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Combining beef cattle and sheep in an organic system. I. Co-benefits for promoting the production of grass-fed meat and strengthening self-sufficiency

Sophie Prache [a,*], Karine Vazeille [b], Weaam Chaya [a], Bernard Sepchat [b], Priscilla Note [b], Guillaume Sallé [c], Patrick Veysset [a], Marc Benoît [a]

[a] *Université Clermont Auvergne, INRAE, Vetagro Sup, UMR Herbivores, F-63122 Saint-Genès-Champanelle, France*
[b] *Université Clermont Auvergne, INRAE, HERBIPOLE, 63122 Saint-Genès-Champanelle, France*
[c] *UMR Infectiologie et Santé Publique, INRAE, 37380 Nouzilly, France*

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ABSTRACT

Numerous advantages of combining cattle and sheep have been demonstrated at the grazing-season level, but the effects of this practice on system self-sufficiency require system-level and longer-term studies. We established three grassland-based organic systems as separate farmlets: one mixed system combining beef cattle and sheep (**MIX**) and two specialised systems, beef cattle (**CAT**) and sheep (**SH**), to serve as reference points. These farmlets were managed for 4 years, to assess the benefits of combining beef cattle and sheep in promoting the production of grass-fed meat and strengthening system self-sufficiency. The ratio of cattle to sheep livestock units in MIX was 60:40. The surface area and stocking rate were similar across all systems. Calving and lambing were adjusted to grass growth to optimise grazing. Calves were pasture-fed from 3 months old on average until weaning in October, fattened indoors with haylage and slaughtered at 12–15 months. Lambs were pasture-fed from 1 month old on average until slaughter; if lambs were not ready for slaughter when the ewes mated, they were stall-finished with concentrates. The decision to supplement adult females with concentrate was based on the achievement of a target body condition score (**BCS**) at key periods. The decision to treat animals with anthelmintics was based on mean faecal egg excretion remaining below a certain threshold. A higher proportion of lambs were pasture-finished in MIX vs SH ($P < 0.001$) due to a higher growth rate ($P < 0.001$) which led to a lower age at slaughter (166 vs 188 days, $P < 0.001$). Ewe prolificacy and productivity were higher in MIX vs SH ($P < 0.02$ and $P < 0.065$, respectively). The levels of concentrate consumption and number of anthelmintic treatments in sheep were lower in MIX vs SH ($P < 0.01$ and $P < 0.08$). Cow productivity, calf performance, carcass characteristics and the level of external inputs used did not differ between systems. However, cow BW gain during the grazing season was higher in MIX vs CAT ($P < 0.05$). These outcomes validated our hypothesis that the association of beef cattle and sheep promoted the self-sufficient production of grass-fed meat in the sheep enterprise. It also promoted better ewe and cow BCS and BW at key stages of the reproduction cycle and better development of the females used for replacement, which may enhance animal and system resilience.

Implications

The association of beef cattle and sheep showed benefits at the grazing-season level, but its implications on system self-sufficiency require system-level and longer-term studies. We demonstrated that combining beef cattle and sheep within a mixed system was beneficial to the production of grass-fed meat and reduced the use of external inputs in the sheep enterprise. It also improved ewe and cow body condition and live weight at key periods of the reproduction cycle and improved the development of females used for replacement, which may strengthen the adaptative capacities of females to withstand possible shocks and improve resilience.

Introduction

The development of agriculture in Western countries since the 1950s has been based on the increasing specialisation of animal

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* Corresponding author.
E-mail address: sophie.prache@inrae.fr (S. Prache).

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and plant production (Thornton, 2010; Mahieu and Arquet, 2019). However, there has been renewed interest in incorporating greater animal and plant diversity in agricultural farming systems due to its presumed effects on system performance, efficiency and resilience, and the provision of ecosystem services (Martin et al., 2020; Dumont et al., 2020). Animal diversity may be approached from different dimensions, such as animal genotypes and species (Magne et al., 2019; Martin et al., 2020). The association of domestic animal species has been the subject of numerous studies worldwide, in temperate, tropical and Sahelian geographical areas (see the review by Martin et al., 2020) since the early work of Nolan and Connolly (1989). The sheep-cattle association has been the most studied (Abaye et al., 1994; Wright et al., 2006; Marley et al., 2006; d'Alexis et al., 2014; Fraser et al., 2014).

Several benefits of combining beef cattle and sheep in pastures have been demonstrated, such as improved BW gain per animal and per hectare (d'Alexis et al., 2014; Fraser et al., 2014; Jerrentrup et al., 2020), improved production efficiency (Fraser et al., 2014), reduced infection by gastrointestinal nematodes and reduced use of anthelmintic drugs (Marley et al., 2006; d'Alexis et al., 2014), reduced methane emissions (Fraser et al., 2014), greater habitat diversity and enhanced biodiversity (Fraser et al., 2014). These benefits are based on (i) taking advantage of the between-species complementarity in diet selection and foraging behaviour to obtain better value from the different resources available and better maintain the nutritive value of forage sources throughout the grazing season (Diaz Falu et al., 2014; Fraser et al., 2014, d'Alexis et al., 2014) and (ii) the dilution of certain parasites, such as nematodes, that are relatively strict towards their host (Marley et al., 2006; d'Alexis et al., 2014; Mahieu and Arquet, 2019). This farming practice could thus generate ecosystem services, e.g., better integrated management of parasites (via a bioagressor regulation service), better use of the available resources and improved forage nutritive value, which may enable the system to remain productive at reduced input levels, thereby increasing the efficiency of the system and reducing its environmental footprint while preserving animal health. However, most of these benefits have only been studied over relatively short time-spans of a few weeks or at the grazing-season level, and the broader effects on system self-sufficiency, resilience and environmental footprint require system-level and longer-term studies. A comprehensive assessment at the system level is lacking despite its necessity for the development of consistent recommendations to improve the performances of farms that already combine beef cattle and sheep or introduce a new animal species to a specialised farm (Martin et al., 2020). To address this gap, we designed a system-level experiment and performed a comprehensive multi-year assessment of a mixed grassland-based livestock system combining beef cattle and sheep that aimed to produce grass-fed meat self-sufficiently from permanent pasture herbage in an upland area. The present paper focused on animal performance and the level of external input use (concentrate and veterinary drugs). We tested the hypothesis that the association of beef cattle and sheep promoted the production of grass-fed meat and strengthened system self-sufficiency. We also quantified the gains of the association of beef cattle and sheep and highlighted i) where the gains were obtained in the production cycle of the two animal species and ii) the interactions and knock-on effects between the different periods of the reproduction cycle and the different groups of animals. A companion paper (Benoît et al., 2023) addresses economic outputs, greenhouse gas emissions, non-renewable energy consumption and feed-food competition, which are important dimensions in farm sustainability that have been under-investigated in experiments combining livestock species.

Material and methods

The present study was performed at the Laqueuille site of INRAE's 'Herbipôle' experimental unit, which is located in a highland area (Laqueuille, France, 1 100–1 400 m asl) and converted to organic farming (the conversion started 1 year before the beginning of the experiment). This site is characterised by a low annual average temperature (8 °C), abundant rainfall spread over the year (1 100 mm/year), and long snowy winters. Cropping is not possible due to local climate conditions, and the entire area is covered by permanent grassland. The grazing period is short, and the long winter-feeding period indoors demands a large quantity of conserved forage. Spring is late, with a risk of frost and snow until mid-May. Pasture biomass surges from mid-May to July, with good regrowth in September. The grazing period ends in late October.

Experimental design

We compared three organic upland livestock farming systems aimed at producing grass-fed meat self-sufficiently for 4 years: a mixed (**MIX**) system combining beef cattle and sheep, a mono-specific beef cattle system (**CAT**) and a mono-specific sheep system (**SH**). Sheep represented 40% of total livestock units in the MIX system, which is similar to the value identified by d'Alexis et al. (2014) as the optimum for average daily gain (**ADG**) per hectare in mixed grazing. The two mono-specific systems served as reference points to quantify the effects of combining beef cattle and sheep within a single mixed system.

Each system used 29 livestock units and 39 ha of permanent grasslands. A total of 171 plant species were present in the grasslands at the beginning of the experiment, but 24 of these species were dominant (i.e., they covered approximately 75% of the total area) (Table 1). Grasses, legumes and forbs covered 49, 13 and 37% of the grassland area, respectively. The main grass species

Table 1
Botanical composition of grasslands used (percentage cover) in the three established organic systems (one mixed system combining beef cattle and sheep, and two specialised systems, a beef cattle-only system and a sheep-only system). Only the main species (covering approximately 75% of the total area) are given, with species ranked in descending order of percentage cover in all grasslands.

Species	All grasslands	Meadows	Pastures
Agrostis capillaris L., 1753	12.5	7.8	15.7
Trifolium repens L., 1753	9.6	12.5	7.6
Festuca rubra subsp. *rubra* L., 1753	6.6	0.6	10.7
Taraxacum officinale F.H.Wigg., 1780	5.0	10.5	1.3
Bistorta officinalis Delarbre, 1800	4,0	8.6	0.9
Anthoxanthum odoratum L., 1753	3.7	5.0	2.8
Achillea millefolium L., 1753	3.4	0.1	5.7
Plantago lanceolata L., 1753	3.2	2.4	3.7
Dactylis glomerata L., 1753	3.1	5.7	1.3
Lolium perenne L., 1753	2.7	3.8	2.0
Poa pratensis L., 1753	2.5	4.1	1.4
Holcus mollis L., 1759	1.8	3.7	0.6
Phleum pratense L., 1753	1.8	3.5	0.6
Meum athamanticum Jacq., 1776	1.8	0.01	3.0
Bromus hordeaceus L., 1753	1.7	4.2	
Ranunculus acris L., 1753	1.6	2.7	0.9
Festuca lemanii Bastard, 1809	1.5		2.6
Nardus stricta L., 1753	1.5		2.5
Rumex acetosa L., 1753	1.5	3.5	0.2
Anthriscus sylvestris (L.) Hoffm., 1814	1.5	3.6	
Poa chaixii Vill., 1786	1.4	0.03	2.3
Trifolium pratense L., 1753	1.1	0.1	1.7
Cynosurus cristatus L., 1753	1.0	0.1	1.6
Carex caryophyllea Latourr., 1785	1.0		1.6
146 other species	24.6	17.5	29.4

were *Agrostis capillaris* L., *Festuca rubra subsp. rubra* L., *Anthoxanthum odoratum* L., *Dactylis glomerata* L., *Lolium perenne* L., and *Poa pratensis* L. The main legume species were *Trifolium repens* L. and *Trifolium pratense* L., and the main forb species were *Taraxacum officinale* F.H.Wigg., *Bistorta officinalis* Delarbre, *Achillea millefolium* L., *Plantago lanceolata* L., *Meum athamanticum* Jacq. and *Ranunculus acris* L. The complete botanical composition is given in Supplementary Table S1. The mean annual stocking rate was 0.75 livestock units/ha, which was chosen based on our knowledge of forage production at the experimental site and our previous experiment in which an experimental site had been converted to OF (Benoit et al., 2009). The initial grasslands and animal characteristics were similar across the three systems. Grasslands were randomly assigned at the beginning of the experiment to one of the three systems based on altitude, type of use (mowing/grazing), production potential and location (e.g., proximity to buildings, water points and shelter). The meadows were fertilised with manure, and the pastures received only the faeces and urine of the animals rejected during the grazing period. The same staff managed all three systems throughout four consecutive campaigns. The experimental site was free of sheep prior to commencement of the experiment. The sheep were imported from another farm and were not treated for parasites before arriving at the experimental site. We converted the experimental site to organic farming. Organic systems are often more diversified, seek to manage animal health in a more integrated way, and have a greater incentive to use grassland for meat production because organic concentrates cost much more than conventional concentrates. Details on the three farming systems are given in Fig. 1.

Animals

The mean annual number of ewes over 12 months of age was 74.8 in the MIX system and 178.0 in the SH system. The ewes (Limousine breed) were managed as one flock before the experiment and then randomly allocated at the beginning of the experiment based on BW, body condition score (**BCS**), age, milk production and prolificacy genetic indices to form two flocks of similar characteristics but different sizes. The mean ewe BW, BCS and age at the beginning of the experiment were 65.7 kg (SD 14.06), 3.0 (SD 0.35), and 3.3 (SD 2.24) years, respectively. Most ewes were crossed with Suffolk rams to facilitate the production of grass-fed lamb, and the remainder (32%) were mated with Limousine rams for ewe lamb replacement. The ewe lambs were

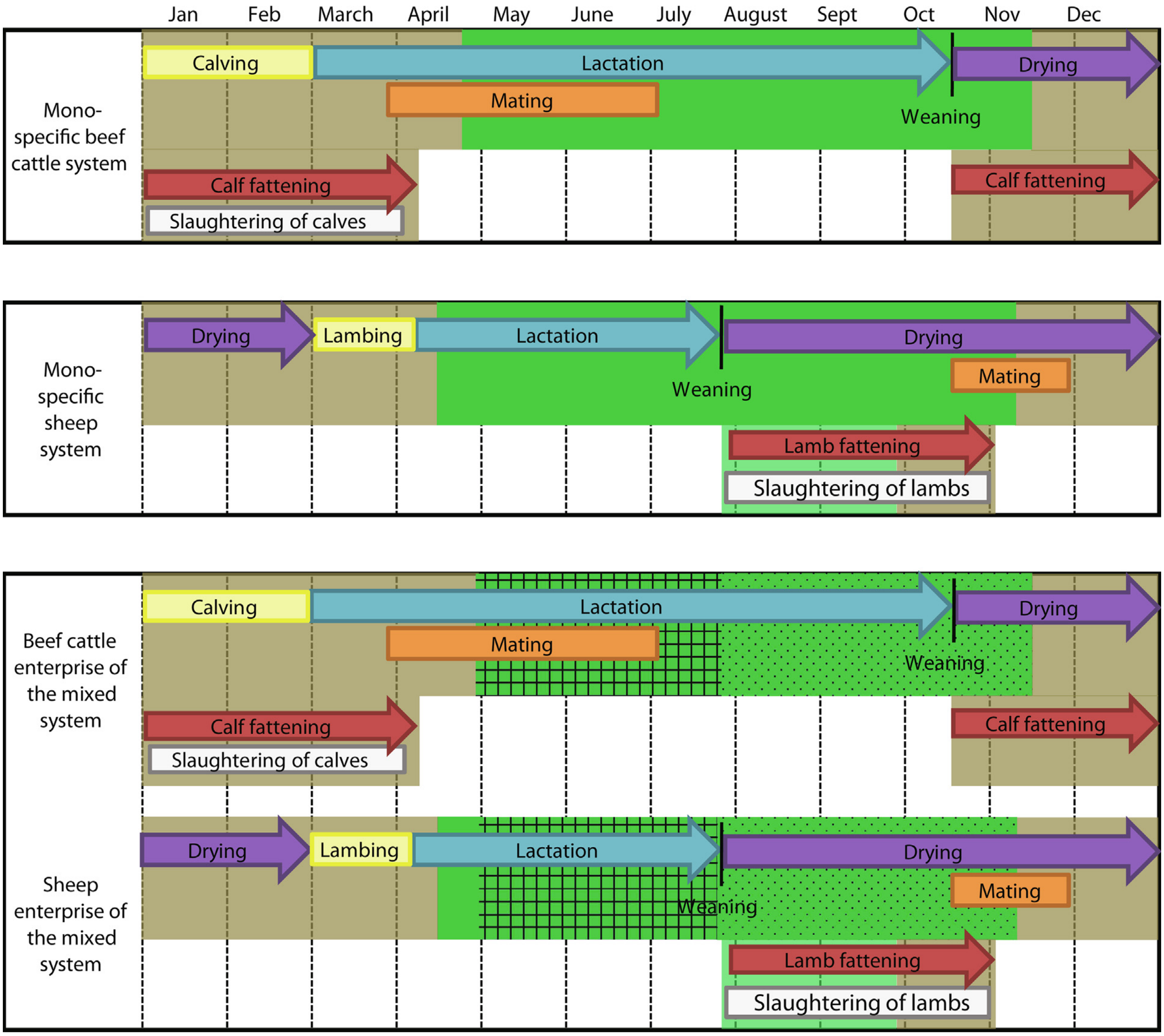

Fig. 1. Overview of the characteristics of the mono-specific beef cattle and sheep ‘control’ systems and the mixed system combining beef cattle and sheep. Green and brown colours refer to the grazing and stall periods, respectively. For the grazing period, areas with a grid correspond to co-grazing, where sheep and cattle grazed together, areas with dots correspond to sequential grazing, where beef cattle grazed first, then dry ewes, the other areas were grazed by one animal species only.

reared within the system and first lambed when they were 2 years old (mating duration: two cycles). The mean annual number of cows was 12.3 in the MIX system and 21.4 in the SH system. The cows (Salers breed) were managed as one herd before the experiment then randomly allocated at the beginning of the experiment based on BW, BCS, age and milk production to form two herds of similar characteristics but different sizes. The mean cow BW, BCS, age and milk production at the beginning of the experiment were 678.4 kg (SD 61.90), 2.2 (SD 0.31), 5.1 (SD 1.82) and 8.1 kg (SD 1.15), respectively. We crossed the Salers cows with Angus bulls to facilitate the fattening of young animals using grass diets and the production of grass-fed beef (Dufey et al., 2002; Keane and Drennan, 2008; Warren et al., 2008; Bures and Barton, 2018). Because the beef cattle herds were small, all Salers cows were crossed (natural service), and cow renewal was ensured by purchasing Salers heifers from the experimental unit at 2 years of age just before the mating period. The beef cattle replacement rate was approximately 12% to limit animal purchases. We castrated the young males in both species to further facilitate their fattening using grass and avoid any problems arising from early sexual maturity.

Management

Sheep

Lambing occurred between beginning of March and mid-April (March 20th on average over the four campaigns) to allow lambs to be turned out to pasture at 1 month of age on average. Lambs at this age could withstand the vagaries of highland weather, and it optimised the proportion of pasture-finished lambs before the end of the grazing period (Fig. 1). Any lambs that could not be suckled by a dam (e.g., from triplet and quadruplet litters) were removed from the experiment and sold at approximately 5 kg for artificial rearing in another farm; removed lambs were discarded from this study. Most of the other lambs were turned out to pasture with their dams without any concentrate supplementation. A few lambs were not turned out to pasture (n = 2 and 5 in MIX and SH, respectively, over the four experimental campaigns) or were put in stalls early (n = 1 and 6 in MIX and SH, respectively) because they were considered too weak, or the lamb or dam had health problems that excluded pasture feeding. The lambs were weaned during the second half of July (on the 23rd and 20th on average over the four campaigns, in MIX and SH, respectively) at an average of 125 (MIX) and 120 (SH) days of age. All of the lambs that were not finished at pasture (ready for slaughter) 3–4 weeks before the mating period began in mid-October were stall-finished indoors using a concentrate-based diet to minimise competition for pasture grass between ewes and lambs. On average over the four campaigns, the mating period occurred between 15 October and 21 November and lasted 37 days in both systems. The rams were changed from one system to the other every 10 days to avoid confounding effects of system and ram.

Beef cattle

Angus bulls were introduced in both cow herds from end of March to early-July and calving occurred between January and beginning of March (24 and 22 January on average over the four campaigns, for CAT and MIX, respectively) to ensure that the dam's lactation needs would coincide with pasture herbage availability (Fig. 1). All calves and their dams were turned out to pasture in spring (on 26 April on average over the four campaigns), when the calves were 3 months old on average, without any concentrate supplementation until weaning in October (on 18 October, on average over the four campaigns). After weaning, the young calves (males and females) were fattened indoors with haylage from natural mountain grasslands without any concentrate supplementation (except in the first experimental campaign) until slaughter, which occurred at 12–15 months (i.e., before the new grazing season started). The combination of (i) a severe drought and scarce forage and (ii) market uncertainty tied to the COVID pandemic during the last campaign meant that most of the calves produced had to be sold off before they had reached a satisfactory degree of fatness. The data on calf performance during the fattening period and resulting carcass characteristics only refer to the first three campaigns.

Grazing management

Grazing management was carefully considered to optimise the quality of the herbage and its parasite contamination level in relation to the needs and sensitivity to parasites of the different animal categories. Producing high-quality forage is essential for the self-sufficient production of grass-fed meat. The beginning of the grazing season was a key time point. Early turn-out to pasture was essential to sustain high-quality pastures further into the grazing season, but it also exposed animals to climate hazards that may severely impact pasture growth and animal welfare and productivity. A target of 300 degree-days was retained for lactating animals (cows and ewes with their offspring) turned out to pasture, but the animals with lower requirements (ewe lambs and the few ewes that did not lamb) were turned out to pasture earlier, at approximately 270 degree-days. The value of degree-days refers to the sum of temperatures calculated by the accumulation of mean daily air temperatures bounded to a minimum of 0 °C and a maximum of 18 °C from February 1st to August 31st (Deroche et al., 2020).

Cattle and sheep were assembled to give the best trade-off between workload, nutrient requirements and sensitivity to parasites of the different animal categories. All animals grazed together from turn-out to pasture in spring until weaning of the lambs at the end of July (Fig. 1). Splitting the herd according to the needs of the different categories of animals was of low interest because of the extra work involved. Conversely, from the weaning of lambs until the end of the grazing season, differences in the nutrient requirements of the different animal categories and their sensitivity to parasites prompted the following management strategies: (i) weaned lambs and ewe lambs kept for ewe replacement grazed on aftermaths; (ii) sequential grazing first by cows and calves then by dry ewes on pastures that had already been grazed; and (iii) ewes grazed on aftermaths from 3–4 weeks before the mating period began until mid-November. After weaning the calves in October, ewes and cows grazed for as long as the pasture was available and/or weather conditions permitted and were then brought indoors to overwinter.

Monitoring animal body condition score at key periods in the production cycle to contain the use of inputs without unduly penalising reproductive performance

An important rule for combining high animal productivity with feed self-sufficiency was to monitor female BCS at critical physiological periods, e.g. mating and the peri-parturient period. Because the ewes were highly productive, the minimum ewe BCS benchmarks (3.0 at mating and lambing) were strictly designed to sustain high ewe prolificacy and ensure high lamb BW at birth and high ewe milk production (Knight et al., 2020), which are key factors for successfully fattening lambs at pasture (Prache and Thériez, 1988) and carcass and meat quality attributes (Knight et al., 2020; Prache et al., 2022a). If the average ewe BCS was ≤2.5 at 2 weeks premating, then all of the ewes were supplemented with concentrate during mating. Otherwise, they grazed without supplementation. At 8 weeks prelambing, ewes with a BCS below 3.0 were out-sorted to receive more concentrate than their counterparts. Similarly, the minimum cow BCS benchmark at mating and calving was 2.5. The cow diet was also adjusted if necessary using concentrates to ensure calf viability and good milk production for high calf ADG. The BCS of young animals was also strictly evaluated to out-sort animals of sufficient fatness for slaughter and limit competition for herbage availability or use of concentrate for stall-finished lambs.

Integrated parasite management to contain the use of anthelmintics

Grazing systems expose animals to parasites, and more productive animals are more parasite-sensitive. Integrated parasite management combines four means of control that are summarised by four key words: avoid, resist, treat, and monitor. Low-input and OF systems favour a combination of these four means, and the use of veterinary drugs is only recommended as a last resort when all other options were insufficient. The 'avoid' component involves minimising contact between the animals that are most sensitive or receptive to infestations (i.e., particularly young animals) and parasites. The present study achieved this mean via pasture management and farming practices that favoured greater milk intake by young animals. The two most important pasture management practices were (i) reserving the least-contaminated plots for the most parasite-sensitive animals (the aftermaths were reserved for the weaned lambs) and (ii) natural pasture clean-up via the simultaneous co-grazing of sheep and beef cattle to dilute parasites (practised before the lambs were weaned) or sequential grazing (each animal species in turn) to disrupt the life cycle of the parasites (practised after the lambs were weaned and until the ewes mated) (Fig. 1). In addition, because lambs with a low milk intake level ingest grass earlier and in greater quantity, they infest earlier and more severely (Prache and Thériez, 1988). A good BCS of the dam at the end of gestation is thus essential to ensure a high lamb birth weight, which gives the lamb greater resistance, and high milk production, which allows the lamb to avoid parasite infestation to some extent (Prache and Thériez, 1988).

Egg excretion per gram faeces (**EEGF**) was an important monitoring indicator to check the parasite burden and help decide whether a treatment was needed. Gastrointestinal nematode EEGF was measured regularly on 15 randomly selected male lambs (because males are more parasite-sensitive than females) every 15–30 days from turn-out to pasture onwards to provide a rough estimate of the digestive parasite burden of the lamb batch. If the average EEGF exceeded 500 eggs/g faeces, then all male lambs were individually sampled to determine whether to administer an anthelmintic treatment to the entire group of lambs (using the same cut-off value of 500 eggs/g faeces). EEGF was measured on all male calves at weaning. If the average EEGF exceeded 200 eggs/g faeces, then all calves were treated. EEGF was measured in adult ewes before turn-out to pasture to determine whether an anthelmintic treatment was needed. Ewe lambs were given an anthelmintic treatment just before their turn-out to pasture and just after the grazing season. Cows did not receive any anthelmintics.

Lamb and calf slaughter

Lambs and calves were slaughtered when their fat class on the EUROP grid reached approximately three. Most of the animals were slaughtered at a commercial abattoir, where the carcasses were weighed and graded for conformation and fatness. However, some animals, including all male lambs produced in the first campaign, and all young beef cattle produced in the second campaign were slaughtered at the INRAE experimental abattoir for finer-grained measurements (Liu et al., 2022; 2023).

Data recordings and measurements

Fertility (ewes) and pregnancy rate (cows) were calculated using the ratio of pregnant females at the time of pregnancy diagnosis/(number of mated females - number of females that died between previous mating and pregnancy diagnosis). Prolificacy in sheep was calculated as the ratio of (number of lambs born + number of stillborn lambs)/number of ewes having lambed. Ewe productivity (i.e., number of lambs produced per ewe per year) and ewe mortality were calculated according to Benoit and Laignel (2006) and Benoît et al. (2023). Cow productivity was calculated as the number of calves weaned per female mated. Mortality events and the reason for the mortality were recorded. The BW of all animals was recorded regularly throughout the production cycle. The dam BCS was recorded at key periods of the reproduction cycle: pre- and postmating, two months before the end of gestation and weaning of the offspring in ewes; and mating, calving and weaning of the offspring in cows. Concentrate consumption by a given category of animals was calculated based on the amount of concentrate distributed to that category and the number of animals. Total annual concentrate consumption was expressed per cow (or per ewe over 12 months of age) based on the mean annual number of animals. The nematodes, *Moniezia* faecal egg and the faecal oocyst counts were measured according to Raynaud (1970). The total annual number of drenches against nematodes, *Moniezia* and coccidiosis was expressed per cow (or per ewe over 12 months of age) based on the mean annual number of animals. Sheep and calf carcass characteristics were measured 24 h *post-mortem*. Conformation and fatness were assessed by visual evaluation, using the EUROP classifications of conformation and fatness transformed into two variables that ranged from 1 to 15.

Pasture herbage samples were collected each year (except the last year due to the COVID pandemic) from each paddock to be grazed. Depending on the size of the paddock, between 4 and 13 quadrats (70 cm × 70 cm) were cut to a height of 3.5 cm. These samples were dried at 60 °C for 72 h, ground through a 1-mm mesh and bulked for each paddock. DM digestibility, neutral detergent fibre, acid-detergent fibre, CP (g/kg DM), and net energy content (Unités Fourragères Lait (**UFL**)/kg DM) were determined for each bulked sample by near-infrared reflectance spectroscopy using in-house calibration equations. The nutritive value of the pasture herbage on offer was then averaged over the 3 years on a week basis. Samples of haylage fed to the calves during the fattening period were taken weekly, dried for 72 h at 60 °C, pooled and subjected to similar analyses.

Statistical analysis

Data for lamb BW, growth and carcass characteristics were analysed using ANOVA in a mixed model (SAS Institute Inc., 2014) with system, breed and sex as fixed factors (and interaction terms between fixed factors) and year as a random factor. Data for calf BW, growth and carcass characteristics were analysed using ANOVA in a mixed model with system and sex as fixed factors (and interaction terms between fixed factors) and year as a random factor. The statistical unit was the animal.

Data for adult ewe and cow BW and BCS, ewe carcass weight, and cow BW change between turn-out to pasture and weaning were analysed using ANOVA in a mixed model with system as a fixed factor and year as a random factor. Student's *t-test* was used to compare female BCS at mating and calving/lambing against the set threshold value (2.5 for cows and 3.0 for ewes). The statistical unit was the animal.

Data for ewe lamb BW change from birth until 2 years were analysed for three ewe lamb cohorts born within the SH and MIX systems (cohorts born in campaigns 1, 2 and 3) using a mixed model with system as a fixed factor and cohort as a random factor. The statistical unit was the animal.

A chi-squared test was used to compare the distribution in MIX vs SH of (i) lambs born as singletons, twins and triplets (+quadruplets), (ii) lambs suckled as singletons or twins, (iii) lamb fates (dead during the experiment, artificially reared, kept for ewe replacement, and slaughtered), and (iv) lamb slaughter dates. A chi-squared test was also used to analyse between-system differences in (i) ewe fertility and cow pregnancy rate, (ii) proportion of lambs finished at pasture, (iii) proportion of ewe lambs culled or dead before first lambing, and (iv) reasons for ewe mortality. The statistical unit was the animal.

We used a *t-test* for paired samples to analyse between-system differences in ewe prolificacy and productivity, total concentrate consumption per year, and the total number of drenches used per year against nematodes, *Moniezia* and coccidiosis (expressed per ewe). A *t-test* for paired samples was also used to analyse between-system differences in total concentrate consumption per year and total number of drenches used per year against parasites (expressed per cow). The statistical unit was the system.

Results

Climate conditions during the four experimental campaigns were drier and warmer than the averages over the previous 20 years, and details are given in Benoît et al. (2023). The mean net energy value and CP content of the pasture herbage about to be grazed were high and close between the three systems (Figs. 2 and 3). Overall, the mean net energy value was highest between weeks 19–22 and lowest at turning out to pasture, between weeks 33–34 and at the end of the grazing period. The CP content was highest between weeks 19–22 and lowest at turning out to pas-

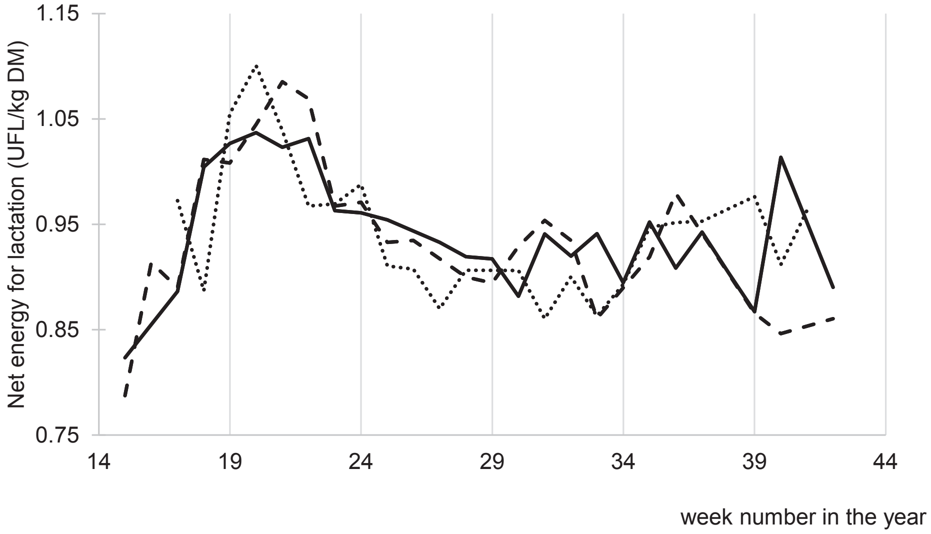

Fig. 2. Mean net energy for lactation (Unités Fourragères Lait/kg DM) of pasture herbage about to be grazed by the herd. The solid line, dashed line and dotted line refer to the mixed system combining beef cattle and sheep, the mono-specific sheep-only system, and the mono-specific beef cattle-only system, respectively.

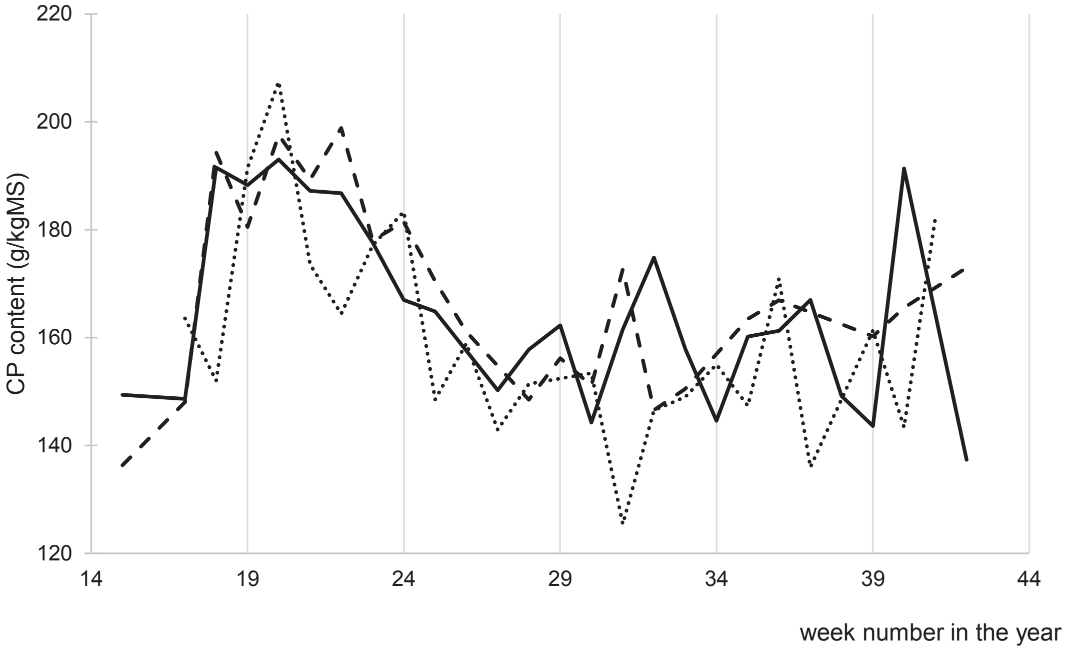

Fig. 3. Mean CP content (g/kg DM) of pasture herbage about to be grazed by the herd. The solid line, dashed line and dotted line refer to the mixed system combining beef cattle and sheep, the mono-specific sheep-only system, and the mono-specific beef cattle-only system, respectively.

ture, between weeks 27–35 and 37–39 and at the end of the grazing period. Net energy value of the pasture herbage from April (week 17) to July (week 29), which was the period when all animals in the mixed system grazed together, was high and similar for all three systems. Net energy value over this period averaged 0.96 (range: 0.87–1.10) UFL/kg DM, 0.97 (range: 0.89–1.04) UFL/kg DM, and 0.98 (range: 0.89–1.09) UFL/kg DM in CAT, MIX and SH, respectively (Fig. 2). CP content over this period averaged 168 (range: 143–207) g/kg DM, 173 (range: 149–193) g/kg DM, and 175 (range: 148–199) g/kg DM in CAT, MIX and SH, respectively (Fig. 3).

Sheep enterprise

The set threshold of 3.0 for mean ewe BCS at postmating was reached each year in both systems (Fig. 4). Ewe fertility was high and similar in both systems (96.05%). Ewe prolificacy was higher in MIX vs SH (1.96 vs 1.83, $P < 0.02$), with a higher proportion of triplet (and quadruplet) lambs (20.04 vs 13.61%) and a lower proportion of singleton lambs (8.67 vs 13.78%), the proportion of twin lambs being similar (71.29 vs 72.60%). Ewe productivity tended to be higher in MIX vs SH (1.53 vs 1.41, $P = 0.065$).

There were 1 687 lambs born over the four experimental campaigns. The proportions of lambs that died (13.3%) were artificially reared (12.3%), were kept for ewe replacement (12.0%), or were slaughtered (62.4%) did not differ between systems. A total of 1 052 lambs were slaughtered, 730 in SH and 322 in MIX. The proportion of lambs finished at pasture was higher in MIX than SH (99.1 vs 84.8%, $P < 0.001$) (Fig. 5). Most lambs were finished at pasture in MIX, whereas the proportion of lambs finished at pasture in SH ranged between 74.0 and 97.3% depending on the year (with the lowest proportion observed during the third campaign, which was hit by drought).

Lamb birth BW did not differ between systems (Table 2), but crossbred lambs were 0.98 kg heavier than purebreds ($P < 0.001$), and castrates were 0.24 kg heavier than females ($P < 0.05$). The proportions of lambs suckled as singletons (72.5%) or twins (27.5%) also did not differ between systems. The number of lambs suckled per ewe was 1.60 and 1.56 in MIX and SH, respectively. Lamb ADG from birth to weaning (**ADG**$_{\text{bw}}$) differed between systems ($P < 0.001$), breeds ($P < 0.001$) and sexes ($P < 0.001$). Lamb ADG_{bw} was 29 g/d higher in MIX than SH, 13 g/d higher in crossbred lambs than pure Limousine lambs, and 14 g/d higher in castrates than females. Lamb ADG from birth to slaughter (**ADG**$_{\text{bs}}$) and lamb age at slaughter also differed between systems ($P < 0.001$), breeds ($P < 0.001$) and sexes ($P < 0.001$). Lamb ADG_{bs} was 33 g/d higher in MIX than SH, 26 g/d higher in crossbred lambs than pure Limousine lambs and 13 g/d higher in castrates than females. MIX lambs were slaughtered 22 days earlier than SH lambs. Crossbred lambs were slaughtered 19 days earlier than pure Limousine lambs, and castrates were slaughtered 9 days earlier than females. Therefore, the frequency distribution of lamb slaughter dates differed between systems, with a higher proportion of lambs sold in July and August in MIX vs SH (52.2 vs 24.7%, $P < 0.001$). The duration of the finishing period for stall-finished SH lambs averaged 48 (SD 12.5) days. Lamb ADG_{bw}, BW at the beginning of the stall-finishing period and ADG during this period averaged 138 (SD 27.8) g/d, 29.0 (SD 3.39) kg and 221 (SD 80.8) g/d, respectively.

Lamb carcass weight differed between systems ($P < 0.001$), breeds ($P < 0.001$) and sexes ($P < 0.001$) (Table 2). The carcass weight was 0.48 kg higher in MIX lambs than SH lambs, 0.65 kg higher in crossbred lambs than pure Limousine lambs, and 2.14 kg higher in castrates than females. Carcass conformation and fatness did not differ between systems, but conformation was higher in crossbreds (by 0.68 units, $P < 0.001$) and castrates (by 0.67 units, $P < 0.001$) and fatness was higher in castrates (by 0.32 units, $P < 0.01$). Carcass conformation averaged 6.19 in MIX and 6.05 in SH, which corresponds to the range O+ to R– in the EUROP classification. Carcass fatness averaged 7.21 in both systems, which corresponds to the range 3- to 3 = in the EUROP classification.

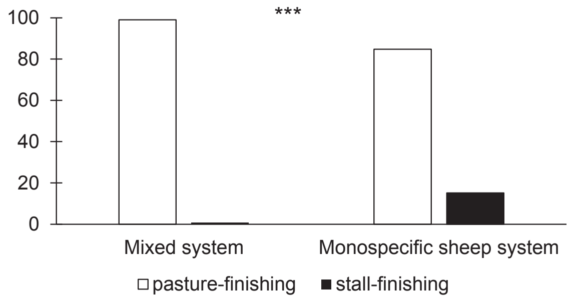

Fig. 5. Proportion of pasture-finished or stall-finished lambs in the mixed system combining beef cattle and sheep and in the mono-specific sheep-only system. ***$P < 0.001$.

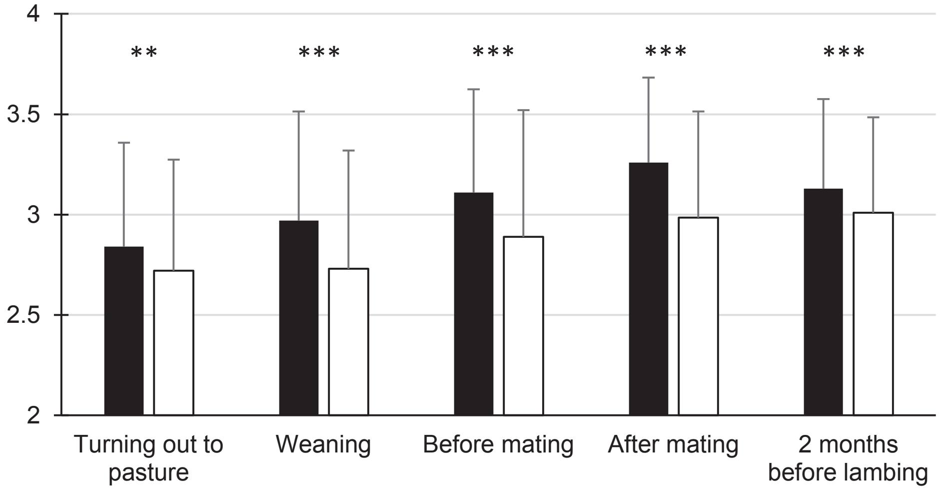

Fig. 4. Ewe mean body condition score at key periods of the reproductive cycle. Solid symbols refer to the mixed system combining beef cattle and sheep. Open symbols refer to the mono-specific sheep-only system. Bars refer to standard deviation. **$P < 0.01$, ***$P < 0.001$.

Table 2
Lamb performances and carcass characteristics.

Item	System[1]		Breed[2]		Sex		SEM	*P*-value		
	Mixed (n = 322)	Mono (n = 730)	Cross (n = 827)	Pure (n = 225)	Male (n = 630)	Female (n = 422)		System	Breed	Sex
BW at birth (kg)	4.79	4.84	5.30	4.32	4.93	4.69	0.079	0.3607	<0.001	<0.001
BW at weaning (kg)	31.42	27.17	30.72	27.89	30.51	28.07	0.502	<0.001	<0.001	<0.001
BW at slaughter (kg)	38.41	37.24	38.81	36.84	40.04	35.61	0.579	<0.001	<0.001	<0.001
ADG_{bw}[3] (g/d)	213	184	205	192	207	193	6.3	<0.001	<0.001	<0.001
ADG_{bs}[4] (g/d)	211	179	208	182	202	188	8.7	<0.001	<0.001	<0.001
Age at slaughter (d)	166	188	167	186	181	172	4.4	<0.001	<0.001	<0.001
Carcass weight (kg)	15.40	14.92	15.49	14.84	16.23	14.09	0.438	<0.001	<0.001	<0.001
Carcass conformation	6.19	6.05	6.46	5.78	6.45	5.78	0.089	0.0657	<0.001	<0.001
Carcass fatness	7.21	7.21	7.13	7.29	7.37	7.05	0.121	0.9604	0.1670	<0.005

[1] Mixed: mixed system combining beef cattle and sheep; Mono: mono-specific sheep-only system.
[2] Cross: crossbred (Suffolk × Limousine); Pure: pure Limousine.
[3] Average daily gain from birth to weaning.
[4] Average daily gain from birth to slaughter.

The distribution of ewes in the different BCS classes did not differ between systems at turn-out to pasture (data not shown), but it differed between systems for the other key periods of the reproduction cycle, i.e., at weaning, just before mating, just after mating and 2 months before lambing ($P < 0.001$ for all periods). The proportion of ewes considered under-conditioned at these different periods was lower in MIX ewes than SH ewes (Fig. 6). The mean ewe BCS was higher in MIX than SH at turn-out to pasture ($P < 0.01$), weaning, pre- and postmating and 2 months prelambing ($P < 0.001$) (Fig. 4). Ewe BW was higher in MIX than SH, at turn-out to pasture ($P < 0.05$) and at weaning, pre- and postmating, and 2 months prelambing ($P < 0.001$) (Fig. 7). The carcass weight of culled ewes was higher in MIX vs SH (25.9 vs 23.0 kg, $P < 0.001$). Ewe mortality was lower in MIX vs SH (4.28 vs 7.28%, $P < 0.05$), with no between-system differences in the proportion of ewes that died for health reasons (55%) or other reasons (45%).

Three cohorts of ewe lambs were kept for ewe replacement, with a total of 52 ewe lambs in MIX and 117 ewe lambs in SH. Ewe lamb BW did not differ between MIX and SH at birth, but subsequent BW was always higher in MIX vs SH (from 1.76 kg at weaning ($P < 0.05$) up to 4.37 kg 2 months before the first lambing ($P < 0.001$)), except for the third turn-out to pasture at approximately 2 years old (Fig. 8). Ewe lamb fertility and prolificacy were high and similar in both systems (96.83% and 1.61, respectively), as were the proportions of singletons (23.26%) and twin lambs (76.73%). The proportion of ewe lambs culled or dead before first lambing (15.38%) was similar between systems.

Total concentrate consumption per year was lower in MIX than SH (56.2 vs 69.5 kg/ewe, $P < 0.025$, Fig. 9). The mean concentrate consumption per lamb was lower in MIX lambs than in SH lambs (2.3 vs 9.7 kg, $P < 0.05$). Concentrate consumption by stall-finished SH lambs averaged 60.0, 53.6, 47.6 and 60.6 kg in campaigns 1, 2, 3 and 4, respectively. Mean concentrate consumption per ewe lamb from weaning until the second turn-out to pasture (at approximately 13 months) tended to be lower in MIX than SH (31.9 vs 41.4 kg). Mean concentrate consumption per ewe tended to be lower in MIX than SH at the mating period (6.9 vs 10.6 kg), during gestation (10.2 vs 10.6 kg/ewe) and during lactation (28.8 vs 29.9 kg/ewe). The total number of drenches against gastrointestinal nematodes per year tended to be lower in MIX than in SH (2.50 vs 3.12 per ewe, $P = 0.0795$, Fig. 10). The total number of treatments against *Moniezia* and coccidiosis per year was not

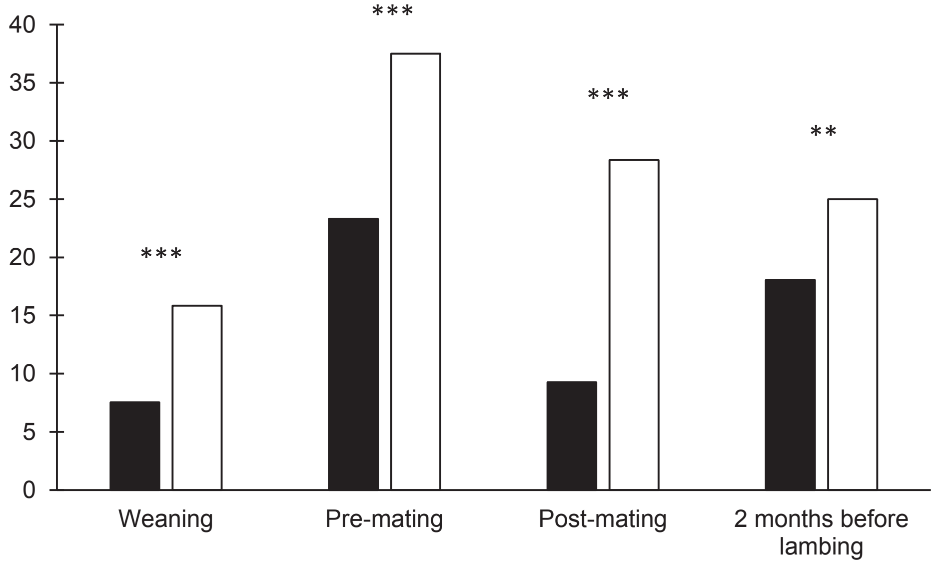

Fig. 6. Proportion of ewes considered under-conditioned at the different periods of the reproductive cycle. Solid symbols refer to the mixed system combining beef cattle and sheep. Open symbols refer to the mono-specific sheep-only system. Ewes were considered under-conditioned when their body condition score was ≤2.0 at weaning and ≤2.5 at premating, postmating, and two months before lambing. **$P < 0.005$, ***$P < 0.001$.

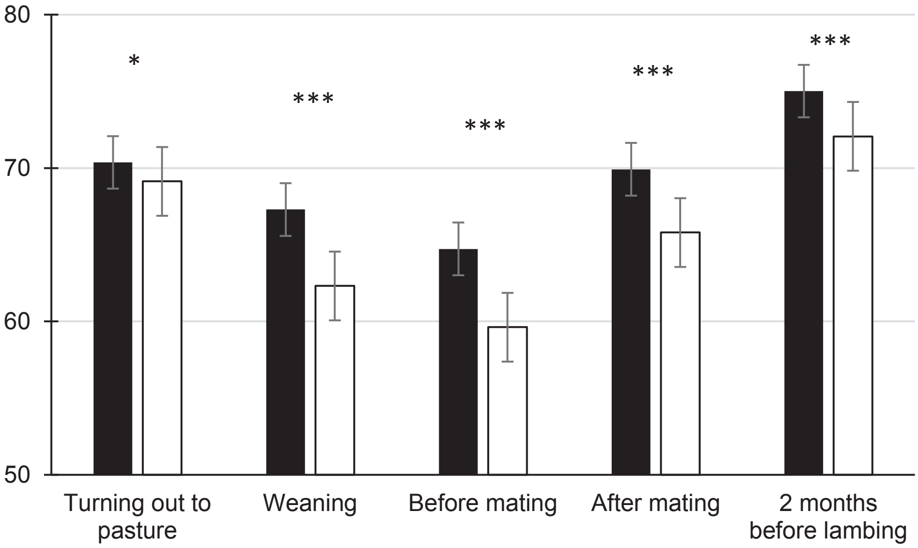

Fig. 7. Ewe mean BW (kg) at key periods of the reproductive cycle. Solid symbols refer to the mixed system combining beef cattle and sheep. Open symbols refer to the mono-specific sheep-only system. Bars refer to standard deviation. $^{*}P < 0.05$, $^{***}P < 0.001$.

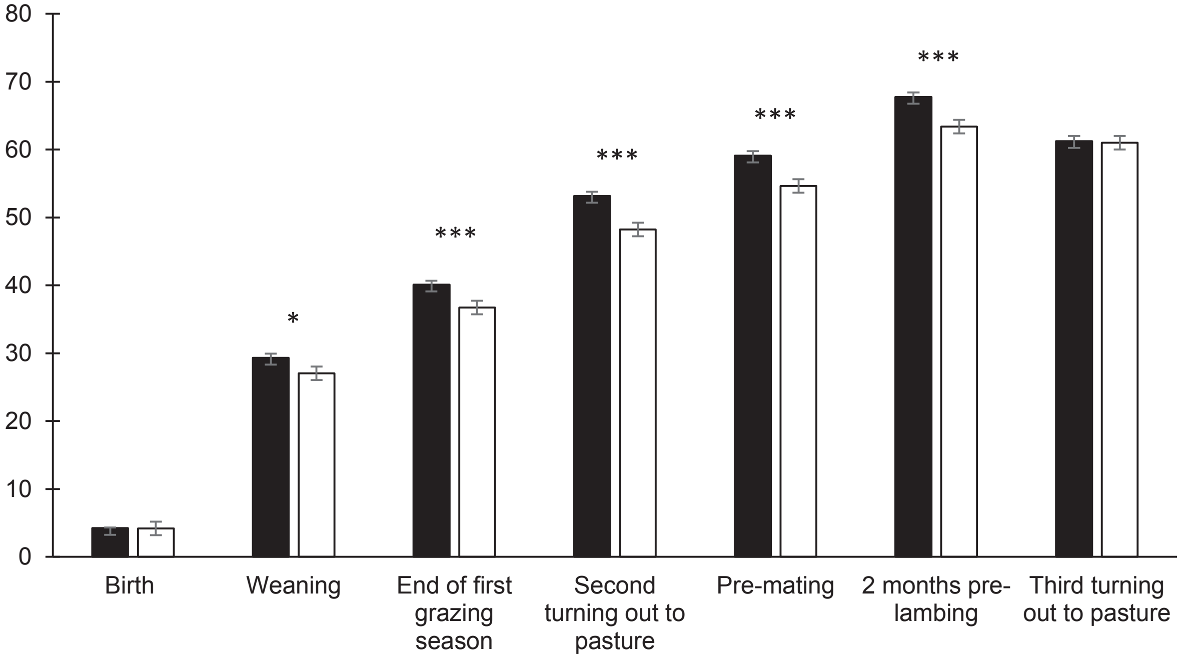

Fig. 8. Change in ewe lamb BW (kg) from birth until the third turn-out to pasture. Solid symbols refer to the mixed system combining beef cattle and sheep. Open symbols refer to the mono-specific sheep-only system. Bars refer to standard deviation. $^{*}P < 0.025$, $^{**}P < 0.01$, $^{***}P < 0.001$.

different between MIX and SH (1.95 vs 2.15 per ewe, $P = 0.44$, and 1.1. vs 1.30 per ewe, $P = 0.51$, respectively).

Beef cattle enterprise

Cow BCS was higher in MIX than CAT at mating (2.21 vs 2.01, $P < 0.01$), calving (2.28 vs 2.00, $P < 0.001$) and weaning (2.12 vs 1.94, $P < 0.005$). Cow BW was higher in MIX than CAT at mating (694 vs 663 kg, $P < 0.05$), calving (777 vs 735 kg, $P < 0.005$) and weaning (712 vs 663 kg, $P < 0.001$). Average BW gain between turn-out to pasture and weaning, i.e., during most of the grazing season, was higher in MIX vs CAT suckler cows (13 vs 3 kg, $P < 0.05$). The set threshold of 2.5 for mean BCS at mating and calving was reached in two of the 4 years in MIX but was never reached in CAT ($P < 0.005$–0.001) (Fig. 11). The proportion of cows considered under-conditioned was lower in MIX cows than CAT cows at calving and mating ($P < 0.001$ and $P < 0.005$, respectively) (Fig. 12) and tended to be lower in MIX vs CAT cows at weaning ($P = 0.07$). The mean BCS of the cows at mating was particularly low in the last campaign and reached a critical value of 1.6 in CAT (Fig. 12). The cow pregnancy rate and mean interval between calvings were not significantly different between systems (91.15% and 355 days, respectively). Cow productivity was not significantly different between MIX and CAT (0.842 vs 0.898).

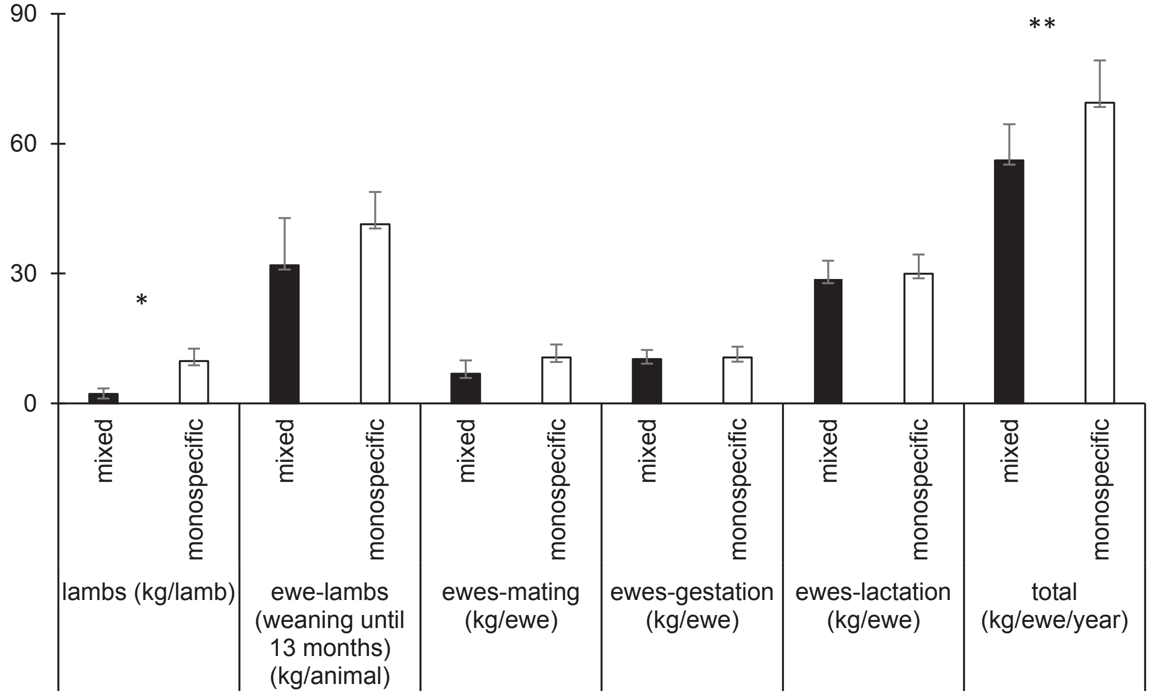

Fig. 9. Average concentrate consumption (kg, as-fed basis) by sheep at the different periods of the reproductive cycle and total consumption per ewe per year (kg). Solid symbols refer to the mixed system combining beef cattle and sheep. Open symbols refer to the mono-specific sheep-only system. Bars refer to standard deviation. $^{*}P < 0.05$, $^{**}P < 0.025$.

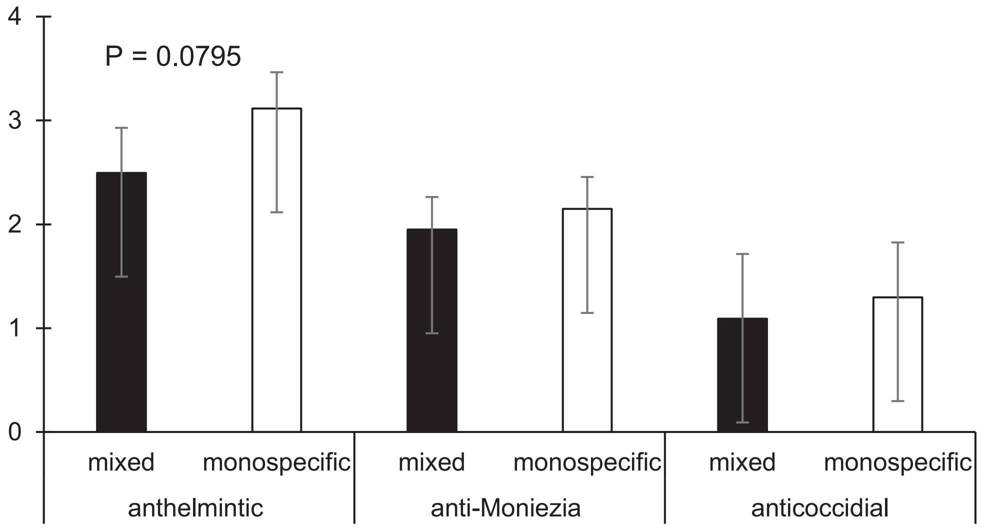

Fig. 10. Average number of anti-parasite drenches used (per ewe per year). Solid symbols refer to the mixed system combining beef cattle and sheep. Open symbols refer to the mono-specific sheep-only system. Bars refer to standard deviation.

There were 141 calves born over the four experimental campaigns (88 CAT, 53 MIX). Out of these calves, eight died (two CAT, six MIX), 100 were slaughtered (63 CAT, 37 MIX), and the remaining 33 (23 CAT, 10 MIX) were sold off mid-fattening due to the combination of (i) severe drought and scarce forage and (ii) market uncertainty tied to the COVID pandemic. Calf birth weight did not differ between systems, but castrates were 2.3 kg heavier than females ($P < 0.05$) (Table 3). Calf ADG_{bw}, calf BW and BCS at weaning also did not differ between systems, but they were lower in females than castrates ($P < 0.001$).

The nutritive value of the haylage fed to the calves during fattening averaged 0.71 Unités Fourragères Viande/kg DM (net energy for meat production), 109 g CP/kg DM, and 81 g Protéine digestible dans l'intestin (**PDI**) (truly digestible protein)/kg DM (INRA, 2018). Calf ADG between weaning and slaughter, i.e., during the fattening period, did not differ between systems (899 g/d in MIX and 860 g/d in CAT), but it was 47 g/d higher in castrates than females ($P < 0.05$) (Table 3). BW at slaughter was not different between systems (480 kg in MIX and 473 kg in CAT, $P = 0.19$), but was 47 kg higher in castrates than in females ($P < 0.05$). Age at slaughter did not

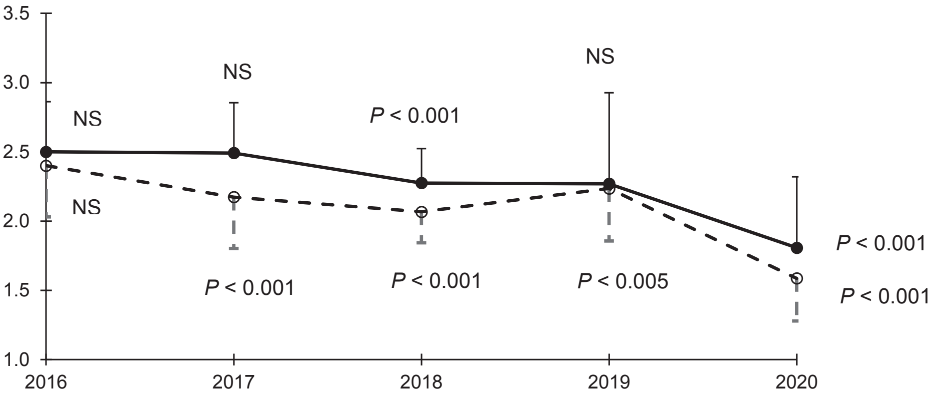

Fig. 11. Change in cow mean body condition score at mating. Solid symbols refer to the mixed system combining beef cattle and sheep. Open symbols refer to the mono-specific beef cattle-only system. Bars refer to standard deviation. The probability refers to the Student's *t*-test used to compare body condition score against the set threshold value of 2.5. NS: not significantly different from the set threshold of 2.5.

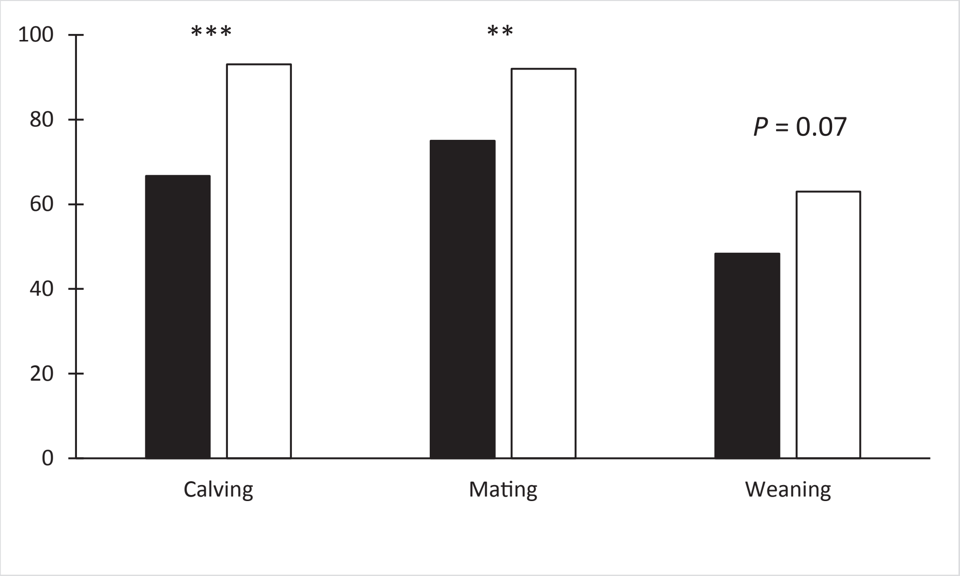

Fig. 12. Proportion of cows considered under-conditioned at the different periods of the reproductive cycle. Solid symbols refer to the mixed system combining beef cattle and sheep. Open symbols refer to the mono-specific beef cattle-only system. Cows were considered under-conditioned when their body condition score was ≤2.0 at weaning and ≤2.5 at mating and calving. $^{**}P < 0.005$, $^{***}P < 0.001$.

differ between systems, but cold carcass weight was higher in MIX vs CAT (244 vs 235 kg, $P < 0.005$) and 15 kg higher in castrates than females ($P < 0.001$). Carcass conformation and fatness did not differ between systems or sexes. Carcass conformation averaged 6.3 in CAT and 6.8 in MIX, which corresponds to the range O + to R- in the EUROP classification. Carcass fatness averaged 6.7 in both systems, which corresponds to 3- in the EUROP classification, and nearly achieved the satisfactory degree of fatness targeted for slaughtering young bovines in this study.

Total annual concentrate consumption did not differ between systems (294 and 290 kg/cow in MIX and CAT, respectively). Annual concentrate consumption was high in both systems (817 kg/cow on average) in the first campaign, because young cattle were supplemented with concentrate during the fattening period (3.4 kg/d on average for 183 days). Because young cattle were grass-fattened without concentrates in the last three campaigns, total annual concentrate consumption averaged 96 and 139 kg/cow in MIX and CAT, respectively. The annual number of drenches used against parasites (expressed per cow) did not differ between MIX and CAT. The cut-off value of 200 EEGF for young calves was never reached.

Discussion

Combining beef cattle and sheep in a mixed system was beneficial to the production of grass-fed lamb via an increase in lamb growth rate

One of the main results of the present study is that most lambs were pasture-finished in the MIX system compared to 84.8% in the SH system, which validates our hypothesis that the association of beef cattle and sheep promotes the production of grass-fed lamb in grassland-based systems. This result did not occur via a higher

Table 3
Calf performances and carcass characteristics.

Item	System[1]		Sex		SEM	*P*-value		
	Mixed	Mono	Male	Female		System	Sex	Inter.[2]
From birth to weaning								
Number of animals	50	87	80	57				
BW at birth (kg)	43.4	42.0	43.8	41	0.85	0.181	0.020	0.363
BW at weaning (kg)	306	299	312	293	9.0	0.194	<0.001	0.316
ADG$_{bw}$[3] (g)	1 018	1 003	1 044	977	19.4	0.407	<0.001	0.702
BCS[4] at weaning	2.6	2.6	2.4	2.7	0.09	0.657	<0.001	0.267
From weaning to slaughter								
Number of animals	37	63	60	40				
Age at slaughter (d)	451	445	439	458	14.4	0.288	<0.001	0.794
BW at slaughter (kg)	480	473	484	470	16.4	0.191	0.008	0.341
ADG[5] during the fattening period (g/d)	899	860	903	856	0.7	0.088	0.043	0.861
Carcass weight (kg)	244	235	247	232	10.5	0.004	<0.001	0.202
Carcass conformation	6.8	6.3	6.8	6.3	0.67	0.102	0.101	0.180
Carcass fatness	6.7	6.7	6.9	6.6	0.74	0.959	0.224	0.408

[1] Mixed: mixed system combining beef cattle and sheep; Mono: mono-specific beef cattle-only system.
[2] Inter.: Interaction.
[3] Average daily gain from birth to weaning.
[4] Body condition score.
[5] Average daily gain.

lamb birth BW or a lower number of lambs suckled per ewe, because these variables were not significantly different between the two systems. This result was due to a higher lamb ADG$_{bs}$, which led to a lower age at slaughter. This increase in lamb ADG$_{bs}$ was due more to a lower level of parasites (Marley et al., 2006; d'Alexis et al., 2014; Mahieu and Arquet, 2019) than to a better nutritive value of the pasture herbage. The latter factor was indeed similar in the MIX and SH systems during the lamb suckling period, which is consistent with the results of Joly et al. (2022), who attributed most of the improvement in BW gain of ewe lambs co-grazed with cattle to the dilution of parasites rather than an improvement of the nutritive value of the pasture herbage. After the lambs were weaned, there was likely no difference in the nutritive value of the pasture herbage (aftermaths). The 16% increase in lamb ADG$_{bw}$ during the co-grazing period from turn-out to pasture until weaning is consistent with the value measured by Jerrentrup et al. (2020). This increase in lamb ADG$_{bw}$ may be due to a direct effect on lambs and an indirect effect via the increased milk production of less-infested ewes. Furthermore, although our lambs grazed on aftermaths separately after weaning, the increase in ADG for MIX lambs was maintained until slaughter. Our results also suggest that the mixed system was less sensitive to yearly variations in climate conditions than the sheep-only system because most lambs were pasture-finished in the MIX system, whereas the proportion of pasture-finished lambs was much more variable between years in the SH system, ranging from 74.0% to 97.3%.

The association of beef cattle and sheep, in co-grazing (before weaning the lambs) or sequential grazing (after weaning the lambs), had no effect on calf ADG$_{bw}$, which is consistent with Jerrentrup et al. (2020) and Bam et al. (2022). The underlying reason is likely that cattle are less susceptible to parasites than sheep (Marley et al., 2006). Therefore, the improvement in lamb ADG$_{bw}$ was not achieved at the expense of calf performance, which is sometimes observed in situations where the two animal species are in competition for pasture availability (Wright et al., 2006). For the last three campaigns, ADG during the fattening period was 880 g/d, which is consistent with the nutritive value of the haylage, which was relatively low.

Ewes and ewe lambs performed better in the mixed system

Although ewe BCS was not measured at lambing, values for lamb birth BW, which were high and similar for both systems, suggest that the ewes' nutritional status during the last weeks of gestation and their BCS at lambing were satisfactory in both systems. In contrast to Jerrentrup et al. (2020), we found evidence that MIX ewes performed better at pasture than SH ewes when no supplementation was offered, i.e., from turn-out to pasture until premating. We found indeed between-system differences in ewe BW and BCS, which increased from turn-out to pasture to the premating period. Ewe BW was 1.79 kg higher in MIX vs SH at turn-out to pasture but increased to 7.99 kg higher at weaning and 8.55 kg higher at premating. Likewise, ewe BCS was 0.12 points higher in MIX vs SH at turn-out to pasture, and reached 0.24 points higher at weaning and 0.22 points higher at premating. Furthermore, the proportion of ewes considered under-conditioned was much lower in the MIX system compared to the SH system at weaning and premating (7.54 vs 15.84% and 23.30 vs 37.50%). The development of ewe lambs until first lambing was also faster in MIX vs SH. These between-system differences in ewe and ewe lamb performances had important consequences for the BW of culled ewes at slaughter (higher in MIX) and the level of concentrate fed to ewes and ewe lambs that was needed to reach the threshold BCS at key subsequent periods of reproduction (lower in MIX). These between-system differences in ewe and ewe lamb performances may also impact the adaptative capacities of animals and beyond the system to withstand possible shocks (e.g., grass shortage or parasite outbreaks) and therefore animal and system resilience (Mottet et al., 2020). The level of concentrate supplementation needed for the development of ewe lamb BW and to reach the threshold ewe BCS of 3.0 at mating was much lower in MIX. Moreover, although ewe lamb fertility and prolificacy and the proportion of ewe lambs culled or dead before first lambing were similar between MIX and SH, the higher ewe prolificacy in MIX vs SH may be explained by the between-system differences in ewe BCS at mating. The underlying reason for these between-system differences in ewe performances, beyond that already given for lamb performance (notably, lower level of parasites), is most likely less competition for available pasture between lambs on one side and ewes and ewe lambs on the other side, because pasture-fed MIX lambs were sold younger. This outcome, which is a new finding, demonstrates the value of whole-system-level experiments.

Cows performed better in the mixed system

In contrast to the ewes, the set threshold of 2.5 for mean BCS of cows at mating and calving was not always reached, especially in CAT cows. However, this result did not reduce reproductive performance, because the pregnancy rate was excellent, and milk production remained satisfactory based on the average calf ADG_{bw}. As observed for ewes, cows performed better in MIX than CAT, with higher BCS and BW and a lower proportion of cows considered under-conditioned at key periods of the reproduction cycle (mating, calving and weaning). Moreover, cow BW gain over the full course of the grazing season was higher in MIX than CAT, which is consistent with Jerrentrup et al. (2020). Because the nutritive value of the pasture herbage was not different between CAT and MIX between April and July (i.e., the period when all animals in the mixed system grazed together), this difference may be attributed to the fact that the cows and their calves grazed the plots before the dry ewes (sequential grazing) from the end of July until end of September, and so these animals selected the best-quality herbage on offer. Like for sheep, this between-system difference in cow performances may have huge implications for the subsequent phases of the reproduction cycle and the adaptative capacities of the animals and beyond the system to withstand possible shocks, therefore for animal and system resilience (Mottet et al., 2020). We did not observe any between-system differences in dam productivity during the 4-year scale, but differences may emerge over a longer-term time scale.

Reduced dependence on concentrate for sheep in the mixed system, at different periods of the production cycle and for different animal categories

The level of concentrate-feed consumption was low in the sheep enterprise in MIX and SH compared to levels observed in organic and conventional sheep farms in the same geographical area (Benoit et al., 2009; Experton et al., 2017). All of the systems studied here were indeed designed to produce grass-fed meat self-sufficiently. A new finding from the present study is that the association of beef cattle and sheep enabled the sheep enterprise to reduce its reliance on bought-in concentrate feed while increasing ewe productivity, which increased resource-use efficiency and strengthened system self-sufficiency. The biggest differences between MIX and SH in the level of concentrate-feed consumption occurred when finishing the lambs, rearing ewe lambs after weaning, and mating the ewes. Because most MIX lambs were pasture-finished without concentrate feed, whereas only 84.8% of SH lambs were purely pasture-finished, the level of concentrate used for MIX lambs was automatically reduced. Another important new finding is the difference between MIX and SH systems in the level of concentrate used for ewes during the mating period and ewe lambs before their first mating. This outcome may have occurred via (i) a direct positive effect of combining beef cattle and sheep on ewe and ewe lamb BW and BCS and (ii) an indirect effect linked to lower competition for available pasture between groups of sheep (fattening lambs on one side and ewe lambs and mated ewes on the other side). Indeed, during the mating period, these two groups of animals, which both have high nutrient requirements, may become competitive at grazing, and we showed that the association of beef cattle and sheep enabled a sheep-limited competition. To the best of our knowledge, the present study is the first study to report and quantify these knock-on effects of combining beef cattle and sheep, which escaped investigation in previous studies that were performed at the grazing-season scale (Jerrentrup et al., 2020) or excluded certain groups of animals (Fraser et al., 2014). Because the level of concentrate consumption by lambs finished indoors at the end of the grazing period was high, we further propose removing these lambs earlier from the pastures to stall-feeding, which was proposed by Prache et al. (1986). This procedure could reduce (i) concentrate consumption level, (ii) pasture contamination, because these lambs frequently carry and excrete the most parasites, and (iii) competition between animals for available pasture.

Reduced dependence on anthelmintics for the sheep enterprise in the mixed system

The association of beef cattle and sheep also reduced reliance on anthelmintic treatments in sheep. First, the parasite burden may have been reduced via a dilution effect when both animal species co-grazed or a disruption of parasite cycles when sequential grazing was used. Second, the higher ewe and ewe lamb BCS and BW throughout the grazing season may have decreased their sensitivity to parasites. The reduced duration of lamb exposure to parasites via a lower lamb age at slaughter cannot be advanced as an explanation here because anthelmintic treatment was never used for pasture-fed lambs after weaning. Note that the strategy of reserving the least-contaminated pastures (aftermaths) for the most parasite-sensitive animals (weaned lambs) was a very effective integrated parasite management measure. Beyond the reduction in veterinary costs and the improvement in animal welfare, this outcome may have important long-term benefits by reducing anthelmintic resistance and the impact on dung beetles (Sands and Wall, 2018; Mahieu and Arquet, 2019). However, we took many faecal samples and ran regular analyses to monitor parasite burden and help determine whether a treatment was needed, which would not be feasible on commercial farms. A weight-based targeted selective treatment of parasites, in which only a proportion of the flock is treated on the basis of change in animal BW using automated weighing technology, could be an alternative (Stafford et al., 2009).

Although the beef sensory and nutritional quality attributes were satisfactory, carcass characteristics in beef cattle did not fit the meat industry demand

Crossing the rustic breed with the Angus breed, which is capable of early-life fat deposition (Keane and Drennan, 2008), made it possible to produce carcasses with a satisfactory degree of fatness within a short fattening period, which is consistent with Dufey et al. (2002), Keane and Drennan (2008), Warren et al. (2008) and Bures and Barton (2018). Moreover, the beef produced showed a beneficial fatty acid profile and above-average eating quality (Liu et al., 2022; 2023). The reasons for the higher carcass weights in MIX vs SH or CAT animals are not clear, but the differences were of low biological amplitude (+3.2% for lamb and +3.8% for calf carcass weight in MIX vs SH or CAT animals, respectively). However, although (i) Angus × Salers crossbreeding led to the production of carcasses with a satisfactory degree of fatness, meat sensory and nutritional quality attributes, and (ii) a variety of consumer groups are willing to pay a premium for a ‘pasture-raised’ attribute above a price premium for ‘organically farmed’ (Stampa et al., 2020), calf carcass characteristics were not appreciated by industry, which considered their weight and conformation insufficient. Therefore, these carcasses were sold at a low price, which impaired the economic results of the bovine enterprise (Benoît et al., 2023). This primacy given to commercial characteristics (as carcass value criteria dictate payment to farmers) fails to reflect and value other quality attributes and makes it harder to move to more agroecological practices (grass finishing) that promote the meat’s nutritional quality and image-value attributes (Prache et al., 2022a; 2022b; Clinquart et al., 2022; Davis et al., 2022).

Here, we highlight a strong sociotechnical standard that acts as a barrier to grass-finishing young calves. This lock-in issue may be at least partially overcome by opting for direct sales and/or short-supply-chain channels or by extending the production cycle of young calves by an additional grazing season because direct marketing is not practicable for all farmers. Another way to overcome this lock-in issue may be to use purebred Angus animals because there is a small specific market for premium Angus meat. However, this strategy requires the purchase of a much larger number of animals than crossbreeding, and crossbreeding is a much more readily available method for already established farmers if this research is to be adopted in the field. Another difficulty stems from the seasonality of animal sales in beef cattle and sheep because the downstream sector wants a regular supply throughout the year (Benoit et al., 2019; Prache et al., 2022a; Clinquart et al., 2022). These difficulties illustrate the dependency of farmers on upstream (commercial carcass criteria guiding genetic selection) and downstream (primacy given to carcass characteristics, distribution of sales during the year) factors that slow or even block any deep change in farming practices. Moreover, extension services do not promote mixed systems because the flocks are smaller and they are less well-equipped to give advice (Prache et al., 2018). The quality attributes of the lamb meat produced in this study will be analysed in a future paper.

Potential limitations of combining beef cattle and sheep in a mixed system

The potential limitations of combining beef cattle and sheep should be noted. The greater complexity of managing mixed systems may result in a higher workload (Martin et al., 2020). We did not quantify workload in the present study, and surveys by Mugnier et al (2021) showed that the facts are not clear. In addition, the potential risks of interspecies transfer of parasites and/or pathogens cannot be excluded (Martin et al., 2020). Cattle in mixed systems may be more exposed to blue malignant catarrhal fever, which is asymptomatically carried by sheep but highly contagious in cattle. Parasites potentially crossing the species barrier should also be carefully considered because mixed grazing experiments have already reported clinical ostertagiosis in sheep, which is a disease caused by the bovine nematode parasite *Ostertagia ostertagi* (O'Callaghan et al., 1992). However, we did not observe these interspecies transmissions in the present study.

Conclusion

This system-level experiment demonstrated that the association of beef cattle and sheep promoted pasture finishing in lambs and decreased the level of external inputs used while maintaining (beef cattle) or increasing (sheep) animal productivity, which improved system self-sufficiency and resource-use efficiency, particularly on the sheep enterprise side. It also promoted better ewe and cow body condition and body weight at key periods of the reproduction cycle and better development of the females used for replacement, which will likely enhance animal and system resilience. The implications for environmental and economic performance are examined in a companion paper (Benoît et al., 2023). Because this study used a likely optimal ratio of beef cattle and sheep, specific pasture and animal managements and was performed in a particular soil-climate context, further studies are needed to investigate the magnitude of the effects of combining beef cattle and sheep under wider sets of varying conditions.

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.animal.2023.100758.

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 that support the study findings are available to reviewers.

Author ORCIDs

S. Prache: https://orcid.org/0000-0003-1660-5058.
B. Sepchat: https://orcid.org/0000-0002-9751-351X.
G. Sallé: https://orcid.org/0000-0002-4032-139X.
P. Veysset: https://orcid.org/0000-0002-8914-0143.
M. Benoit: https://orcid.org/0000-0001-6190-866X.

Author contributions

SP: Conceptualisation, formal analysis, investigation, writing - original draft, writing - review and editing, project administration, funding acquisition and supervision. **KV:** Investigation, resources, validation, data curation, formal analysis and supervision. **WC:** formal analysis and writing - original draft. **BS:** Formal analysis, investigation and writing - original draft. **PN:** Investigation, resources, formal analysis and writing - original draft. **GS:** Investigation and writing - original draft. **PV:** Conceptualisation, investigation and writing - original draft. **MB:** Conceptualisation and investigation.

Declaration of interest

None.

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