\chi_{Fij}}$ ; DM: dry matter.

### 3.3. Economic indicators

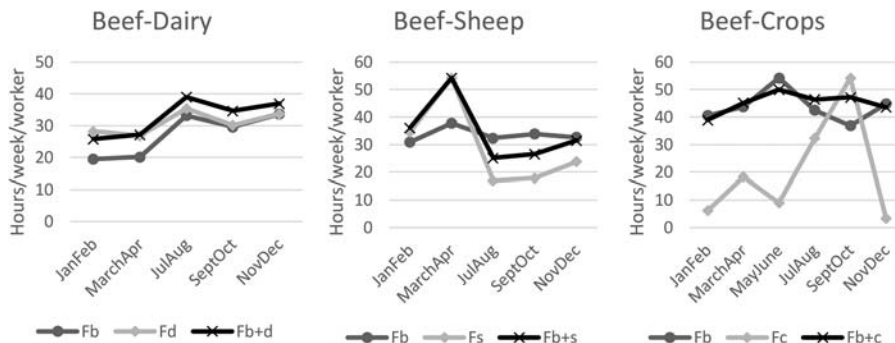
#### 3.3.1. Input efficiency

The simulated results showed that it was less costly to produce two or more outputs jointly within one farm than to produce them separately (Table 3), underlying economies of scope for all three types of mixed farms. The gain in total production costs for an equal quantity of outputs produced was in average 2%. Compared to the specialized farms of similar size, mixing livestock enterprises had almost no impact on fixed costs since all of the simulated machines were used by both herds. Fixed costs were increased by 5% for the beef-crop farm. The mixed farm had more machines (Table 2) since some machines were specific to each enterprise. Consequently,

depreciation and maintenance costs were higher for the mixed beef-crop farm in spite of some adaptations of the size of machines to farm need (see Section 3.1). The largest cost reduction came from variable costs (between 6% and 15%). It was the result of lower concentrate purchases for the mixed livestock farms, lower fertilizer purchases and extensification of fodder area management for the beef-crop farm.

#### 3.3.2. Income

Owing to economies of scope, integrating two enterprises in a mixed system increased income by approximately 10% for the mixed livestock farms and 19% for the beef-crop farm relative to the simple weighted addition of the income of each enterprise (Table 3).

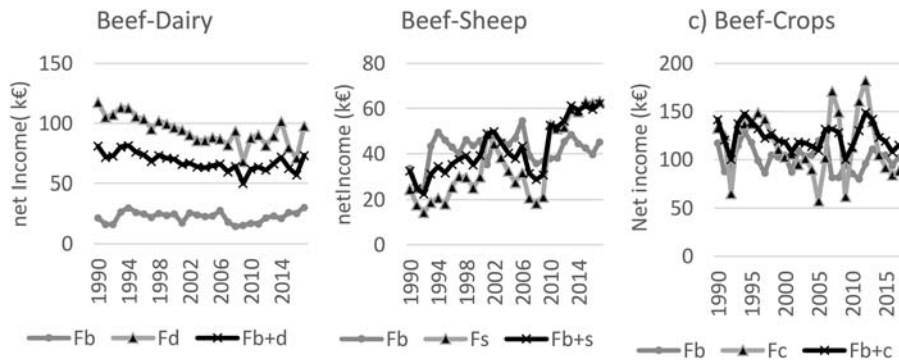
**Figure 3.** Workload distribution in the year.

Notes: F<sub>b</sub>, F<sub>d</sub>, F<sub>s</sub>, F<sub>c</sub> resp. farm specialized in beef, dairy, sheep and cash crops.

**Table 3.** Impact of mixing farming enterprises on some sustainability indicators.

Social	$w_i$	Beef + Dairy			Beef + Sheep			Beef + Crops			Beef + Crops							
		$F_{b1}$	$F_d$	$F_{b+d}$	$\Delta X_{bd}$	$\Delta Y_{b1/bd}$	$\Delta Y_{d/bd}$	$F_{b2}$	$F_s$	$F_{b+s}$	$\Delta X_{bs}$	$\Delta Y_{b2/bs}$	$F_{b3}$	$F_{c}$	$F_{b+c}$	$\Delta X_{bc}$	$\Delta Y_{b3/bc}$	$\Delta Y_{c/bc}$
Workload	hr.week <sup>-1</sup>	63	114	92	1%	0%	0%	69	110	97	-1%	-10%	154	22	108	2%	0%	52%
Work Peaks	max hr.week <sup>-1</sup>	48	48	48	-9%	0%	0%	58	48	52	-1%	8%	58	27	58	-9%	0%	5%
Concentrate feed	ton	63	60	57	-17%	-10%	-6%	69	75	75	-10%	8%	65	59	63	-16%	-4%	5%
	t.kg <sup>-1</sup> beef	1.5	1.0	1.0	-42%	-10%	-10%	1.8	1.6	1.6	-4%	-8%	2.1	2.4	2.4	-19%	14%	14%
	t.kg <sup>-1</sup> other *	0.3	0.2	0.2	-6%	-6%	-6%	4.8	4.1	4.1	-2%	-2%	5.5	0	21	-70%	-38%	-38%
Environment Nitrogen Balance	Kg N.ha <sup>-1</sup>	62	64	60	-1%	0%	-3%	63	73	66	-5%	1%	69.5	418	1138	-8%	-3%	-3%
GWP (CO <sub>2</sub> e)	ton	567	679	621	-1%	0%	-3%	758	733	726	-2%	-2%	11.3	10.9	10.9	-4%	-6%	-6%
	kg.kg <sup>-1</sup> beef	15.3	15.3	15.3	-2%	-4%	-3%	13.7	13.8	13.8	-4%	-1%	11.4	10.9	10.9	-3%	-3%	-3%
	kg.kg <sup>-1</sup> other*	1.3	1.2	1.2	9%	52%	-12%	217	256	239	-2%	-1%	411	297	358	-3%	-6%	-15%
Economics Total Cost	€	169	282	227	9%	52%	-12%	343	342	342	-3%	-3%	256	180	156	19%	42%	-122%
	€:kg <sup>-1</sup> Beef	399	435	422	15%	60%	-7%	42	36	42	11%	-41%	35	44	47	26%	45%	-61%
	€:kg <sup>-1</sup> other*	22	94	68	18%	-18%	-33%	31	16	22	21%	59%	38.1	147.0	66.1	-28%	28%	-465%
Average net income	€	17	40	35	11%	11%	11%	31	17	28	21%	18%	5.1	7.2	6.3	18%	18%	18%
CVaR	€	16	77	58	15%	60%	-7%	23	8	14	-12%	-12%	6.8	5.3	4.9	-28%	28%	28%
SD net Inc.	€	12	32	30	18%	-18%	-33%	6.9	16	12	-12%	-12%	5.1	40.4	7.2	28%	28%	28%
	€:WU <sup>-1</sup>	4.5	12	7.4	11%	11%	11%	5.1	7.2	6.3	11%	11%	5.1	40.4	7.2	28%	28%	28%
	€:WU <sup>-1</sup>	3.4	5.1	3.8	11%	11%	11%	5.1	7.2	6.3	11%	11%	5.1	40.4	7.2	28%	28%	28%

Notes:  $F_b$ ,  $F_d$ ,  $F_s$ ,  $F_c$ : resp. farm specialized in beef, dairy, sheep and cash crops.  $w_i$  weight of enterprise  $i$  in the mixed farm.  $\Delta X_{ij} = 1 - \frac{\omega_i X_{Fi} + \omega_j X_{Fj}}{X_{Fij}}$ ;  $\Delta Y_{ij} = 1 - \frac{Y_{Fi}}{Y_{Fij}}$ ; WU: Worker Unit; LU: livestock unit, kg LW: kilogram liveweight, \* per kg of liveweight of sheep, per kg of milk or per average economic value of one ton of cash crop. CVaR: Conditional Value at Risk of the 20% lowest net income; SD: Standard Deviation of net income.



**Figure 4.** Evolution of net income between 1990 and 2017 for the (a) Beef-Dairy farm, (b) Beef-Sheep farm and (c) the Beef-crops farm. Notes: Fb, Fd, Fs, Fc resp. farm specialized in beef, dairy, sheep and cash crops.

Considering the prices and subsidies recorded over period 1990–2017, the value at risk increased also in all mixed farms, especially on the beef-crop farm (26%), indicating that mixed farm had lower exposure to the risk of low income. Mixed farms exhibited lower standard deviation of income than the weighted sum of each specialized enterprise managed separately which means that incomes of mixed farms were more stable. The reduction of standard deviation of income was the highest for the beef-crop farm (–28%) which had the lowest coefficient of correlation between the two enterprises (–0.22).

The mixed farms exhibited higher average income and lower income risks than the weighted averaged of each enterprise managed separately. If the difference in average income between the two enterprises had been small, one might have expected that each specialized farm would have had an incentive to diversify in order to increase its average income. This is not the case in this simulation. The mixed farm incomes were generally not better than the best performing specialised enterprise alone, for a given indicator. With the parameters considered for these three farm types, the crop enterprise generated the highest income per worker unit, the dairy enterprise came second and the sheep enterprise was the least profitable (Table 3). The beef enterprise incomes were rather low but differed between farms according to the animal productivity, labour productivity, grassland potential, subsidies and prices associated to each farm (Appendix 2). The enterprises which had the highest income per WU reduced their average income per WU by diversifying. For instance, the farm specialized in cash crop

production lost income per WU by adding beef. The value at risk varied generally in the same direction since the whole income distribution was moved upward or downward by the introduction of a more or less profitable enterprise. Regarding the standard deviation, aggregating one enterprise to a riskier one resulted in an increase in income variability. There was a trade-off between the gain in average income and the reduction of income standard deviation except for the beef-sheep farm for which the sheep enterprise was both riskier and less profitable. Nonetheless, the Figure 4 showed that over the period 2013–2017, the difference in profitability between the different enterprises was reduced and the sheep enterprise became more profitable.

#### 4. Discussion

In this study, the functioning and some indicators of performance of mixed farms and their counterpart specialized farms were estimated with the Orfee model. Simulations showed that in most cases, mixing different productions globally improved the sustainability indicators compared with the separate management of these productions.

Significant input savings were simulated for the mixed livestock systems due to their complementarity in the use of grassland resources. The better use of grass was also cited as a major advantage of mixed systems by 84% of the farmers surveyed in Auvergne by Mugnier et al. (2020) but the practices of co-grazing are heterogenous: cows and sheep graze either simultaneously, successively or in separate parcels. Further research is required to fine-tune the

simulations for effects of co-grazing according to practices on parasites, herbage availability, group behaviour and sheep production, but also on predation (Anderson et al., 2012). In a context of heterogeneous plant resources, considering the ability of sheep to graze on rangelands, intercropping and fallow land would make this production all the more complementary to cattle production or cash crops (Villano et al., 2010). Regarding mixed beef and dairy farms, the reduction of variable costs for the dairy enterprise was namely dependent on the grazing areas accessible to dairy cows. These areas are highly variable between farms. As a consequence, the share of dairy and beef cows should be adapted to each farm structure (Diakité et al., 2019). Integrating crop and beef saved purchased fertilizers and made better use of the straws, which were partly buried in specialized crop systems. However, as also reported by Veysset et al. (2014), the consumption of concentrate feed increased in the simulated crop livestock farm because these on-farm cereals became cheaper than some grass-based or corn-based forages. This raises the issue of feed-food competition, as most of the cereals could directly be consumed by humans (Wilkinson, 2011).

Like Diakité et al. (2019) or Sneessens et al. (2016), we found that mixing agricultural enterprises increased average income per farm compared to the weighted sum of each enterprise run separately. In Veysset et al. (2014), most of the surveyed mixed crop-beef farms in France did not obtain a higher income than specialized beef farms due to a less efficient use of inputs, except for a quarter of the mixed farms that made economies of inputs (Minviel & Veysset, 2021). We simulated a 13% increase of mechanization costs in the beef-crop farm. The beef farm grew corn silage and required machines for ploughing, spreading etc. that were also used to produce cash crops. The difference in fixed costs would have been greater if the specialized beef farm had been 100% grassland based. Limited labour availability can also lead to invest in time-saving but costly machines that reduce the performance of mixed farm. Veysset et al. (2014) suggested that the crop livestock farms simplified their practices, missing potential economies of scope. Farmers may perform less well when managing larger and more complex systems (de Roest et al., 2018; Kingwell, 2011), since managing several activities on a farm requires more skills and time to acquire knowledge and market products. This difficulty in developing the double skill set may be

less important for two meat livestock production: only 40% of the beef-sheep farmers surveyed (Mugnier et al., 2020) mentioned the problem of double skill as a limit of mixed livestock farming systems.

Regarding the evolution of income over time, this analysis isolated the effects of price and market variability. We also found that mixing agricultural enterprises reduced income risk per farm compared to the weighted sum of each enterprise income run separately. It confirms the perception of the beef-sheep farmers surveyed, 86% of whom cited income security as one of the main advantages that led them to opt for a mixed system (Mugnier et al., 2020). We demonstrated in this study that the benefit of integration was not equally shared within the two enterprises: the mixed systems were less profitable together than the more profitable enterprise alone. Nonetheless, there were some trade-offs between profitability and variability, as underlined by (Chavas, 2008; Kim et al., 2012), and a more profitable enterprise such as cash crops could take advantage of livestock production to reduce income variability. The simulated evolution did not mirror that of real trends, since we did not account for the evolution of the production systems. Over this period, farms grew significantly, while the number of workers remained stable. This expansion was made possible by a marked increase in mechanization costs and in the consumption of concentrated feed (Veysset et al., 2015). Other hazards also arose, such as crop production variations due to weather, pest and weed hazards or a high variability of ewe reproductive performance. These could have both reduced income variability assuming production and price risks to be independent, but they could also have increased the risk exposure of the enterprise that was more sensitive to production risks such as crops or sheep.

Mixed farming systems reduced GWP through the reduction of input consumption, while maintaining production levels. These reductions were moderate (less than 2% at farm level for mixed livestock farm, 8% for the crop livestock farm). However, Mosnier et al. (2019) state that little GWP abatement can be achieved in livestock production at a low cost without reducing production level. In addition, the reduction of parasite pressure and the better quality of the grass would make it possible to sell younger animals (d'Alexis et al., 2014), which would reduce GWP. Mixed farming systems thus offer an interesting win-win strategy to reduce emissions and improve other indicators of sustainability.

## 5. Conclusion

The objective of this work was to quantify the potential benefits of integrating two agricultural productions within the same farm. Its originality lies in the assessment of these benefits in several components of sustainability: labour, average income, income variability, production costs, feed concentrate consumption and greenhouse gas emissions, and with two scales: aggregated performance at farm scale (the combined farms perform better than the weighted sums of each enterprise run independently) and per unit of product or labour performance (whether a product was produced more sustainably and a worker had higher and more stable income in a mixed farm). We analysed these benefits considering potential complementarities between the farm enterprise regarding the sharing of machinery, the distribution of work over the year, the benefits of manure and grasslands for cash crops, and the use of grasslands.

Mixed farms improved most indicators of aggregated performance, except for the workload per worker unit and the beef-crop farm consumption of concentrate feed, which increased. As expected, the simulated mixed systems always exhibited higher and less variable income than the weighted sum of the separate enterprises. Nonetheless, adding a very risky enterprise or much less profitable one could increase the income variability or reduce average income per worker unit relative to the specialized system. To support these promising systems, the CAP should continue to modify support in order to reduce the incentive to specialize in the most profitable enterprise and the self-insurance properties of diversified systems should be considered in insurance schemes. Outsourcing more tasks could also help to reduce fixed costs and skill needs in mixed farming systems.

## Notes

1. Indices are IPPAP, IPAMPA and 'indice annuel des prix à la consommation – ensemble des ménages': Insee <https://www.insee.fr/fr/statistiques?debut=0&theme=30&conjoncture=49>
2. Source: *Entraide*: <http://www.hautsdefrance.chambres-agriculture.fr/exploitation-agricole/gerer-son-exploitation/fermages-baremes/bareme-entraide/>

## Disclosure statement

No potential conflict of interest was reported by the author(s).

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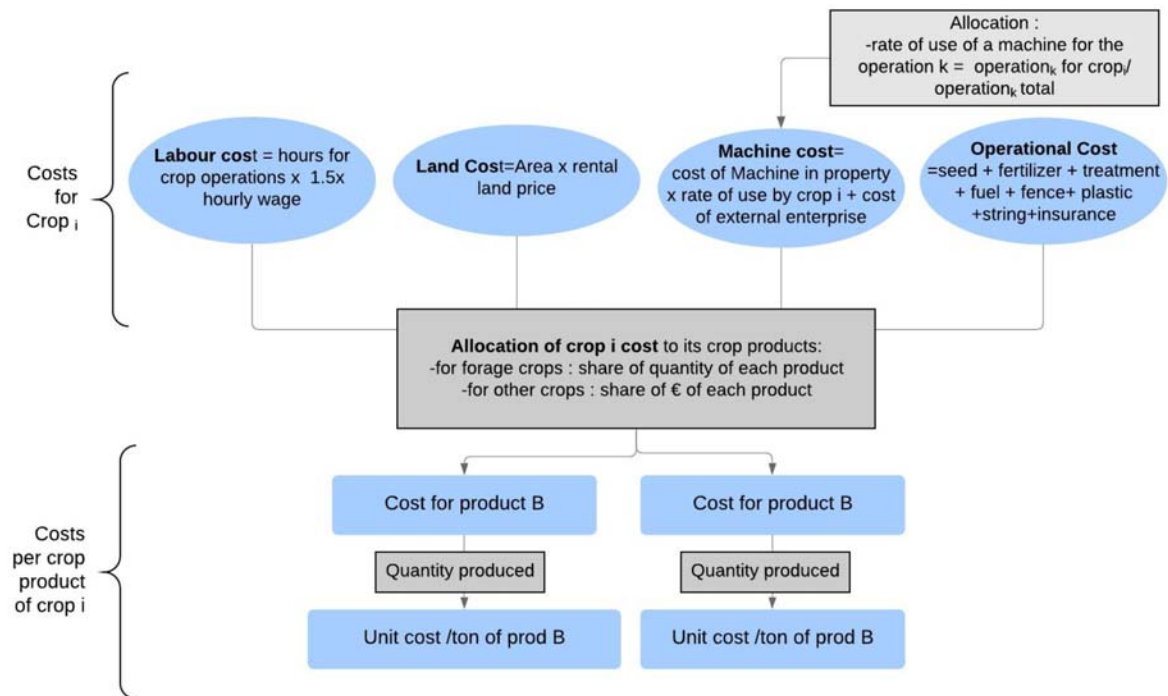
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## Appendices

### Appendix 1. Calculation of crop product unit production costs



**Appendix 2. Comparison of the simulated results for the reference year of each farm type**

	Beef-Dairy		Beef-Sheep		Beef-Crop	
	Ref <sup>a</sup>	Base	Ref <sup>b</sup>	Base	Ref <sup>c</sup>	Base
Dairy cows or ewes (head)	49	49	840	840		
Beef cows (head)	45	45	40	40	137	137
Beef meat sold (kgLW/LU)	312	303	328	332	372	370
Sheep meat sold (kgcarc/ewe)			24.3	24.7		
Milk produced (1000 L/cow)	6.4	6.4				
Concentrate for beef (kg /LU beef)	404	166	546	471	780	880
Concentrate in kg/1000 L for dairy	231	252				
Concentrate in kg/ewe for sheep			110	80		
Forage harvested (tons DM)	342	334	224	215	449	456
Animal sales (k€)	157	158	158	165	204	214
Cash crop sales* (k€)	3	3	5.6	5.2	148	135
Subsidies (k€)	59	59	72	77	102	95
Operating costs (k€)	66	65	70	66	131	139
Fixed costs (k€)	109	109	127	112	202	155
Net income (k€)	44	44	39	71	123	149

Notes: Base: scenario where the number of reproductive females, the type of animals produced and land use are fixed according to the farm type reference and the reference year.: <sup>a</sup>Farm-type BL22, Référentiel Cantal, 2016, <sup>b</sup> Farm-type 'Mixtes Ovins dominants – BV', Référentiel Auvergne, 2015, <sup>c</sup> farm type 31060, Référentiel Charolais, 2012. [http://idele.fr/no\\_cache/recherche/publication/idelesolr/recommends/cas-types-bovins-lait.html](http://idele.fr/no_cache/recherche/publication/idelesolr/recommends/cas-types-bovins-lait.html) (Retrieved March 2020).