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ABSTRACT

Combining several animal species to optimise the performance of the whole farming system is one of the core tenets of agroecology. Here, we associated sheep with beef cattle (40–60% livestock units (**LU**)) in a mixed system (**MIXsys**) and compared its performances to those of a specialised beef cattle-only system (**CATsys**) and a specialised sheep-only system (**SHsys**). All three systems were designed to have identical annual stocking rates and similar farm areas, pastures and animals. The experiment was conducted for four campaigns (2017–2020) in an upland setting exclusively on permanent grassland under certified-organic farming standards. The young animals were fattened almost exclusively with forages: at pasture for lambs and indoors with haylage in winter for young cattle. Abnormally dry weather conditions led to hay purchases. We compared between-system and between-enterprise performances based on technical, economic (gross product, expenses, margins, income), environmental (greenhouse gas emissions (**GHG**), energy consumption) and feed–food competition balance indicators. The mixed-species association only benefited the sheep enterprise, with +17.1% meat production per LU ($P < 0.03$), −17.8% concentrate used per LU ($P < 0.02$), +10.0% gross margin ($P < 0.07$) and +47.5% income per LU ($P < 0.03$) in MIXsys vs SHsys, as well as environmental performance benefits via a reduction of 10.9% in GHG emissions ($P < 0.09$) and 15.7% in energy consumption ($P < 0.03$), and a 47.2% improvement in feed–food competition ($P < 0.01$) in MIXsys vs SHsys. These results are due to both better animal performance and lower concentrate consumption in MIXsys, as presented in a companion paper. These benefits outweighed the additional costs of the mixed system, especially for fencing, in terms of net income per sheep LU. There were no between-system differences in productive and economic performance (kilos live-weight produced, kilos concentrate used and income per LU) for the beef cattle enterprise. Despite good animal performances, the beef cattle enterprises in both CATsys and MIXsys had poor economic performance due to large purchases of conserved forages and difficulty selling the animals, which were ill-adapted to the traditional downstream sector. This multiyear study at the farming-system level, which has thus far been underresearched for mixed livestock farming systems, highlighted and quantified the benefits for sheep when combined with beef cattle on economic, environmental, and feed–food competition performance.

Implications

Associating sheep and beef cattle in a 40–60% livestock unit mix improved the economic and environmental performances of a mixed system compared to beef cattle-only or sheep-only systems. The economic and environmental performance of the sheep enterprise was higher in the mixed system than in the specialised system due to better animal performance and lower feed purchases. Conversely, there were no between-system differences in performance for the beef cattle enterprise. The economic benefit of the mixed system outweighed the additional costs required for fencing.

Introduction

The diversification of farming systems is one of the core tenets of agroecology. It can be applied to livestock farming systems by combining several animal species on the same farm. The literature shows that this strategy can not only improve overall productivity but also increase resilience to various types of hazards (Altieri et al., 2015; Dumont et al., 2020). Sheep and beef cattle are two of the most widely used grazing species on natural grasslands

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and rangelands across the world. Decades of evolution have led to essentially specialised beef and sheep herds (Thornton 2010), but historically, the two species were often associated. In the Auvergne region of France, where livestock farming is highly represented, the area used by farms combining beef cattle and sheep has shrunk fourfold between 1995 and 2015 (Benoit and Lherm, 2018). Nevertheless, d'Alexis et al. (2014) showed that mixed beef-sheep farming improves productivity in terms of BW production per ha. The main mechanisms involved are the complementary foraging behaviour of the two species (Abaye et al., 1994) and the dilution of helminth burden (Marley et al., 2006).

However, the effects of combining sheep and cattle have mainly been studied at the grazing-period scale, which fails to capture overall effects on economic and environmental performances, which demand a full farming-system cycle analysis, preferably over several years. This full cycle encompasses fodder system management (grazed and/or harvested areas) and reproductive performance of the animals, which is highly dependent on feed resources and health control. Furthermore, differences in production performance may have a knock-on effect on the types of products marketed and their seasonality of sale, which affects price levels. Marketing is therefore a key determinant for understanding the performance of mixed livestock systems (Martin et al., 2020). This experiment was set up in a global context characterised by major challenges of climate change, energy consumption and land use competition for food and feed. It was designed in this framework, and we used the associated indicators to judge the objectives reached and highlight their determinants.

Thus, we set up a farming-system level experiment to investigate the effects of combining meat sheep and beef cattle on the economic and environmental performances of a grassland-based system aiming to produce grass-fed meat self-sufficiently in an upland area. Over four campaigns, we compared a system combining sheep and beef cattle to a sheep-only system and a beef cattle-only system, both specialised systems serving as reference points. All three systems were designed to have similar average annual stocking rates, farm areas, pastures and animals. A companion paper gives full details on the experimental design and management and goes deeper into the various periods of the production cycle to explain the differences observed (Prache et al., 2023).

Material and methods

The experiment was based on the exclusive use of permanent grasslands (Prache et al., 2023), the most represented ecosystem on the planet, with 52.5 million km^2 (Suttile et al., 2006). It was located on the INRAE HerbiPôle experimental farm in Laqueuille. The experiment lasted from the beginning of May 2017 to the end of April 2021, i.e., four campaigns. The three systems, which aimed to produce grass-fed meat, were managed as three separate farmlets that were identical in size (39 ha) with plots being equally distributed across altitude and soil-quality gradients. The surface area and stocking rate (29.5 ± 0.6 LU per farmlet) were similar across systems (Prache et al., 2023).

In the following, mixed system (**MIXsys**), cattle-only system (**CATsys**), and sheep-only system (**SHsys**) refer to the mixed sheep–beef cattle system, specialised beef cattle system, and specialised sheep system, respectively. cattle enterprise in the specialised cattle-only system (**CATspe**), cattle enterprise in the mixed beef cattle–sheep system (**CATmix**), sheep enterprise in the specialised sheep-only system (**SHspe**) and sheep enterprise in the mixed beef cattle–sheep system (**SHmix**) refer to the beef cattle enterprise within the specialised system, the beef cattle enterprise within the mixed system, the sheep enterprise within the specialised sheep system, and the sheep enterprise within the mixed system, respectively.

The ratio of SHmix LU to CATmix LU was set at 40%, which d'Alexis et al. (2014) identified as the optimal ratio for maximising animal productivity per hectare at the grazing-season level, based on a meta-analysis that pooled studies conducted in different regions of the world. Each system had its own buildings for animal and forage stocks. The manure from each system was composted and spread back on the system's own land. Compost spreading and forage harvesting were carried out using the experimental farm's equipment. We therefore performed modelling to size and scale the cost of equipment necessary for the management of each system. In MIXsys, all the plots intended exclusively for grazing were fenced with both sheep wire and barbed wire. We considered that each system can be managed by 0.5 human work units.

The farmland and livestock animals had acquired 'certified-organic' status (European harmonised certification) just before the experiment began. The pedoclimatic conditions correspond to a volcanic soil at 1 100–1 450 m asl, with an annual rainfall of 1 069 mm (years 2000–2021 average). The botanical composition of the grasslands is given in Prache et al. (2023). The experimental years (2017–2020) had an average rainfall deficit of 44% in July and August compared to the 2000–2016 period, with individual deficits up to 50 and 61% in July and August 2019 and 83% in July 2020. Deficits were 29 and 25% in May 2019 and May 2020, respectively, whereas May is a crucial month for herbage production (Fig. 1).

Number of breeding females and livestock units

We chose to use a similar annual stocking rate (LU/ha pasture) across all systems to provide all herds, *a priori*, with comparable quantities of biomass. The stocking rate was set at 0.75 LU/ha based on our expertise of the agronomic potential of these farm areas managed without chemical fertilisation (Prache et al., 2023). The usual coefficients were used to estimate the number of animals needed, e.g., 0.86 LU for a cow and 0.14 LU for an ewe (Benoit and Veysset, 2021). The calculation of LU for each category of animal was based on the average annual number of animals for each category calculated on a daily basis. Table 1 gives the LU values for each animal enterprise (beef cattle, sheep) and each system. In MIXsys, sheep represented, on average, 40.7% of the system's LUs over the four campaigns, as planned.

Animal and forage-resource management

Animal management

Crossbreeding was used, as is common in Europe (Great Britain, for example). In the beef cattle enterprise, purebred Salers cows were covered by Angus bulls to produce crossbred calves, and replacements were purchased each year (2-year-old heifers). Cows calved on average on January 23 and turned out to pasture on average on April 26. The calves were weaned at 9 months of age (i.e., on October 18, on average) and fattened indoors with haylage, the objective being to send them to slaughter with a satisfactory degree of fatness before the new grazing season started. Sales were made in long-supply-chain channels (a cooperative of breeders) except for the second campaign (short-supply-chain channels, i.e., INRAE employees). In the last campaign, given the prevailing drought conditions, low forage stocks, and an opportunity for early sales in an uncertain market due to the COVID-19 pandemic, the date for marketing was brought forwards, and the young cattle were sold lighter.

In the sheep enterprise, the ewe breed was Limousine. Suffolk rams were used to produce crossbred lambs for finishing, and limousine rams were used to produce purebred lambs for replacement. If the number of purebred limousine replacement ewe lambs

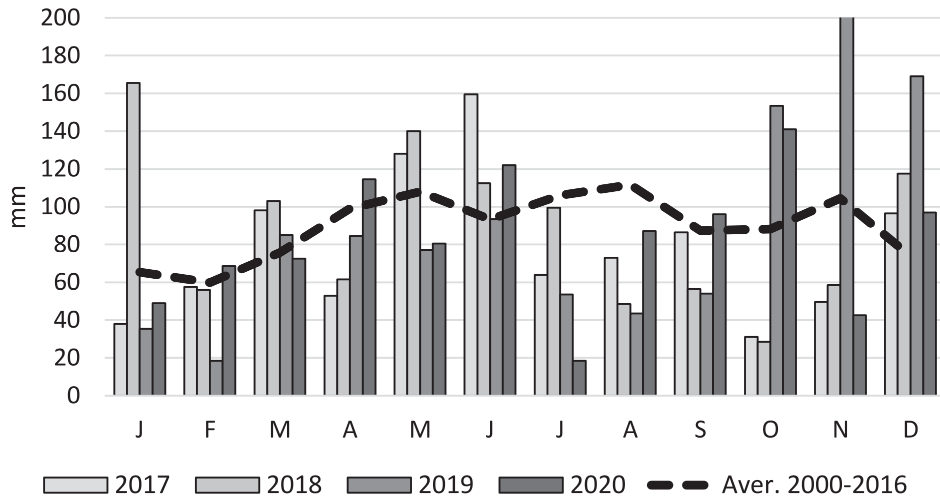

Fig. 1. Monthly rainfall (mm) at the experimental site in the four experimental years on the sheep and beef cattle enterprises and on average from 2000 to 2016.

Table 1
Number of animals in each animal category and livestock unit values for breeder females and other animals (young animals and breeding males) in each animal enterprise (beef cattle, sheep) and for each system, averaged over the four campaigns.

Items	CATsys	% LU	MIXsys	% LU	SHsys	% LU
Cows number	21.43	–	12.27	–	–	–
Cow LU	18.43	61.2	10.56	60.3	–	–
Other beef cattle LU	11.66	38.8	6.95	39.7	–	–
Total beef cattle LU	30.09	100	17.51	100	–	–
Ewes (+12 months) number	–	–	74.8	–	178.0	–
Ewe LU	–	–	9.65	81.0	23.1	79.9
Other sheep LU	–	–	2.31	19.0	5.82	20.1
Total sheep LU	–	–	11.96	100	28.92	100
Total system LU	30.09	–	29.47	–	28.92	–

Abbreviations: LU = Livestock Unit; CATsys = beef cattle-only system; MIXsys = mixed beef cattle–sheep system; SHsys = sheep-only system.

was insufficient, purchases were made. The ewe lambs were mated at 19 months of age. The ewes lambed on March 20 on average and were turned out to pasture on April 25 on average. The lambs were weaned on July 20 on average and were then pasture-finished, except those that were not ready for slaughter 3–4 weeks before the ewes were scheduled for mating, which were finished indoors with a concentrate-based diet. The lambs were slaughtered at 35–40 kg BW when they had reached a satisfactory degree of fatness, and they were sold via long-supply-chain channels.

Forage-resource management

For the sheep enterprise, one of the priorities was to have good-quality pasture herbage for finishing lambs from July to October and for mated ewes in October. The lambing and calving dates were chosen to ensure lactations at pasture in good conditions. Full details on all farming-strategy practices, particularly grazing management, can be found in a companion paper (Prache et al., 2023).

Use of concentrates

As organic concentrates are 50–70% more expensive than conventional ones and the additional price mark-up on the sale of organic animals is relatively low, the use of concentrates had to be reduced to a strict minimum to achieve decent profitability. This limitation in the use of concentrates is also consistent with the concept of feed–food competition (Laisse et al., 2019). The use of concentrates was therefore restricted to key periods and animal categories. Full details are given in a companion paper (Prache et al., 2023). As a measure to further reduce the use of concentrates, from the second campaign onwards, we stopped feeding concentrate to young cattle during the fattening period, even if it meant selling lighter carcasses. In sheep, almost all the lambs were pasture-finished in SHmix, whereas 26% of them were finished indoors in SHspe (Prache et al., 2023). The concentrates came from commercial suppliers and were balanced in terms of energy and protein to best meet the requirements of the animals (females at the end of gestation or animals being fattened).

Indicators for multiperformance assessment

We used a number of classical indicators applicable in various farming conditions, for sheep or for cattle (Benoit and Laignel, 2006; Mosnier et al., 2021). These technical, economic and environmental (greenhouse gas (**GHG**) emissions and energy consumption) indicators were calculated using cross-cutting functional units applicable to both animal species, in particular LU, kg BW produced (including variations in animal stocks and deducting animal purchases), and ha of land used. The mean number of females present over the campaign was used as the denominator in several indicators. For the sheep enterprise, we used the number of females over 12 months of age (Ewe + 12 months) (Benoit and Laignel, 2006). The number of females over 6 months of age can also be used, as widely practised in reference systems (Idele and Chambres d'Agriculture, 2020b). For the beef cattle enterprise, we used the number of females mated and the number of calvings. The technical, economic and environmental assessments were carried out per campaign, from May 1st of year n to April 30th of year n + 1, which was close to the start of the grazing season and therefore to the period when the stored forage stocks were lowest. Data for lambings in March-April and calvings in January of year n were integrated and analysed in the campaign from 01-05-n to 30-04-n + 1 to match reproductive performance with economic data, which are highly correlated (Benoit and Laignel, 2011).

Technical indicators

In the sheep enterprise, we calculated lambing rate (number of lambs born per Ewe + 12 months per year), prolificacy (number of lambs born alive + number of lambs born dead)/(number of ewes that lambed), and lamb mortality rate (from birth to sale or to six months of age for replacement females) (Benoit and Laignel, 2006). In the cattle enterprise, we used pregnancy rate (number of calves born per cow mated), prolificacy, calf mortality rate (from birth to weaning) and calving-to-calving interval. Ewe productivity was calculated as the ratio (number of lambs sold + ewe lambs kept)/Ewe + 12 months. Cow productivity was calculated as the ratio of the number of young animals weaned/females mated.

We also evaluated the capacity of the systems to provide fattened market animals using a maximum of resources that do not compete with human food, e.g., cereals, to address the issue of feed–food competition (Wilkinson, 2011; Ertl et al., 2016). We used the method proposed by Laisse et al. (2019) who calculated the net human-edible feed conversion efficiency for protein, an indicator representing the ratio of human-edible protein produced by the livestock system to human-edible protein consumed by the animals.

Economic indicators

The economic calculations are fairly standard and follow the general accounting framework used by the Farm accountancy data network at the European level (European Commission, 2022). This method is specified in Benoit and Laignel (2006) for livestock production (sheep). Gross product for each enterprise (sheep or beef) includes animal output (sales of animals - purchases of animals + changes in stocks), wool sales, the possible sale of surplus forages, and subsidies received under the first and second Common Agricultural Policy pillars. First-pillar subsidies are delivered per production (per cow or per ewe) plus general Common Agricultural Policy subsidies paid per ha (basic payment, green payment and redistribution payment). Second-pillar subsidies cover the compensatory allowance for permanent natural handicaps and conversion to organic farming.

All costs were taken into account, whether they were operational (per enterprise) or fixed costs, which were computed at the system level but can be allocated to each subenterprise using allocation keys (Table 2). Operational costs included purchased feed (concentrates, forages, minerals and vitamins), veterinary expenses (products and fees), miscellaneous livestock expenses, and grassland-area expenses (particularly twine and tarp for hay and baling).

Fixed costs were partially modelled. Indeed, (i) the workforce had research-institute status, with salaries and social charges paid elsewhere and employees implementing protocols not associated with the running of the farming system, (ii) systems were smaller than commercial farming systems, but the farm equipment was borrowed from the hosting research unit and was therefore oversized for the three experimental systems, and (iii) the three buildings built specifically for this experiment had the specific high cost of an experimental farm.

The fixed costs were therefore calculated using a number of conventions and references:

- Labour costs: for 0.5 workers, payroll contributions were estimated at €4 000 per year (Idele and Chambres d'Agriculture, 2020a; 2020b).
- Mechanisation and building costs: a census of the equipment (type and size adapted to the farm areas and herds) was carried out to cover each system and all the work (traction, haymaking, distribution, land-applying manure). The costs of depreciation, use, maintenance, insurance, and fuel consumption were modelled according to mutual-aid and cost-of-use scales for agricultural equipment (CUMA Auvergne Rhône-Alpes, 2020). Likewise, we modelled building investments and depreciation (amortised over 25 years) based on regional references for space required per animal and for straw and forage storage (Chambre d'Agriculture, 2021; CIIRPO, 2021).
- Fencing costs: when the three systems were set up, all the fencing was done by a company; we considered this investment to be amortised over 25 years.
- Land charges: We considered the entire agricultural area utilised for tenant farming by applying an annual rent corresponding to the locally observed average rates.
- Financial costs (or debt interest): it was considered that the system's real capital (breeding stock, fences) or modelled capital (buildings, equipment), excluding land, was financed to 33% by a loan at an interest rate of 1.5% over 20 years. The financial expense adopted (financial costs) was that of the tenth year.
- Other expenses: the costs per LU for management, travel, water and electricity, and other supplies or services were taken from values observed in farm networks (Idele and Chambres d'Agriculture, 2020a; 2020b).

The gross margin of each enterprise was calculated by subtracting its operational costs from its gross product after factoring in the subsidies specific to the enterprise. Net income was calculated by subtracting the fixed costs from the overall gross margin of the system (total products minus all operational charges).

Table 2
Allocation keys between the sheep and beef cattle enterprises in the mixed system, based on share of livestock units from each species in total livestock units.

Items	Keys Beef cattle:Sheep
Share of theoretical LU originally planned	0.600:0.400
Share of LU observed (four campaigns)	0.594:0.406
Conserved forage purchases	0.776:0.224
Fuel	0.633:0.367
Livestock buildings	0.684:0.316
Forage storage building	0.733:0.267
Total buildings	0.692:0.308
Mechanisation (excluding fuel)	0.594:0.406
Payroll contributions	0.594:0.406
Fencing	0.594:0.406
General aids	0.594: 0.406

Abbreviation: LU = Livestock Unit.

Allocation keys between sheep and cattle enterprises in the mixed system

Allocation keys are needed to assign certain expenses to each of the two enterprises studied. This involves defining allocation coefficients. The study of multispecies livestock systems specifically raises this question, which must be addressed accurately to ensure a reliable assessment of the performance of each enterprise. We hypothesised, based on the results of d'Alexis et al. (2014), that the performances of the two species in MIXsys were not affected to the same extent by the association. To judge this, it was necessary to calculate the results (technical, economic, environmental) for each of the two enterprises, which in turn led to the question of how to allocate expenses in the most reliable way possible between both enterprises. The value of the allocation keys depends on each context, but this approach is relevant in all production contexts.

The items concerned by expense allocations between CATmix and SHmix are specified in Table 2. To allocate the purchased forages between animal enterprises, we first considered a virtual system based on the sum of the two systems, i.e., CATspe and SHspe and using the per-species proportions of LU in the MIXsys. This allowed us to calculate a theoretical forage purchase per LU for this virtual system. As this purchase was 20.6% higher than that observed in MIXsys, we applied this reduction in the same way to CATmix and SHmix. Thus, we obtain the real amount of fodder purchases in the MIXsys system while taking into account the reality of the operation of the sheep and cattle enterprises on the basis of the CATsys and SHsys. This led to an allocation key for purchased conserved forages of 77.6% for CATmix and 22.4% for SHmix, which was linked to the high consumption of conserved forages by young cattle in winter.

For fuel, the allocation between animal enterprises was based on the area of conserved forage harvested and the quantities consumed by each animal species, minus conserved forage purchased. On this basis, 63.3% of the harvested conserved forages consumed were attributed to CATmix and 36.7% to SHmix.

For livestock buildings, the cattle enterprise bore 68.4% of the total cost, and the sheep enterprise bore 31.6% (higher cost of housing for cattle LU compared to sheep). For the conserved forage storage facilities, the corresponding building surfaces were calculated according to the volume of conserved forage consumed (including hay purchased) and straw.

For fencing, the cost (depreciation) was allocated to CATmix and SHmix *pro rata* to their respective LU, without assigning the fences extra cost totally to SHmix or totally to CATmix. The global fencing cost was independent of the proportion of sheep in the system, which does not allow us to identify a fraction of the extra cost to be allocated to one or the other of the two.

Environmental indicators

The environmental indicators used in this paper refer to GHG emissions (in Equivalent CO_2 (**EqCO₂**)) and fossil-energy consumption (in mega-joules (**MJ**)) and were calculated using the CAP2ER® method developed by the Institut de l'Elevage (Moreau, 2018). The CAP2ER® method is a cradle-to-farm-gate life-cycle analysis that factors in elements of the GESTIM method (Gac et al., 2011). As the contribution of mechanisation and buildings to GHG emissions and energy consumption is not taken into account in the CAP2ER ® method (except for direct energy: fuel and electricity), we added it using the Dia'Terre method (SOLAGRO, 2009). For GHG emissions, we estimated gross emissions as well as net emissions, i.e., deducting carbon sequestration in grasslands, based on a rate of 570 kg C/ha/year (Dollé et al., 2013).

Statistical analysis

T-tests for paired samples were used for between-system and between-enterprise comparisons.

Results

Reproductive performance

For the beef cattle enterprise, cow productivity and mean calving-to-calving interval were not significantly different between CATspe and CATmix (0.90 and 0.84, respectively, and 355 days, on average). For the sheep enterprise, ewe productivity tended to be higher in SHmix than in SHspe (1.53 vs 1.41; $P < 0.07$), due mainly to a higher prolificacy (1.96 vs 1.83, $P < 0.02$) and, to a lesser extent, a lower lamb mortality (11.7% vs 14.0%, P = 0226). Ewe lambing rate was not significantly different between SHmix and SHspe (Table 3).

BW production and gross product

MIXsys produced more meat per ha than CATsys and SHsys, with 233 kg BW, 226 kg and 217 kg, respectively, but these differences were not significant. MIXsys also tended to have higher BW production per LU than CATsys (309 kg BW/LU vs 290 kg BW/LU, P = 0.26) and SHspe (292 kg BW/LU, P = 0.13). This was explained by a higher BW production in SHmix than in SHspe (342 kg BW/LU vs 292 kg BW/LU, $P < 0.04$) due to (i) higher ewe productivity, (ii) higher BW of culled ewes (Prache et al., 2023), and (iii) higher number of culled ewes sold in proportion to the size of the enterprise, as mortality was only 25% of culled ewes in SHmix vs 40.6% in SHspe. This between-system difference in BW production translated into a higher gross product for SHmix vs SHspe (€905/LU vs €791/LU, $P < 0.04$). This production advantage for SHmix was partly offset by the sale of hay by SHspe (€29/LU) and its surplus of general aid (€12/LU) linked to the slightly lower stocking rate (−2.8%), given that this aid is paid per ha (Fig. 2c). Gross product per LU ultimately tended to be higher in SHmix than SHspe (€1592/LU vs €1520/LU, P = 0233).

For the beef cattle enterprise, BW produced per LU and gross product per LU were not significantly different between CATmix and CATsys. Note that both CATmix and CATsys experienced a sharp drop in BW produced per LU in the last campaign due to the early date to market (Figs. 3a and 2b). SHsys ultimately had the highest gross product per LU (€1520/LU), followed by MIXsys (€1466/LU) and CATsys (€1377/LU; Fig. 2a).

The selling price per kg BW (lambs and ewes) remained relatively stable throughout the experiment for sheep (Fig. 3b). For cattle, the market struggled to accept the type of animal produced (young, crossbred animals and light carcasses), and the carcasses were undervalued (Prache et al., 2023) (Fig. 3b). Marketing via a short-supply-chain channel in the second campaign led to a better price.

Note that total subsidies for the three systems represented 58% of gross product, which diluted the differences in gross product linked to differences in BW production.

Inputs used

Young beef cattle were supplemented only during the first campaign, with 3.4 kg concentrate per animal per day (183 days fattening period; Fig. 4). During the last two campaigns, cows were supplemented after calving and before turn-out to pasture due to insufficient body condition score and a limited forage stock (Prache et al., 2023). Overall, annual concentrate consumption was not significantly different between CATmix and CATspe (196 kg/LU and 205 kg/LU, respectively).

In the sheep enterprise, SHmix consumed less concentrate than SHspe (351 kg/LU vs 427 kg/LU on average, $P < 0.02$). The difference remained stable across all campaigns, but consumption was much

Table 3
Mean reproductive performances in the sheep enterprise over the four experimental campaigns.

Items	SHspe Average (SD)	SHmix Average (SD)	*P*-value
Ewe productivity	1.41 (0.04)	1.53 (0.06)	<0.07
Prolificacy	1.83 (0.07)	1.96 (0.04)	<0.02
Lamb mortality (%)	14.0 (2.6)	11.7 (2.1)	0.226
Lambing rate	0.90 (0.005)	0.89 (0.020)	0.317

Abbreviations: SHspe = sheep enterprise in the specialised sheep-only system; SHmix = sheep enterprise in the mixed beef cattle–sheep system.

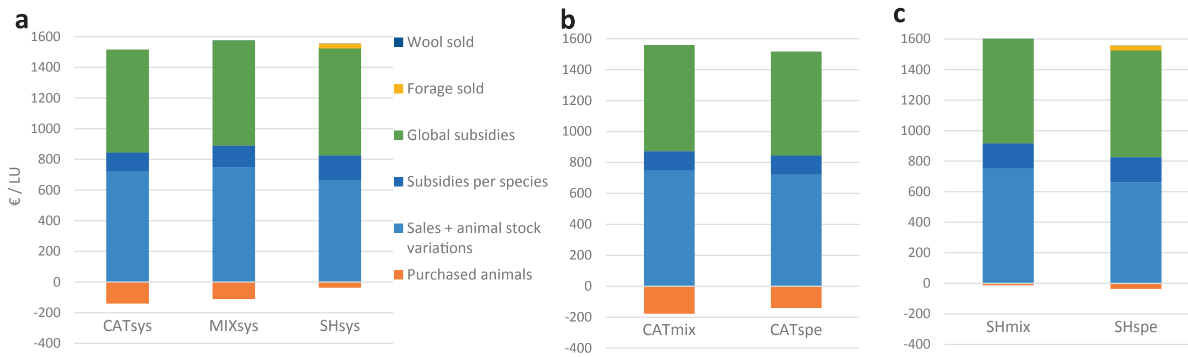

Fig. 2. (a) Gross product (€/LU) with its components (Wool, Forage sold, Global subsidies, Subsidies allocated to the enterprise, Sales minus animals purchased and variation in animal stocks) for the three systems. (b) Gross product (€/LU) for each beef cattle enterprise. (c) Gross product (€/LU) for each sheep enterprise. Abbreviations: LU = Livestock Unit; CATsys = beef cattle-only system; MIXsys = mixed beef cattle–sheep system; SHsys = sheep-only system; CATmix = cattle enterprise in the mixed beef cattle–sheep system; CATspe = cattle enterprise in the specialised cattle-only system; SHmix = sheep enterprise in the mixed beef cattle–sheep system; SHspe = sheep enterprise in the specialised sheep-only system.

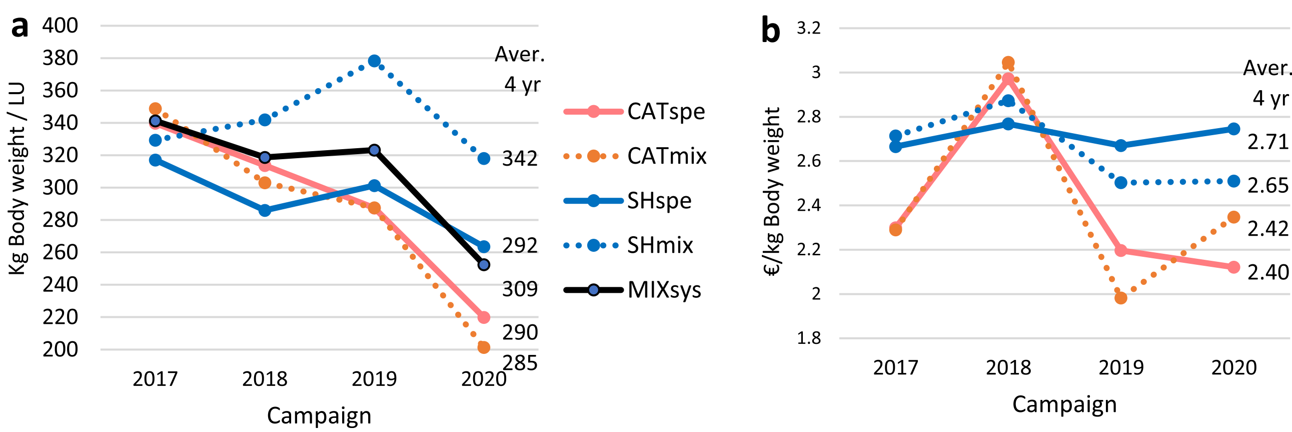

Fig. 3. (a) BW production (kg/LU) for the four enterprises and the mixed sheep–beef cattle system. (b) Selling price (€/kg BW) for the four enterprises studied. Values are per campaign and on average over the four campaigns. Abbreviations: LU = Livestock Unit; CATspe = cattle enterprise in the specialised cattle-only system; CATmix = cattle enterprise in the mixed beef cattle–sheep system; SHspe = sheep enterprise in the specialised sheep-only system; SHmix = sheep enterprise in the mixed beef cattle–sheep system; MIXsys = mixed beef cattle–sheep system.

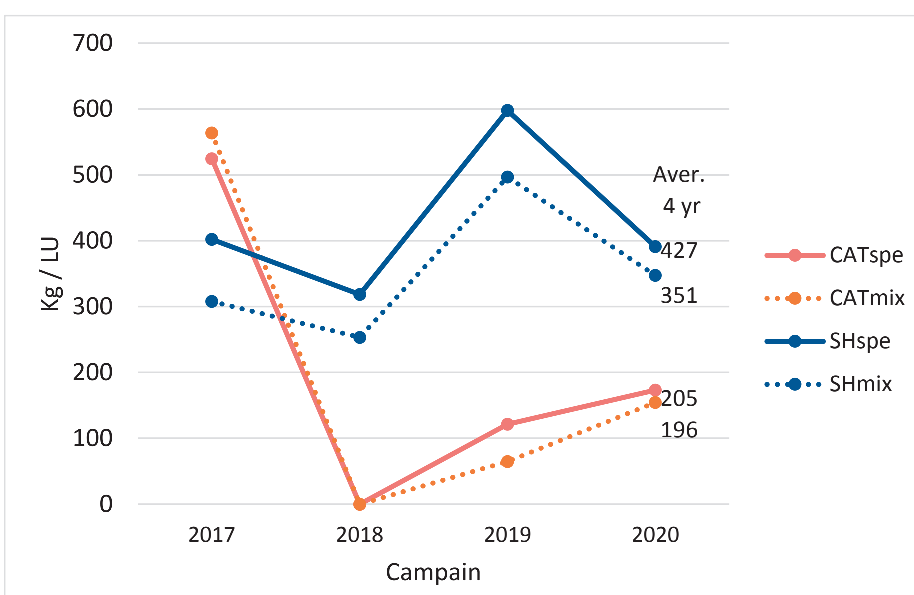

Fig. 4. Concentrate consumption (kg/LU) for each of the four campaigns and on average over the four campaigns for the four enterprises studied. Abbreviations: LU = Livestock Unit; CATspe = cattle enterprise in the specialised cattle-only system; CATmix = cattle enterprise in the mixed beef cattle–sheep system; SHspe = sheep enterprise in the specialised sheep-only system; SHmix = sheep enterprise in the mixed beef cattle–sheep system.

higher in the third campaign due to a severe drought. Full details and analysis of this between-system difference (period in the reproduction cycle, animal category involved, and likely explanations) are given in Prache et al. (2023). On average over the four campaigns, concentrates represented 45.9% of operational expenses for SHspe and 40.1% for SHmix, vs only 17.6% for CATspe and 16.4% for CATmix (Fig. 5b and c).

The lower concentrate consumption in SHmix vs SHspe translated into an economic gain in concentrate cost (€198/LU vs €240/LU, respectively; $P < 0.003$) but was offset by two higher operational expenses: (i) straw purchases (+€9/LU), as SHspe used more hay refusals for bedding, whereas these refusals were fed to the beef cattle in MIXsys, (ii) veterinary expenses (+€6.6/LU, i.e., +15%) due to lower economies of scale in veterinary product purchases (smaller packaging for SHmix due to the smaller number of animals and amount of products; Fig. 5c). Ultimately, the difference in operational expenses between SHmix and SHspe was not significant, at €28.4/LU (€493.1/LU and €521.5/LU for SHmix and SHspe, respectively).

Straw and conserved forage purchases were the top two operational expenses for beef cattle, accounting for 30.7 and 23.9% of the total, respectively (average for both enterprises) (Fig. 5b).

Ultimately, the total operational expenses were not significantly different between sheep enterprises and beef cattle enterprises. However, due mainly to straw and conserved forage purchases, the operational expenses per LU were on average 16.6% higher in the beef cattle enterprises than in the sheep enterprises, although concentrate, veterinary and miscellaneous livestock expenses per LU were 46.6%, 13.3% and 17.2% lower, respectively.

Gross margin

The gross margin per LU varied strongly year-on-year. The good conditions for marketing young cattle in the second campaign resulted in a high gross margin per LU for CATspe and CATmix (Fig. 6). The severe drought conditions in the third campaign had a severe impact on the gross margin, largely because it compelled forage purchases. The two beef cattle enterprises had very similar mean gross margins (€793/LU and €779/LU for CATspe and CATmix, respectively; Fig. 6). In sheep, SHmix tended to have a higher gross margin than SHspe (€1099/LU vs €998/LU, respectively, $P < 0.07$). The gross margin per LU was €998 for SHspe vs €793 for CATspe; the difference was not significant ($P = 0.139$) due to a strong increase in both beef cattle enterprises in the second campaign because of specific marketing. However, the gross margin was higher in SHmix than in CATmix (€1099/LU vs €779/LU, respectively, $P < 0.05$).

Fixed costs

The mean fixed costs per LU varied from €751 (SHmix) to €806 (CATmix; Fig. 7). This low variability, however, masked marked differences between the sheep and beef cattle enterprises on three items (Fig. 8). First, fencing costs were twice as high per metre for sheep, which led to a cost of €10.5/LU in CATsys, €21.1/LU in SHsys, and €24.1/LU in MIXsys. Second, building costs were higher for beef cattle, for housing the animals and for storing higher amounts of conserved forage (Fig. 8a). Third, due to larger buildings and to the high economic value of the beef cattle herd, beef enterprises had higher capital than sheep enterprises and thus more debt and higher financial costs per LU (+37% for CATsys vs SHsys; Fig. 8a). Mechanisation costs were slightly higher for CATmix vs CATspe (€172/LU vs €166/LU, respectively, Fig. 8b). Indeed, the share of purchased forages was €20/LU lower in CATmix vs CATspe (Fig. 4), as sheep consume less forage than cattle, which resulted in a higher share of forages harvested on-farm.

Net income

In sheep, net income was higher in SHmix than in SHspe (€331/LU vs €224/LU, $P < 0.03$). The high level of conserved forage purchases in the third campaign led to a sharp drop in net income, particularly for beef cattle enterprises. In the last campaign, in the COVID-19 pandemic context, young cattle were sold at a lighter BW with low prices, resulting in a negative average income, both for CATspe (−€4/LU) and CATmix (−€49/LU) (Fig. 9). The difference in net income between CATspe and CATmix was not significant. The difference observed in the year 2020 campaign was due to a higher calf mortality in CATmix (four calves died vs one in previous years).

Feed–food competition

The net human-edible feed conversion efficiency for protein was not significantly different between CATmix and CATspe (1.66 and 1.62, respectively). Both beef cattle enterprises were therefore net producers of human-edible protein, thanks to the forage-fattened animals. These values were much higher than the value close to 0.7 given in Laisse et al. (2019) and Mosnier et al. (2021), except for an Irish grassland system that had a net human-edible feed conversion efficiency for protein of 1.9. In

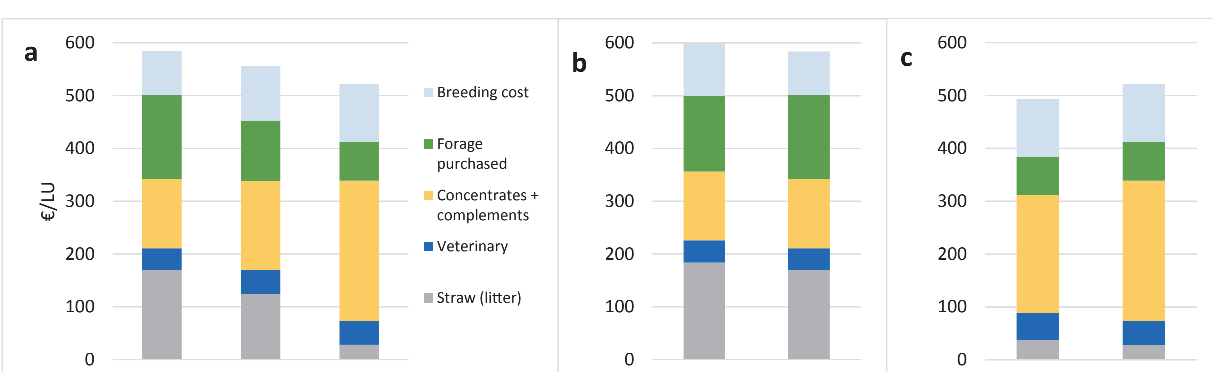

Fig. 5. (a) Breakdown of mean operational expenses (€/LU) for the three systems, (b) for the two beef cattle enterprises, and (c) for the two sheep enterprises. Five components for operational expenses: breeding costs, forage purchased, concentrates and complementation (mineral, vitamins), veterinarian expenses, and straw. Abbreviations: LU = Livestock Unit; CATsys = beef cattle-only system; MIXsys = mixed beef cattle–sheep system; SHsys = sheep-only system; CATmix = cattle enterprise in the mixed beef cattle–sheep system; CATspe = cattle enterprise in the specialised cattle-only system; SHmix = sheep enterprise in the mixed beef cattle–sheep system; SHspe = sheep enterprise in the specialised sheep-only system.

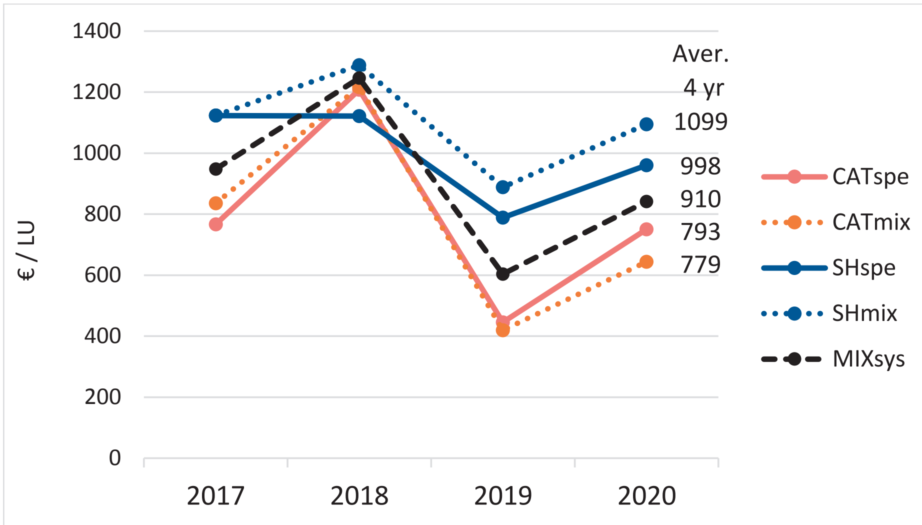

Fig. 6. Gross margin (€/LU) for each campaign and on average over the four campaigns for the four enterprises and the mixed sheep–beef cattle system. Abbreviations: LU = Livestock Unit; CATspe = cattle enterprise in the specialised cattle-only system; CATmix = cattle enterprise in the mixed beef cattle–sheep system; SHspe = sheep enterprise in the specialised sheep-only system; SHmix = sheep enterprise in the mixed beef cattle–sheep system; MIXsys = mixed beef cattle–sheep system.

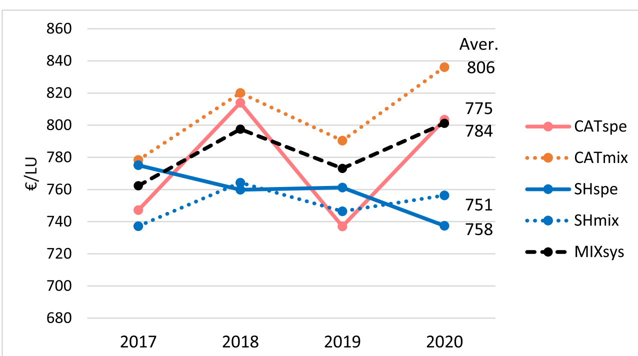

Fig. 7. Fixed cost (€/LU) for each campaign and on average over the four campaigns for the four enterprises and the mixed sheep–beef cattle system. Abbreviations: LU = Livestock Unit; CATspe = cattle enterprise in the specialised cattle-only system; CATmix = cattle enterprise in the mixed beef cattle–sheep system; SHspe = sheep enterprise in the specialised sheep-only system; SHmix = sheep enterprise in the mixed beef cattle–sheep system; MIXsys = mixed beef cattle–sheep system.

sheep, this indicator was higher in SHmix than in SHspe (0.85 vs 0.58, $P < 0.01$). Despite a strategy aiming for high consumption of pasture herbage, both sheep enterprises remained net consumers of human-edible protein.

Greenhouse gas emissions

CH_4, CO_2 and N_2O emissions represented, on average, 76, 10 and 14% of the total emissions for the three systems, respectively (Fig. 10a). The gross GHG emissions were not significantly different between the three systems (Fig. 10a). They tended to be lower in SHmix than in SHspe (16.0 kg vs 17.9 EqCO_2/kg BW, $P < 0.09$) (Fig. 10c). The level of enteric CH_4 emissions was the main explanatory factor, with 9.7 kg EqCO_2/kg BW for SHmix and 10.7 kg for SHspe ($P < 0.12$). When expressed per LU, these GHG emissions were not significantly different between SHmix and SHspe. CATmix had higher GHG emissions than CATspe, both per LU (6 799 and 6 431 kg EqCO_2, respectively) and per kg BW (19.3 vs 18.4 EqCO_2, Fig. 10b), but these differences were not significant. Carbon sequestration in grasslands averaged 41.8 and 40.9% of gross emissions for CATspe and CATmix and 51.2 and 50.3% for SHspe and SHmix, respectively.

Non-renewable energy consumption

The energy consumption levels were 28.7, 26.5 and 24.1 MJ/kg BW for CATsys, MIXsys and SHsys, respectively. The components of energy consumption were purchases of concentrates, hay and straw (32.5% of total energy consumption); fuel (29.3%); equipment, buildings and fences (20.3%); animal purchases (10.1%); and electricity (7.9%) (Fig. 11a). Energy consumption per kg BW was 20.3 MJ/kg BW for SHmix vs 24.1 for SHspe ($P < 0.03$). When expressed per LU, it reached 7053 MJ/kg BW vs 7403 for SHmix and SHspe, respectively ($P < 0.07$) (Fig. 11c). CATmix had a higher energy consumption than CATspe, per LU (10968 vs 10139 MJ/LU) and per kg BW (31.0 vs 28.7 MJ/kg BW), but these differences were not significant (Fig. 11b).

Discussion

Profitability could not be compared between the sheep and beef cattle due to the diversity in routes to market in the beef cattle enterprise (short or long-supply chains) and to the differences in meat prices between sheep and beef in relation to the adequacy of animal produced to the downstream sector. However, intraspecies comparisons (CATmix vs CATspe, SHmix vs SHspe) were more instructive since each animal enterprise adopted similar fattening strategies in a given year and used the same marketing channel. Studying between-system differences in performance for a given animal enterprise made it possible to avoid some of the possible biases inherent to economic conditions.

Combining beef cattle and sheep in a mixed system had stronger effects on sheep enterprise performance than on beef cattle enterprise performance

SHmix consistently outperformed SHspe in terms of ewe productivity (+8.6%), BW production per LU (+17.1%), concentrate consumption per LU (−17.8%), gross margin per LU (+10.0%), and income per LU (+47.5%). In contrast, the performances of the beef cattle enterprises were very similar in both systems, both in terms of meat production per LU and economics (gross margin per LU and net income

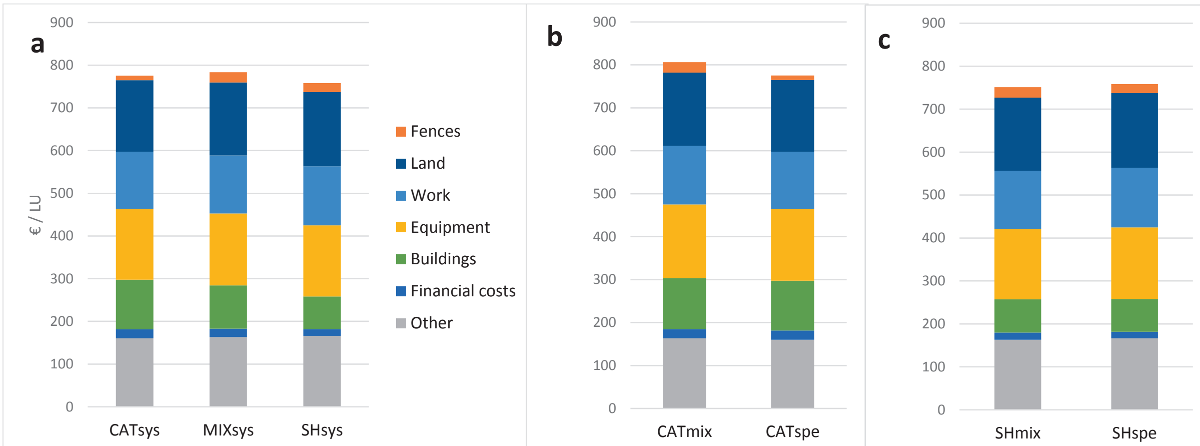

Fig. 8. Breakdown of fixed costs (€/LU) for the three systems (a), the two beef cattle enterprises (b) and the two sheep enterprises (c). Fixed costs include seven components: fencing, land (rental), work (payroll contributions), equipment, buildings, financial costs, and other costs. Abbreviations: LU = Livestock Unit; CATsys = beef cattle-only system; MIXsys = mixed beef cattle–sheep system; SHsys = sheep-only system; CATmix = cattle enterprise in the mixed beef cattle–sheep system; CATspe = cattle enterprise in the specialised cattle-only system; SHmix = sheep enterprise in the mixed beef cattle–sheep system; SHspe = sheep enterprise in the specialised sheep-only system.

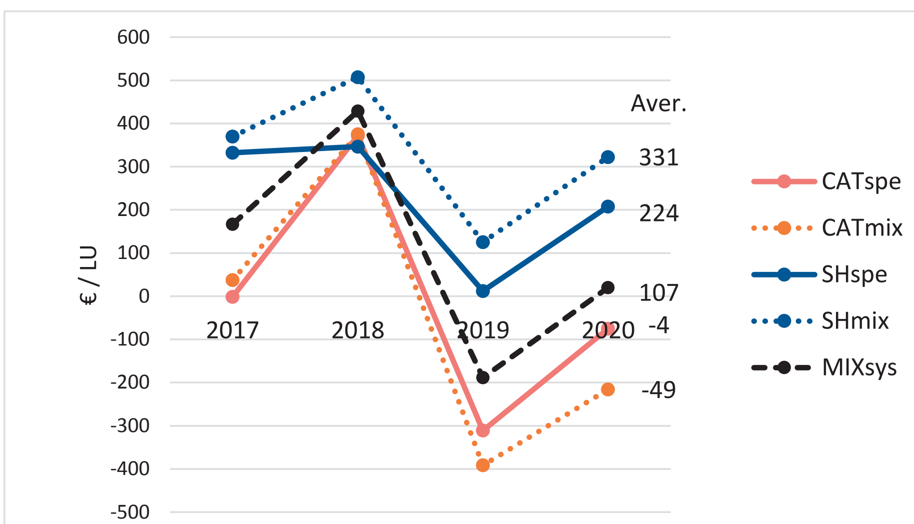

Fig. 9. Net income (€/LU) for each campaign and on average over the four campaigns for the four enterprises and the mixed sheep–beef cattle system. Abbreviations: LU = Livestock Unit; CATspe = cattle enterprise in the specialised cattle-only system; CATmix = cattle enterprise in the mixed beef cattle–sheep system; SHspe = sheep enterprise in the specialised sheep-only system; SHmix = sheep enterprise in the mixed beef cattle–sheep system; MIXsys = mixed beef cattle–sheep system.

per LU), indicating that beef cattle did not clearly benefit from the association with sheep. However, forage self-sufficiency was lower in CATsys than in MIXsys and especially SHsys due to increased purchases of conserved forages. This forage deficit may have contributed to the decrease in the CATsys-cow body condition score (BCS) over the four campaigns (Prache et al., 2023). Note that the combination of beef cattle with sheep benefitted cow BW and BCS maintenance and cow BW gain during the grazing season (Prache et al., 2023). Furthermore, winter feeding was also probably more strained for CATspe cows than for CATmix cows, as the sheep in the CATmix system had lower feed needs, which freed up more of the on-farm harvested forages to feed the cattle.

Combining beef cattle and sheep led to better forage utilisation but with additional costs

The beef cattle enterprise in the mixed system had to bear indirect costs linked to the combination with sheep, particularly the additional fencing-related costs. However, winter resource use was optimised in MIXsys when the cattle consumed the hay refusals left by the sheep. In addition, sheep mulching was more frequent in SMmix, as it was coupled with cattle mulching for an optimal work plan. Ultimately, SHmix used 30% more straw than SHspe.

We assumed that the level of work was similar for all systems. However, it is likely that SHmix required more work due to the presence of two animal species and the increase in the number of interventions on the herd, with more and smaller batches of animals (management of grazing, feeding, sales). However, this potential additional cost could not be estimated.

Net income per LU showed that the extra costs linked to associating two species were more than compensated by both the higher meat production and the lower consumption of concentrates in SHmix compared to SHspe. These advantages were likely due to (i) between-species differences in diet selection and foraging behaviour (Prache et al., 2023), (ii) a dilution of helminth burden

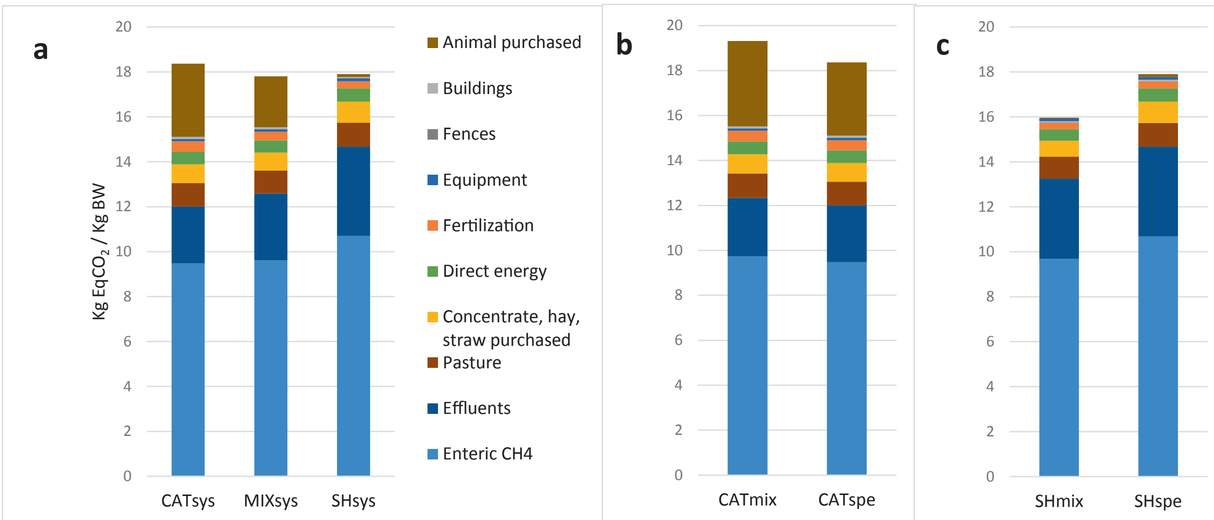

Fig. 10. Greenhouse gases emissions (CO_2 equivalent per kg BW produced) with its components (enteric CH_4, effluents, concentrates, hay and straw purchased, direct energy, fertilisation, equipment, fences, buildings, purchase of animals), (a) for the three enterprises, (b) for the two cattle enterprises and (c) for the two sheep enterprises. Abbreviations: $EqCO_2$ = Equivalent CO_2; CH_4 = methane; CATsys = beef cattle-only system; MIXsys = mixed beef cattle–sheep system; SHsys = sheep-only system; CATmix = cattle enterprise in the mixed beef cattle–sheep system; CATspe = cattle enterprise in the specialised cattle-only system; SHmix = sheep enterprise in the mixed beef cattle–sheep system; SHspe = sheep enterprise in the specialised sheep-only system.

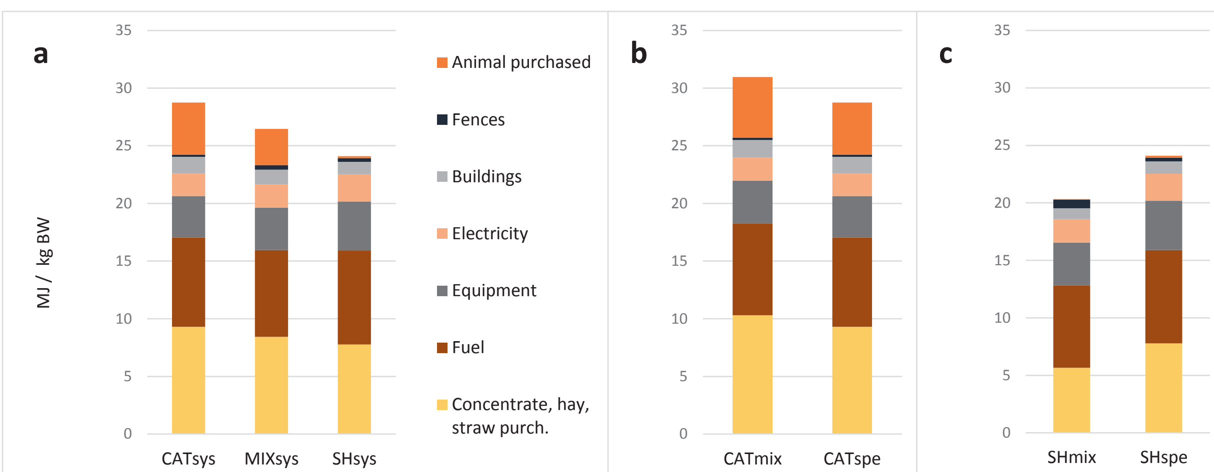

Fig. 11. Energy consumption (MJ per kg BW produced) with its components (concentrates, hay and straw purchased, fuel, equipment, electricity, building, fences, purchase of animals), (a) for the three enterprises, (b) for the two cattle enterprises and (b) for the two sheep enterprises. Abbreviations: MJ = Méga Joules; CATsys = beef cattle-only system; MIXsys = mixed beef cattle–sheep system; SHsys = sheep-only system; CATmix = cattle enterprise in the mixed beef cattle–sheep system; CATspe = cattle enterprise in the specialised cattle-only system; SHmix = sheep enterprise in the mixed beef cattle–sheep system; SHspe = sheep enterprise in the specialised sheep-only system.

(Marley et al., 2006), and (iii) a lower between-animal-batch competition for sheep, which is a new finding from this experiment (Prache et al., 2023).

Beef cattle enterprises are not forage self-sufficient due to both climate conditions and high requirements to fatten young animals

The two species studied have different zootechnical characteristics. While the short fattening cycle of the lambs (age at slaughter: 4–8 months) allows them to be entirely pasture-fattened, the longer fattening cycle of young cattle (age at slaughter: 13–15 months, with weaning at 8–9 months) obliges them to be fattened during the winter on conserved forages (haylage). One consequence is that fattened young cattle represented an important share of the cattle LU, which translated into a high impact on resource use during the winter-period fattening phase. This made this enterprise very sensitive to the availability of conserved forages and straw, with little room for flexibility other than adapting the number of animals to available resources (stocking rate or early sale). The sheep enterprise had high grazing requirements (for pasture-finishing lambs), while the young cattle were fattened with haylage, which can involve significant quantitative and qualitative losses over the course of harvesting, storage and distribution (Savoie et al., 2012). This may partly explain the better forage self-sufficiency in sheep vs beef cattle enterprises during dry campaigns.

Given the similar agronomic potential of the three systems, we aimed for a similar annual stocking rate in all three systems (Prache et al., 2023). For this purpose, when designing the experimental protocol (2014–2015), we used the concept of LU, as it has been used for decades. However, this concept fails to accurately account for the specific needs of animals, such as their size and production level. A more accurate estimation that takes into account the animals' feed requirements would be an improvement

(Benoit and Veysset, 2021). In sheep, calculating LU based on animal net energy requirements could lead to a 15–20% lower value than the value calculated on the basis of 'historical' LU. In beef cattle, the two calculation methods roughly converge. The observed differences in forage availability between the three systems could at least partly be related to the difference in overall animal feeding requirements.

The good technical performance of the sheep enterprise in the mixed system led to better economic and environmental performance compared to the sheep-only system

The higher production performance in SHmix vs SHspe resulted in a higher economic performance. It also resulted in a lower level of CH_4 emissions, expressed in kg $EqCO_2$/kg BW, as the higher growth rate of the lambs led to a lower age at slaughter (Prache et al., 2023), and the CH_4 emitted by the ewes was diluted over a larger amount of meat produced. The lower level of feed purchased in SHmix further reduced the GHG emissions, expressed per kg BW, via a decrease in indirect CO_2 emissions. Overall, these higher technical performances resulted in a 10.9% reduction in gross GHG emissions per kg BW and a 15.7% reduction in non-renewable energy consumption per kg BW. Although the difference was not significant, it should be noted that non-renewable energy consumption was higher in CATmix vs CATspe, whether it was per LU (+7.6%) or per kg BW (+7.1%). Finally, the feed–food competition indicator was improved by 47.2% in SHmix compared to SHspe, driven by lower consumption of concentrates and higher ewe productivity. We thus observed a convergence in economic, environmental and feed–food competition interests. Other environmental effects of combining beef cattle and sheep, such as pasture biodiversity, will be discussed in a further paper.

These grassland-based systems showed good environmental and feed–food performances but posed challenges for the traditional meat downstream sector

The level of animal productivity and GHG emissions obtained were comparable to or higher than those of the recent literature (Audurand et al., 2020). BW production per LU was 291 kg for CATspe and 288 kg for CATmix, which are similar values to the 290 kg found by Audurand et al. (2020). Gross GHG emissions (on the four main items used by CAP2ER®, whereas we performed a fuller assessment including equipment and buildings) per kg of live meat reached 18.0 kg $eqCO_2$/kg BW on average in Audurand et al. (2020), 18.2 for CATspe and 19.1 for CATmix. In the present study, the purchase of all replacement females in beef cattle enterprises penalised their overall GHG balance. Without the indirect impact of these purchased animals, GHG emissions would have reached 14.9 and 15.3 $EqCO_2$/kg BW for CATspe and CAT mix, respectively.

In both sheep enterprises, ewe productivity (per Ewe + 6 mont hs, for consistency with the following references) was high, reaching 1.37 for SMmix and 1.28 for SMspe vs 1.18 in conventional farming and 1.01 in organic grassland systems (Experton et al., 2017). Gross GHG emission levels (without equipment, buildings, fencing) were 17.7 $EqCO_2$/kg BW for SHspe and 15.8 for SHmix, vs 25.4 $EqCO_2$/kg BW on average for organic farms and 27.2 for conventional farms (Experton et al., 2017). Furthermore, the three livestock systems were entirely based on the use of permanent grassland, and therefore, offsetting of gross emissions linked to carbon storage was high (41% for cattle and 51% for sheep) compared to the 32% calculated for cattle in Audurand et al. (2020). It was 60% for organic sheep and 53% for conventional sheep (Experton et al., 2017). Compared to these references, net GHG emissions per kg BW produced were 11.5% lower for the average CATspe and CATmix and 18.8% lower for the average SHspe and SMmix.

However, the countereffect of these high performances was that the product output carried handicaps. In sheep, it was related to marketing seasonality, as lambs were marketed only between the end of July and the beginning of November. In beef cattle, the handicap was that the carcass characteristics did not fit the expectations of the traditional downstream industry in terms of carcass weight (Prache et al., 2023).

Conclusion

In a livestock farming system based on the exclusive use of permanent grasslands, we showed that the combination of beef cattle and sheep in a 60–40% LU ratio in a mixed livestock system afforded benefits on technical and economic performances, on GHG emissions and energy consumption, and on feed-food competition for the sheep enterprise only. The mixed system produced more meat per hectare than either specialised beef cattle only or specialised sheep only. In our economic conditions, the production benefits of the mixed system outweighed the additional induced costs (chiefly fencing). The potential additional constraints in terms of work organisation warrant further investigation. This system was set up in an experimental farm with only permanent grassland and at an altitude that did not allow grazing for more than six months a year. It is reasonable to expect these benefits of combining beef cattle and sheep to be further amplified in the lowlands where sheep can graze the entire farm area during the winter (unlike cattle), with a sharp reduction in dedicated forage stocks for sheep.

The specialised sheep system had a higher forage self-sufficiency than the mixed system and the specialised beef system, primarily as a result of the large share of the animals' needs covered at grazing, whereas in beef cattle, the highest needs were in winter and required large amounts of conserved forages that involve quantitative and qualitative losses compared to grazed forage. Furthermore, the classical estimation of LU used here may have overestimated sheep feeding requirements, thus favouring self-sufficiency in sheep enterprises. Addressing this issue through a finer assessment of animal feed requirements (focusing, for example, on recalculating net energy requirements) would be a methodological improvement. The keys to distributing the different inputs and costs across enterprises in systems combining several animal species also remain a methodological concern that should not be underestimated, as they have a significant impact on the relative performance of each enterprise.

This type of system-level experimentation is cumbersome to set up and manage but makes it possible to take into account the functioning of livestock enterprises on a yearly scale, such as management of the forage system and the interactions between grazing and forage harvesting, as well as the sequencing of zootechnical events and the construction of overall enterprise performance. Longer-term experiments are needed to test for any cumulative mechanisms that could bring further benefit to mixed farming systems.

Ethics approval

All procedures were approved by the C2EA-02 Ethics Committee (APAFIS#1417-2015081011477291 v3 and APAFIS#24191-2015043014541577 v4).

Data and model availability statement

None of the data used have been deposited in an official repository. The data and models that support the study findings are available to reviewers.

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Declaration of interest

None.

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