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Inseminate without hormonal treatment in dairy sheep farms: exploring the consequences on the sustainability of several contrasted production systems



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ABSTRACT

Alternatives to hormonal treatments (**HTs**) in dairy sheep reproduction management are being explored in response to increasing societal concerns regarding animal welfare and food safety. However, hormone-free reproduction implies higher variability in flock performances and additional constraints for timely synchronised artificial insemination (**AI**) in the flock, impacting the diffusion of genetic progress. The use of the male effect, a well-known practice to induce synchronised oestrus, combined with precision tools (e.g., heat detector), is a plausible way to implement AI without HT in dairy sheep farms. To date, the consequences of such alternative reproduction management on the whole farm sustainability remain unknown. To anticipate these potential impacts, a multiagent model (REPRIN'OV) was used to simulate dairy sheep farms' sustainability indicators (biotechnical, economic, environmental and workload). A reproduction management scenario, including the use of the male effect followed by AI on the adult ewes (**HFAI**), was simulated and compared to the current reproduction management of four case study farms (*Early_conv*, *Late_conv*, *Early_org* and *Late_org*). They were selected to represent the different agricultural models (*Conventional* or *Organic*) and reproduction seasons (*Early* – during spring, out of ewes' natural reproduction season – or *Late* – from early summer to the end of autumn) of the Roquefort Basin's farms in Southern France. Simulation results showed that the HFAI scenario had different consequences depending on the farm's production system type. A negative effect on most key sustainability indicators of the *Conv* farms was observed, as a significant reduction in the fertility rate, in the proportion of young ewes born from AI (–54% in both farms; $P < 0.05$) and in the flock's milk production were observed; while the workload and greenhouse gas (**GHG**) emissions were increased compared to the initial scenario. In the *Org* farms, HFAI had neutral to positive effects on most indicators as the fertility, milk production of the flock, workload during milking and GHG emissions were barely affected by this scenario, while an increase in the proportion of young ewes born from AI was observed (+39% and +43% in each farm, respectively; $P < 0.05$), allowing a better farm gross margin. Still, the workload during lambing was increased in *Early_org* (+18%; $P < 0.05$), as *Early* farms, tended to be more negatively impacted by HFAI than *Late* ones. Overall, our simulation approach provides interesting elements to exchange with stakeholders on how to progress towards a socially acceptable reproduction management system, for the dairy sheep sector.

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Implications

In dairy sheep farming, managing reproduction without the use of hormonal treatments aligns with the challenges of agroecology and new societal concerns. However, in major production areas, developing alternatives to hormonal treatments while maintaining the possibility of insemination is necessary for the

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development of selection schemes. The overall consequences of practicing insemination without hormonal treatments on the farm sustainability remain unknown. This simulation work showed that a scenario of reproduction management without the use of hormonal treatments affects farms differently based on their production systems, offering valuable insights for discussions about new reproductive management methods in the dairy sheep industry.

Introduction

Reproduction management is essential to the functioning of livestock farming systems as it determines the number and physiological state of the females in production as well as the temporal scheduling of farm operations. Any change in reproduction management could therefore strongly affect the whole farm functioning and its long-term sustainability. In the major European dairy sheep production regions, the use of hormonal treatments (HTs) to induce and synchronise ewe's oestrus (and thus ovulations) is very common. It allows farmers to overcome the seasonality of small ruminants' reproduction, synchronise reproduction and production phases in the flock and therefore facilitate the work routines while regularly covering market demands for farm products (milk and lambs). By allowing an anticipated synchronisation of oestrus in the flock, the use of HT also makes it possible to inseminate a large number of ewes at the same time and is currently the keystone of successful genetic selection programmes in the main dairy sheep countries (Carta et al., 2009). In dairy sheep production regions, where the use of fresh semen is the most common method to carry out artificial insemination (AI), using such HT is particularly valuable as it allows to programme ewes' insemination within a reduced delay between semen collection and AI service.

Despite these advantages, the use of HT is increasingly being questioned because of its inadequacy with the growing societal demand for a 'cleaner, greener and more ethical' animal production systems that limit the use of external inputs and take better account of animal welfare and environmental issues (Martin et al., 2004). Hormone-free (HF) reproduction management strategies including the use of the male effect (ME) before AI, as an alternative to HT, are thus being explored. The ME is indeed a well-known HF practice to stimulate ewe's ovulation and concentrate the peaks of lambing events in a flock (Rosa and Bryant, 2002; Pellicer-Rubio et al., 2019). Thanks to sensory signals, sexually active males are able to induce and synchronise oestrus and ovulation in anovulatory females (i.e. sexually resting or non-cycling; Thimonier et al., 2000; Delgadoillo et al., 2009). The ME is therefore most effective outside ewes natural breeding season, when most ewes are in seasonal anoestrus, whereas during the natural breeding season, when most ewes are spontaneously cyclic, its effect is reduced. Still, some authors show that the ME can induce a response in anovulatory ewes during the breeding season (Hawken et al., 2007). Provided that ewes oestrus onset are individually detected, oestrus induction practices such as the ME could also be used to facilitate AI implementation without using HT (Mayorga et al., 2019; Debus et al., 2019). It can therefore be used in conventional farms to reduce the use of HT but also to introduce AI in organic farms which, although authorised by the organic farming specifications (2008/889/EC), practice AI very little for lack of an effective protocol. To ensure a sustainable adoption of such reproduction management innovation in commercial farms, it is important to anticipate its implications not only at the flock level but also at the whole farm functioning level (Dedieu et al., 2008; Gouttenoire et al., 2013). It is also essential to ensure that this innovation is not only technically efficient but also that it does not affect negatively other important aspects of the farm's sustain-

ability (economic, environmental or societal) from the stakeholders' perspective (Ingrand et al., 2014; Curry et al., 2021).

The efficiency of the ME for oestrus induction and synchronisation is indeed more variable than conventional HT as it is affected by several individual characteristics of the ewes present in the flock (e.g. age, body condition, milk production level; Debus et al., 2022), by management decision (e.g. time between drying off and mating; Tournadre et al., 2002) and by the reproduction season (Chanvallon et al., 2009). Such variability tends to induce staggering of lambing events, thus disrupting their repartition over time, and leading to inherent disruption in the distribution of milk production over time (Laclef et al., 2023a), all suggesting necessary readjustments in the overall farm functioning (e.g. extending the milking period or revising the feeding system). We thus hypothesise that implementing HF reproduction management practices will have different consequences depending on the farm's initial configuration (Conventional, i.e. using HT, or Organic, i.e. not using HT) and depending on the reproduction season of the farms. Therefore, the objective of this work is to simulate the consequences of introducing an alternative HF reproduction management to perform AI without HT, and their associated management adjustment, in a diversity of typical conventional and organic dairy sheep flocks of the Roquefort Basin (RB; South of France). The effects on several biotechnical, economic and environmental farm performance indicators as well as workload indicators were assessed to explore the overall impact on each farm's sustainability.

Material and methods

Characteristics of the dairy sheep farms in the Roquefort basin and specificities of their reproduction management

The RB is the most important French dairy sheep milk production basin (74% of the national production; *Chambre d'Agriculture Occitanie*, 2021), mainly because a large part of its territory belongs to the Roquefort cheese Protected Designation of Origin (PDO) area (79% of the milk collected in the region is for the Roquefort PDO; *Chambre d'Agriculture Occitanie*, 2021). Situated in the south of France, this RB lies at the interface of Mediterranean and temperate climates, where different soil types and climatic conditions can be found. Dairy sheep farming systems in this area are based on grazing that typically starts in Spring and lasts between 6 and 9 months, depending on weather conditions and grass availability (De Boissieu and Morin, 2022). Feeding systems are completed by stocked fodder (hay, silage) and concentrates (on-farm produced or imported), especially during winter when ewes are kept indoor. In addition, the dairy sheep farms of the RB are strongly influenced by the production constraints of the dairies, mostly determined by the specifications of the Roquefort PDO. Therefore, since the Lacaune breed is the sole one authorised for Roquefort cheese production, this highly productive and long-time selected breed (330 L/lactation/ewe on average in France; IDELE, 2020; Barillet et al., 2001) is the main one in the RB. The selection scheme of this breed is called pyramidal as a "nucleus" population, at the top, benefits from the use of breeding tools (i.e. pedigree recording, milk recording, AI or progeny testing) to control its evolution and generate a genetic progress, which is then transferred to other commercial flocks through AI or natural mating of selected rams (Barillet et al., 2001; Carta et al., 2009).

In terms of reproductive management methods, two groups of farms can be distinguished in the RB: organic and conventional. Conventional farms, on one hand, are characterised by the systematic use of AI on all or part of the flock after a synchronisation of ovulations by HT. Organic farms, on the other hand cannot use HT due to their specification and do not perform AI, for the most

part, due to the complexity of carrying out AI without HT. In addition, in the RB, farms are traditionally categorised into two main groups considering their reproduction period: the so-called “Early” mating system in which farmers mate their ewes in the spring, out of the natural reproduction season for European sheep breeds, thus with lactations between November and August; and the so-called “Late” mating system in which breeders mate their ewes during their natural reproduction season, or close to it (i.e. mid-summer), with lactations between January and October. Indeed, in response to the industry demand, the spread of milk production by splitting the breeding periods between farms has been developed in this large milk production basin so that milk is available throughout the full year for collection by the Roquefort industrial system (Lagriffoul et al., 2016). Early and late mating systems can be found in both organic and conventional farms. In the present study, such diversity of production seasons was represented as well as the diversity of agricultural models (Table 1). Whether it is a “Late” or “Early”, organic or conventional farm, the reproduction of the flock in the RB is usually managed in two batches of ewes: the adult ewes (i.e. ewes that have already performed at least one lactation) and the ewe lambs (i.e. young renewal ewes, in their first production cycle). Adult ewes are put into reproduction before the ewe lambs (typically between 1 and 2 months earlier, depending on the farm; De Boissieu and Morin, 2022) and these two groups of females are managed separately until milking starts.

The REPRIN'OV dairy sheep farm model

For carrying out this study, we used the REPRIN'OV dairy sheep farm model, previously developed by our team (Laclef et al., 2023a). It was designed to simulate different scenarios of flock reproduction management practices (with or without HT) and compare their impact on a series of long-term farm sustainability indicators. The multiagent modelling method was used to design this model. It is a method that suggests representing each of the entities (or agents) composing a given system in order to better simulate and understand the emergent properties resulting from the interactions between the different entities of this system as well as between them and their environment (Bousquet and Le Page, 2004). The model was designed using the GAMA software (Taillandier et al., 2019) destined for multiagent model computational development. Its source code can be accessed at: <https://github.com/elaclef/REPRINOV-model.git>.

This model represents the main entities involved in the functioning of a dairy sheep farm (the ewes, rams, agricultural lands, and farmers), along with their functioning over time. It is composed of a flock functioning sub-model linked with economic, workload and environmental indicator calculation modules. The flock functioning sub-model is central. It includes itself several individual biotechnical sub-models that represent the main biotechnical steps carried out by the ewes and rams (e.g. the individual processes of reproduction, lactation or feeding). It also includes decisional sub-model that represents the management choices and decisions of the farmer. Since the REPRIN'OV model was specifically designed to simulate the impact of introducing new reproduction management methods on the whole dairy sheep farm functioning, the central entities of the flock sub-model are the ewes and the representation of their individual reproduction process have been highly detailed. Their P of manifesting oestrus is notably modelled using P values which differ according to the reproduction season and to whether the reproduction management includes HT or not (Supplementary Table S1 and Figure S1). The P for each ewe to be in oestrus following an HT is fixed to a single value per batch whereas in the HF context with the use of the ME, the oestrus onset is individualised and adjusted depending on

the reproduction season. For the adult batch, the individual response to the ME is especially determined by individual probabilities equations dependent on the ewe's characteristics (age, body condition score, milk production level, number of days between the last lambing and the reproduction start; Laclef et al., 2021). Over the course of a simulated production cycle (i.e. from the flock reproduction start to the end of the associated milking), the ewes pass through several successive physiological stages (pregnant, lambing, lactating) following oestrus onset. The transition from one stage to another is modelled through several probabilities and can occur at a fixed date (e.g. start and end of milking of the flock defined by the farmer) or due to a previous event (e.g. weaning of each lamb 28 days after its lambing). The evolution of the flock composition over the years is also modelled by representing the evolution of the main individual characteristics of the ewes and formalising management rules of the farmer regarding flock renewal. The flock functioning sub-model thus provides annual (e.g. fertility of the flock, number of lambs born, total milk produced) and dynamic outputs (e.g. evolution of physiological stages, lambing and milk distribution of the flock over time) that serve as inputs for the feeding sub-model of the flock (feed being distributed to ewes based on their physiological stages) but also for the farm economy, workload and environmental indicators calculation modules. A full description of the REPRIN'OV model with the equations and parameters used was made in (Laclef et al., 2023a). It should be noticed that this dairy sheep farm model represents the farm functioning under stable environmental and economic conditions.

Farms modelled and simulated scenarios

Four case studies of dairy sheep farms (namely *Early_conv*, *Late_conv*, *Early_org* and *Late_org* respectively), representative of the RB, were analysed in this study. These farms were selected and modelled based on information from the literature and from the Inosys Network database, a database built from a pluriannual monitoring of commercial dairy sheep farms, which aims to provide detailed pictures of the most representative farms in the main French production areas (IDELE, 2014). To cover the diversity of dairy sheep farms of the RB, they differed by i) their agricultural model (conventional or organic) and/or ii) by their reproduction season (early or late). For each modelled farm, a baseline scenario corresponding to the current reproduction management of the farm was established: one corresponding to a management with HT followed by AI practice (**HAI**) for the conventional farms (*Early_conv* and *Late_conv*), or one corresponding to an HF management scenario (**HFM**) with ME followed by direct mating only in the organic farms (*Early_org* and *Late_org*). Then, an alternative HF reproduction management scenario (**HFAI**), including the use of ME followed by AI after oestrus detection on the adult batch was designed for each modelled farm (Supplementary Figure S2). The ME was included in every HF scenario because nowadays farmers of the RB typically implement it regardless of the reproduction season to induce oestrus in as many ewes as possible, but also to maintain a routine and habituate all animals to this practice. In this HFAI scenario, the oestrus detection was considered to be done using an automated oestrus detection device with a 100% detection rate, similar to the one described by Alhamada et al. (2016). However, the acquisition cost of this device was not considered in this work. In addition, in this scenario, AI was only performed on ewes of the adult batch as implementing AI after oestrus detection is presumed to be very demanding in terms of labour time. It has also been shown that young ewes display poor responses to ME, mainly due to the fact that they are mated between 7 and 9 months old (during puberty), they lack of sexual experience and are easily affected by stress (Chanvallon et al.,

Table 1
Characteristics of the simulated dairy sheep farms in each scenario.

Farm name Scenario	Early_conv		Late_conv		Early_org		Late_org	
	HAI (Baseline)	HFAI	HAI (Baseline)	HFAI	HFM (Baseline)	HFAI	HFM (Baseline)	HFAI
Production system type	Conventional		Conventional		Organic		Organic	
Flock size (Number of ewes present at lambing)	460 (330 adults and 130 ewe lambs)		405 (295 adults and 110 ewe lambs)		550 (410 adults and 140 ewe lambs)		430 (320 adults and 110 ewe lambs)	
Dominant breed	Lacaune		Lacaune		Lacaune		Lacaune	
Ewes average live weight (kg)	75		75		75		75	
Renewal rate (%)	28		27		25		26	
Ewes mortality rate (%)	3		1		5		2	
Lambs mortality rate before weaning (%)	20		15		15		13	
Suckling duration (days)	28		28		28		28	
Usable agricultural lands (ha)	66		70		99		127	
Forage and pasture lands (ha)	58		58		79		109	
Cereal lands (ha)	8		12		20		18	
Reproduction period	February 23th, i – July 7th, i		June 9th, n – September 25th, i		April 30th, i – October 15th, i		July 1th, i – October 30th, i	
Reproduction season	“Early”		“Late (Summer)”		“Early”		“Late (Summer)”	
Gap between the start of reproduction of the adult and young batches (days)	51	50	15	15	48	44	19	16
Start of the milking of the flock	Sep 1th, i		Dec 15th, i		Nov 5th, i		Dec 15th, i	
Milking period length (days)	272		217		223		228	
Pasture period	Mars 15th, i – Sep 10th, i	Baseline + 10 days	March 1th, i – Nov 15th, i	Baseline + 10 days	March 15th, i – Sep 30th, i		March 25th, i – Nov 15th, i	
Changes in feeding programme	No	Yes	No	Yes	No	No	No	No
Hormonal treatment	Yes	No	Yes	No	No	No	No	No
Use of male effect practice	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Number of rams	7		6		18		14	
Artificial insemination	Yes	Yes	Yes	Yes	No	Yes	No	Yes
Number of insemination days	1 day for each batch (adults and young)	6 days (between 18 and 20 days and between 24 and 26 days after reproduction period start)	1 day for each batch (adults and young)	6 days (between 17 and 22 days after male introduction)	–	6 days (between 18 and 20 days and between 24 and 26 days after reproduction period start)	–	6 days (between 17 and 22 days after reproduction period start)
Oestrus detection rate	–	100% ^a	–	100% ^a	–	100% ^a	–	100% ^a

Abbreviations: HAI = Hormonal treatment + Artificial Insemination; HFAI = Hormone-free + Artificial Insemination on adult ewes; HFM = Hormone-free + Mating; i = any given year.

^a Oestrus detection rate of 100% considering the use of an automated oestrus detection device (Alhamada et al., 2016).

2010). Moreover, in most farms of the RB, ewe lambs kept for renewal are generally the first born (i.e. from the adult flock). Thus, performing AI only on the adult batch in HFAI allows a compromise between AI conservation in an HF context and an acceptable level of workload during reproduction. It has also been suggested that introducing HF alternative reproduction management practices in conventional farms should be combined with a modulation of the whole flock management to minimise negative impacts linked with an increased variability in the reproductive performances due to the use of ME (Laclef et al., 2023a). An extension of the farm's milking period and a consequent adaptation of the flock's feeding periods during milking were especially suggested to compensate for the delay in the occurrence of the highest peak of milk production observed in previously simulated HF scenarios. Therefore, for each of the modelled conventional farms, the flock's milk production period and the feeding periods per batch during milking were arbitrarily extended by 10 days (based on Laclef et al., 2023a,b, observations) in the HFAI scenario. Table 1 details the farms' characteristics under each simulated scenario. Five consecutive production cycles (N1 to N5) following the introduction of an alternative HFAI reproduction management were simulated for each farm's scenarios. Table 2 details all the model outputs analysed in this study.

Analysis of simulation outputs

Results for each scenario represent the means of 75 simulation runs (threshold value to manage the stochasticity of the flock performances simulated by the flock sub-model; Laclef et al., 2021).

For each farm, two-factors ANOVAs were performed to study the effects of the scenario and production cycle [first (N1) vs fifth (N5) production cycle] on the annual indicators. Additionally, the farm's daily lambing events distribution and daily milk production evolution over time per scenario were plotted (Supplementary Figures S3 and S4) to perform a descriptive analysis of their dynamic progression. Only the results of the comparison between scenarios at N5 are presented here. However, the evolution of the simulated

Table 2

Dairy sheep flock and farm performance outputs, and sustainability indicator outcomes, evaluated with the REPRIN'OV model (from Table 2 in Laclef et al., 2023a).

Annual outputs	Dynamic outputs
Biotechnical indicators	
Fertility rate (%)	Number of ewes lambing/day
Ewes inseminated (%)	Number of ewes lambing from insemination /day
Ewes born from insemination in renewal batch (%)	Milk production (L/day)
Ewes born from insemination in the flock (%)	
Average age at first breeding (months)	
Average milk production (L/ewe)	
Total milk production of the flock (L)	
Forage distributed (kg/L of milk)	
Concentrate feed distributed (kg/L of milk)	
Workload indicators	
Workload during lambing (s/L of milk)	
Workload during milking (s/L of milk)	
Economic indicators	
Gross Margin (€/L of milk)	
Total Gross Margin (€)	
Environmental indicators	
CH ₄ emissions (kg CO ₂ eq/L of milk)	
CO ₂ electricity emissions (kg CO ₂ eq/L of milk)	
CO ₂ feed emissions (kg CO ₂ eq/L of milk)	
Water consumption (L/L of milk)	

outputs between N1 and N5 and its comparison between scenarios were also stated when relevant.

All statistical analyses were carried out using the R 4.2.3 software (R. Core Team, 2023).

Results

Fertility rates, lambing events distributions over time and age at first mating

For both conventional farms, the fertility rate was significantly lower in the HFAI scenarios compared to the HAI baselines at all production cycles, especially in the *Early_conv* farm (−31% and −4% for the fertility rate at N5 in *Early_conv* and *Late_conv*, respectively; $P < 0.05$; Fig. 1). For the organic farms, however, there were no significant differences between the HFAI and the HFM baseline scenarios, regarding the fertility rate. Moreover, for both *Late_conv* and *Late_org* farms, the fertility rates in HFAI remained equivalent between N1 and N5, similar to their baseline scenarios, whereas it decreased significantly in HFAI for both *Early_conv* and *Early_org* farms (−2% in *Early_conv* and −1% in *Early_org*; $P < 0.05$; Supplementary Table S2). In addition, for all farms, the lambing event distribution over the lambing period was different in HFAIs than in baseline scenarios. It took between 8 and 10 days more to reach 25% of the total lambing in HFAI, depending on the farm and the production cycle (Supplementary Figure S3). When comparing to baselines, lower maximum numbers of daily lambing events were also observed when using HFAI strategies in every farm, except for the *Late_org* in which the maximum number of daily lambing events was higher in HFAI (+2 lambing events at N5; Supplementary Figure S3).

The HFAI scenario also led to a lower age at first mating than in the baselines in every farm (−0.2 to −0.4 years at N5, depending on the farm; $P < 0.05$; Supplementary Table S2). This indicator remained stable over the production cycles for every farm and scenario (Supplementary Table S2).

Insemination rates and proportions of ewes born from insemination

For both conventional farms, the AI rate was significantly lower in HFAIs than in the baselines throughout all production cycles, especially in *Early_conv* (−57% and −61% for the AI rate at N5, in *Late_conv* and *Early_conv*, respectively; $P < 0.05$; Supplementary Table S2). Lower proportions of ewes born from AI in the renewal batch were also simulated in HFAIs during all production cycles (−54% of the renewal batch, at N5 for both conventional farms; $P < 0.05$; Fig. 1). On the contrary, for both organic farms, the AI rates as well as the proportions of ewes of the renewal batch born from AI were significantly higher in HFAIs than in their HFM baselines (+39 and +43% of the renewal batch born from AI, at N5 in *Early_org* and *Late_org*, respectively; $P < 0.05$; Fig. 1). In addition, in every farm, HFAI led to a decrease in the AI rate and thus in the proportions of ewes of the renewal batch born from AI, between N1 and N5 (Supplementary Table S2).

Looking at the evolution of the proportion of ewes born from AI in the flock over the production cycles, it remained stable between N1 and N5 in every baseline scenario (98% of the flock born from AI in *Early_conv* and *Late_conv* baselines and 0% in *Early_org* and *Late_org* baselines, respectively), whereas it decreased over time in the HFAI scenario for both conventional farms, especially in *Early_conv* (−38% and −28% of ewes born from AI between N1 and N5 in *Early_conv* and *Late_conv*, respectively; $P < 0.05$; Fig. 2). On the contrary, it increased over time in both organic farms HFAI, especially in *Late_org* (+18 and +25% of ewes born from

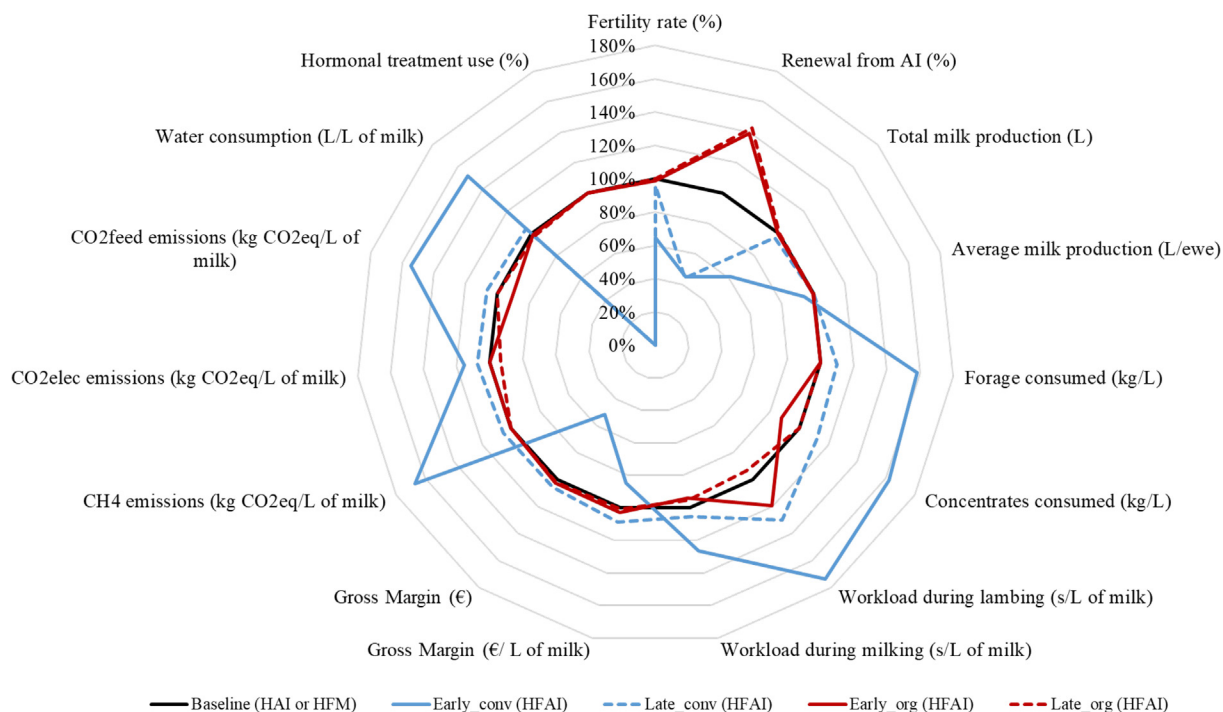


Fig. 1. Radar diagrams illustrating the values of the dairy sheep farms' main sustainability indicators at the fifth simulated production cycle of each scenario. For each farm (Early_conv, Late_conv, Early_org, and Late_org), the value of the indicators in the baseline scenario is set to 100% on the radar scale. The result display is based on the one made in Figure 7 of Laclef et al. (2023a). Abbreviations: AI = Artificial Insemination; HAI = Hormonal treatment + Artificial Insemination; HFAI = Hormone-free + Artificial Insemination on adult ewes; HFM = Hormone-free + Mating; conv = conventional; org = organic; elec = electricity.

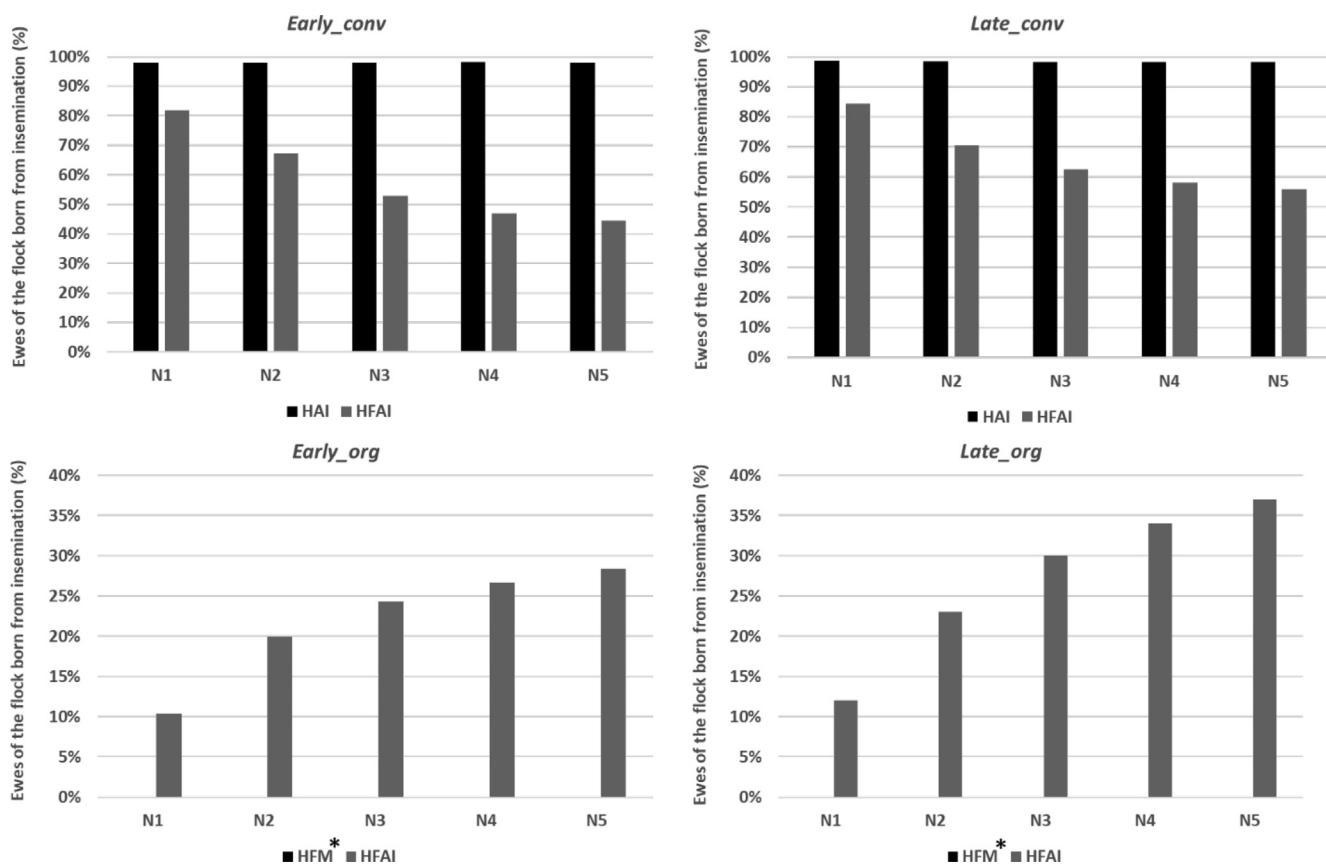


Fig. 2. Evolution of the percentage of ewes born from insemination in each farm (Early_conv, Late_conv, Early_org and Late_org) and scenario (HAI, HFM and HFAI) between the first (N1) and the fifth (N5) simulated production cycle. * In the Early_org and Late_org farms, the percentage of ewes born from insemination is null as no insemination was performed in this scenario. Abbreviations: HAI = Hormonal treatment + Artificial Insemination; HFAI = Hormone-free + Artificial Insemination on adult ewes; HFM = Hormone-free + Mating; conv = conventional; org = organic.

AI between N1 and N5 in *Early_org* and *Late_org*, respectively; $P < 0.05$; Fig. 2).

Proportion of ewes milking and milk production of the flock

For both conventional farms, the proportion of milking ewes was significantly lower over the five production cycles in HFAs compared to their baselines (−30% of ewes milked in *Early_conv* and −4% in *Late_conv* at N5; $P < 0.05$; Supplementary Table S2). It was especially the case in *Early_conv* for which the proportion of ewes milked decreased between N1 and N5 (Supplementary Table S2). In contrast, for the two organic farms, the proportion of ewes milked was equivalent and stable over time in all scenarios (Supplementary Table S2).

The consequences of the HFAI scenario on the flock's average annual individual milk production (in L/ewe) were found to be different depending on the farm. Indeed, the flock's average annual individual milk production was found to be significantly higher in HFAI than in the baseline scenario for the *Late_conv* (+1 L/ewe at N5; $P < 0.05$; Fig. 1), equivalent to that of the baseline in *Late_org* and significantly lower than that of the baseline in *Early_conv* and *Early_org* (−19 L/ewe and −1 L/ewe in HFAI at N5 for *Early_conv* and *Early_org*, respectively; $P < 0.05$; Fig. 1). Moreover, in the *Early_conv* farm, the HFAI scenario led to a milk production decrease over time, whereas, in every other context, it increased (Supplementary Table S2). In *Late_conv*, however, this increase was more important in the HAI baseline than in the HFAI scenario (+13 vs +11 L/ewe in HAI and HFAI, respectively; $P < 0.05$; Supplementary Table S2). In addition, lower values for the total milk production of the flock were simulated in both conventional farms' HFAI scenario (−38% and −4% at N5 for *Early_conv* and *Late_conv*, respectively; $P < 0.05$; Fig. 1). On the contrary, in the organic farms, the total milk production of the flock was equivalent between scenarios over time (Supplementary Table S2).

For both conventional farms, a delay in the occurrence of the highest peak of the flock's daily milk production was also observed in HFAI compared to their HAI baseline scenario (11 days of delay on average; Supplementary Figure S4). The HFAI scenario also led to a higher peak of milk production compared to the baseline in the *Late_conv* farm, whereas it led to a lower peak of milk production compared to the baseline scenario in the *Early_conv* farm (Supplementary Figure S4). Meanwhile, in the organic farms, no delays were observed in HFAs; tendencies that remained stable over time (Supplementary Figure S4). However, for both organic farms, the flock's daily milk production curves started off lower in HFAI than in the HFM baseline while showing higher milk production values at their highest peak of daily production (Supplementary Figure S4).

Feed consumption

For both conventional farms, the quantity of feeds consumed (forages and concentrates) to produce a litre of milk (in kg/L of milk) was significantly higher throughout the production cycles in HFAs; especially in the *Early_conv* farm (+54% for forages and +53% for concentrates at N5; $P < 0.05$; Fig. 1). In the *Late_org* farm's HFAI scenario, the quantity of all feeds consumed was equivalent to the HFM baseline. In the *Early_org* farm, however, the quantity of concentrates consumed was significantly lower in HFAI than in the baseline (−13% at N5; $P < 0.05$; Fig. 1).

Workload indicators

In both conventional farms, the workload during the lambing period (work times in s/L of milk produced) was increased in HFAs; with a bigger increase in the *Early_conv* farm at all produc-

tion cycles (i.e. up to 74% of workload increase during lambing at N5 in *Early_conv*'s HFAI; Fig. 1). In *Early_org*'s HFAI, the workload during lambing was also increased compared to its HFM baseline (+18% at N5; $P < 0.05$; Fig. 1). However, in *Late_org*, HFAI led to lower the workload during lambing compared to its baseline scenario (−2% at N5, $P < 0.05$; Supplementary Table S2).

Regarding the workload during milking, in all organic farms, it was significantly lower in HFAs compared to the HFM baselines (−6 and −5% at N5 in *Early_org* and *Late_org*, respectively; $P < 0.05$; Fig. 1). In contrast, for the conventional farms, the workload during milking was significantly higher in HFAs compared to the HAI baselines (+26% and +6% at N5 in *Early_conv* and *Late_conv*, respectively; $P < 0.05$; Fig. 1).

Farm's economy indicators

Over the five production cycles, the gross margin (GM) per L, in (€/L), was significantly higher in HFAs for all farms except for the *Early_conv* one in which GM per L was reduced by the HFAI scenario (+1%, +3% and +9% for the GM per L in *Late_org*, *Early_org* and *Late_conv* respectively vs −16% in *Early_conv*, at N5; $P < 0.05$; Fig. 1). A similar trend was observed when examining the farm's total GM (+2% and +5% for the total GM in both *Late_org*, *Early_org* and *Late_conv* respectively vs −48% in *Early_conv*, at N5; $P < 0.05$; Fig. 1). In addition, the total GM and the GM per L were found to be decreasing over time for the *Early_conv* farm's HFAI scenario whereas it increased over time in every other context.

Farm environmental indicators: Greenhouse gas emissions (CH_4 and CO_2 from electricity use and feed purchases) and water consumption

For both conventional farms and during all production cycles, the amounts of gases emitted per litre of milk produced for all the simulated greenhouse gas emissions (GHG) (in kg CO_2eq/L of milk) were significantly higher in the HFAI scenarios compared to the HAI baselines, especially in the *Early_conv* farm (Fig. 1). Similar results were observed for water consumption per litre of milk produced (Fig. 1). In the organic farms, HFAs led to lower or equivalent GHG emissions and water consumption compared to the HFM baselines (Fig. 1). The amount of CO_2 emitted due to the feed purchases were particularly lowered in the *Early_org*'s HFAI compared to its baseline (−9% at N5; $P < 0.05$; Fig. 1). In addition, the water consumed and GHG emitted per litre of milk produced decreased between N1 and N5 in all contexts, except in the *Early_conv*'s HFAI scenario for which these indicators were improved over time (Supplementary Table S2).

Discussion

Consequences of the reproduction management scenario without hormonal treatment and with insemination on the flock's reproductive performances

Overall, the simulation results showed that the introduction of the HFAI reproduction strategies negatively affected most of the reproductive performances for both conventional farms, especially in the *Early_conv*, whereas applying HFAI induced mostly neutral or positive consequences on the reproductive performances of organic farms regardless of the reproduction season.

First, in the conventional farms, the introduction of the HFAI alternative resulted in a diminution of the fertility rate. As identified in a previous work (Laclef et al., 2023a), this was a direct consequence of replacing the use of HT by the ME practice while keeping the same mating schedule. The ME efficiency for ewes' oestrus induction and synchronisation is highly affected by ewe's

individual characteristics (e.g. body condition score or age; Laclef et al., 2021; Debus et al., 2022) and therefore more variable than HT. The fertility rate was also much more reduced in *Early_conv* than in *Late_conv*. Indeed, introducing an HFAI strategy in this farm, while keeping the same reproduction schedules, resulted in mating the ewe lambs in May i.e. out of the natural reproduction season, at a time when young ewes experience both puberty and strong seasonal anoestrus in addition to their lack of experience (Chanvallon et al., 2010), thus making them more unlikely to be cyclic (i.e. to fall in oestrus and ovulate). As a result, few ewe lambs were detected in oestrus, and consequently, a low number were covered in *Early_conv*, leading to a significant decrease in fertility rate compared to *Late_conv*. In contrast, for the organic farms that were already not using HT, HFAI did not affect the fertility rates.

Moreover, in both “early” farms, HFAI led to a significant fertility rate decrease over the production cycles. This should be the consequence of the REPRIN’OV model conception, as it includes a representation of the antagonism that exists between a high milk production level before reproduction and a positive response to the ME (Laclef et al., 2021; Debus et al., 2022). In the RB, there usually is a progression in the value of a farm’s flock’s main genetic traits (especially the milk production level) due to the use of AI or mating of selected rams with a good genetic background (Barillet et al., 2001) with ewes resulting from effective replacement strategies. Therefore, the observed decrease of the fertility rates in the “early” farm’s HFAI is linked to the flock’s average milk production level increase over time. When performed during the ewes’ natural reproduction season (as it was the case in the “late” farms), the ME is less effective to induce oestrus because most ewes are already naturally cyclic (Delgado et al., 2009). This could explain why this trend of decreasing fertility rates did not appear in the “late” farms (*Late_conv* and *Late_org*). Overall, the fertility rate decrease observed in the “early” farms HFAI scenarios was not extreme over the five simulated production cycles (less than a 3% decrease). We hypothesise that this phenomenon could be reduced by improving the oestrus synchronisation in the flock during the first AI (or mating) cycle. It might limit the number of ewes lambing late resulting in late milking starts, thereby limiting the number of ewes starting their next reproductive cycle while still in a high milk production phase of the lactation curve, which could lessen the negative retroactivity of high milk production level at reproduction on ewe’s response to ME over time.

In all farms, the lambing event distributions were also affected by the alternative HFAI scenarios as they led to more staggered lambing events. In conventional farms, it was mainly due to the increased variability in estrus onsets compared to HAI. However, for all farms, the shape of these lambing event distributions differed between the baselines and the HFAI scenarios due to the modelled AI protocol in HFAI. Indeed, this protocol targeted 6 specific days, where only ewes in estrus could be effectively inseminated, while delaying the direct mating start of the adult batch. This led to an extension of the lambing period length for the adult batch, especially in the two “early” farms in which the delay between adult and young batches’ reproduction start was over a month. For the *Late_org* farm, however, the AI protocol in HFAI led to a higher maximum number of ewes lambing daily compared to its HFM baseline scenario. This was because for this farm who managed its reproduction during the ewes’ natural reproduction season, the AI protocol led to a better synchronisation of the ewe’s mating times, particularly during the direct mating phase. Indeed, ewes cyclic during the AI period, but not showing estrus on the exact AI days, had to wait until the start of direct mating to be mated with other ewes, leading to a higher number of ewes mated directly by the ram. In addition, it should be noted that the oestrus detection rate was set to 100% in this study, implying that the detection would be perfectly carried out [e.g. using an automated

detection device (Alhamada et al., 2017; Debus et al., 2019)], and suggesting that under a different situation, the lambing distribution could be even more disturbed. The lambing events staggering observed in HFAI, for all farms, also led to ewes being incorporated to their first mating significantly earlier than in their baseline. This diminution was not extreme and did not increase over the five simulated production cycles. However, if it persists over time, it could become problematic as the age at first mating can negatively affect the reproductive performance of the flock if too low (Hernandez et al., 2011; Corner et al., 2013).

As expected, the HFAI scenario allowed to increase the AI rate and thus the proportion of ewes born from AI in organic farms over time. On the contrary, it led to a reduction of these rates in conventional farms due to the increased variability in oestrus onset, the restrictive AI protocol without HT and the cessation of AI on the young ewes’ batch. In addition, in every farm, HFAI led to a decrease in the AI rate, and thus in the proportion of ewes born from AI, over time. Once again, this was because the increase of the flock’s milk potential in these farms had a negative retroactivity on the ewes’ responses to the ME. The evolution of the AI rate in farms should indeed strongly affect the genetic progress of the RB dairy sheep population where the selection scheme is, as in many other large European dairy sheep areas, based on a pyramidal management of the population that includes a first phase of development of the selected traits in commercial “core” farms (Carta et al., 2009). A recent genetic progress model performed for a population of meat sheep with a similarly organised selection scheme showed that reducing the AI rate in these core farms could indeed negatively affect the genetic progress of the populations of the main breeds (Raoul and Elsen, 2020).

Consequences of the reproduction management scenario without hormonal treatment and with insemination on the flock’s milk production

Classically, there is an evolution of the value of a farm’s flock’s main genetic traits due to the use of AI or mating by rams. In fact, in the RB even the farms that do not use AI benefit from good genetics through the use of selected rams of good genetic background (Barillet et al., 2001), combined with the flock renewal strategy that favours keeping ewes with good milk performance. As a consequence, the milk production of the flock increased over time in the majority of the simulated farms. In *Early_conv*, however, the milk production of the flock decreased over time following the introduction of an HFAI reproduction strategy, suggesting that the very low fertility rate (and therefore number of milking ewes) observed in this scenario did not allow to observe the evolution of this farm’s flock milk performance due to its genetic progress.

A shift in the occurrence of the highest peak of milk production was also observed in the HFAI scenario for both conventional farms due to the more important lambing staggering compared to the baseline scenario in these conventional farms, which caused to have more staggered milking entries. This is consistent with previous simulations that showed a similar delay in the milk production highest peak under the HFAI context (Laclef et al., 2023b). In *Late_conv*; however, the highest peak of milk production was delayed but higher than in the baseline, as the delay in milking entries led to reducing the gap in the milking start between the ewes of the adult and young batches, resulting in a higher peak of milk production. In *Early_conv*’s HFAI, the peak of milk production remained lower than in the baseline scenario, as the proportion of ewes milking was too low compared to baseline. In both organic farms, even though the occurrence of the highest peak in milk production was not delayed by HFAI, the flock’s daily milk production curves started off lower in this alternative scenario than in the

HFM baseline while showing higher milk production values at their highest peak of daily production. This is once again due to the AI protocol that delayed the mating start of the adult batch during reproduction.

An adjustment of the milking period (+10 days) was introduced for both conventional farm's HFAl scenarios to compensate for the delay of occurrence in the highest peak of daily milk production. Indeed, in a previous simulation of the HFAl scenario for the *Late_conv* farm, which did not include an adjustment of the milking dates, this delay led to a significant loss of milk marketable (Laclef et al., 2023a). Therefore, the results obtained here showed that increasing the milking duration by 10 days allowed to increase the amount of milk produced in the *Late_conv* farm's HFAl scenario compared to the results obtained in the previous study. Consequently, despite a decrease in the proportion of ewes milked, the flock's average annual individual milk production level (in L/ewe) was higher in HFAl than in the equivalent baseline scenario for this farm whereas in the *Early_conv* farm, the extension of the milking period did not compensate for the lower rates of ewes milked in HFAl. Nevertheless, the increase over time of the flock's average annual individual milk production in the *Late_conv* farm was still higher in the HAI baseline scenario than in HFAl. In contrast, in both organic farms, the flock's total and average milk production values were equivalent between scenarios, suggesting that over the five cycles, the introduction of AI did not lead to a massive genetic progress for dairy performances in these farms.

Consequences of the reproduction management scenario without hormonal treatment and with insemination on the farm's feed consumption

For the organic farms, the feed consumption was equivalent to lower in the HFAl scenario compared to the HFM baseline mainly due to equivalent total feed quantities distributed between scenarios, whereas the flock's milk production was higher in HFAl. On the contrary, in conventional farms, the feed consumption was higher in HFAl than in the HAI baseline mainly due to the reduced total milk production of the flock while the diets remained the same and additional rams, introduced to perform the ME, were fed over the production cycles.

Consequences of the reproduction management scenario without hormonal treatment and with insemination on the farm's economy

In organic farms, HFAl led to an increase of both GM per L (in €/L) and total GM of the farm (in €) mainly because the quality of milk produced was increased thanks to the better genetic background introduced through AI, while the quantity of milk produced was either increased or equivalent. It also suggests that the positive economic benefit of introducing AI into a farm's reproduction management routine compensated for the additional economic cost of performing AI. Additionally, the total GM increase over time was higher in HFAl than in HFM due to the increase in the proportion of ewes born from AI in the flock and the associated genetic progress inducing positive effects on the quantity and quality of milk produced. In conventional farms, results differed according to the reproduction season. Indeed, for *Late_conv*'s HFAl, stopping the HT use while increasing milking duration had a positive impact on the farm's GM per L and total GM as both indicators were higher in HFAl than in the HAI baseline. In *Early_conv*, however, the potential benefit of stopping HT was impeded by the lower flock productivity (in milk and lambs) leading to lower GM per L and total GM in HFAl than in the HAI baseline.

It should be noted that the AI cost simulated here is the one currently applied in the RB. However, in this region, AI is done by external insemination companies. Therefore, if the price of the AI

in HF context is revised (notably to consider the fact that inseminators will have to transport fresh semen on several successive days for a same farm or even manage the oestrus detection), the conclusion drawn here might have to be nuanced depending on the price fixed to do AI without HT. Moreover, only the farm's GM was simulated here. However, the introduction of HFAl also implies structural costs such as the acquisition of automated oestrus detection devices or the adjustment of the number of rams. Building adjustments to practice the ME should also be expected, especially in conventional farms. Indeed, despite the need to have a sufficiently high ewe:ram ratio to achieve an effective ME (Oldham et al., 1990), it is also acknowledged that ewes must be isolated from rams at some point to achieve an effective ME (Delgado et al., 2009), implying that there must be space in the farm to do so.

Consequences of the reproduction management scenario without hormonal treatment and with insemination on the farms' workload indicators

In both conventional farms, the workload during the lambing period (work times in s/L of milk produced) was considerably increased in HFAl due to the bigger spread of lambing events observed in this scenario compared to the HAI baseline at all production cycles. Nevertheless, HFAl also led to a decrease in the maximum number of ewes lambing daily on these farms, which could be a positive aspect as it could allow farmers to take more time to care for ewes and lambs during the lambing period, reduce the lambs' mortality and limit additional labour demand during lambing. In *Early_org*'s HFAl, the workload during lambing was also increased compared to its HFM baseline, due to the increased spread of lambing events following the AI protocol. However, in *Late_org*, implementing HFAl had a positive impact on the workload during lambing as it became significantly lower than in HFM due to a higher maximum number of ewes lambing daily. It should be noted that the additional workload required to perform AI in the HFAl scenario, in particular the time needed to detect ewes in oestrus has not been assessed here, as we did not have the necessary data to do so. The implementation of oestrus detection practices can indeed be time-consuming, even when using automated oestrus detection devices, and must be considered in order to fully address the effect on HFAl on workload during the reproduction period.

Regarding the workload during milking in all organic farms, it was lower in HFAl compared to the HFM baseline, because of the staggering of milking entries that led to a slightly better concentration of lactation stages in the flock during milking and thus a higher peak of milk production in HFAl. In contrast, for the conventional farms, the workload during milking was higher in HFAl compared to the HAI baseline. Indeed, in *Early_conv*, it was mostly because despite a lower number of milking ewes, the quantity of milk produced over an equivalent amount of time was much lower than in HAI. In *Late_conv*, in which milk production was less reduced than in the baseline, it was because the milking period was extended.

Consequences of the reproduction management scenario without hormonal treatment and with insemination on the farm's environmental footprint

In the conventional farms, the simulated GHG emissions (in kg CO₂eq/L of milk) as well as the water consumption (in L/L of milk) were higher in the HFAl scenarios, especially in the *Early_conv* farm. For *Late_conv*, it was because the GHG total emissions values and water consumed were increased. Indeed, the CH₄ emissions were increased as more animals were present on the farm due to the increased number of rams in the farm, while the CO₂ emissions

and water consumption were especially increased due to the extension of milking period which led to feeding lactating ewes during longer periods, but also to a more important use of water and electricity use in the milking parlour. For *Early_conv*, this was once again, due to the lower quantity of milk produced in HFAl while the total emissions values of most GHG and the total quantity of water consumed were reduced in lower proportions (due to a lesser use of the milking parlour) or increased (for the CH₄) due to the increase in the number of rams permanently present in the flock in the HFAl scenario. Overall, HFAl had negative effects on the simulated environmental indicators. However, it should be noted that no HT were used in HFAl compared to HAI, meaning that a possible offset of GHG emissions from HT use can be considered in these conventional farms. The level of this offset is complex to evaluate but should be quantified to fully compare the impact of HFAl on GHG emissions in these conventional farms.

In the organic farms, HFAl led to lower or equivalent GHG emissions and water consumption compared to the HFM baseline. Indeed, an equivalent number of animals were present in these farms and feeding rations were the same in all scenarios. Therefore, the total of CH₄ emitted as well as the quantity of water and feed consumed was equivalent between the two scenarios while milk production was equivalent or increased in HFAl leading to equivalent or lower values per L of milk for the CH₄ and CO₂ feed emissions as well as for the water consumption. For the CO₂ emissions linked to electricity use, the slightly lower values observed, especially in *Late_org*'s HFAl, were the result of the better concentration of lactation stages in the flock during the milking that led to more efficient use of the milking parlour and thus reduced the electricity use per litre of milk produced.

How to manage a reproductive management strategy without hormonal treatment and with insemination in dairy sheep farms?

The REPRIN'OV model used here was built to simulate changes in the reproduction management under stable environmental and economic conditions (Laclef et al., 2023a). In reality, the farms are evolving in a changing environment which should affect the values obtained for the simulated indicators. In addition, the simulations were made over five consecutive production cycles following the implementation of the HFAl strategy in each farm. A study on a longer period of time would strengthen the conclusions, as some tendencies could differ if observed on a longer period of time. Nevertheless, the comparisons made between scenarios and farms in this study give us some first insights on how to manage an HFAl strategy in a diversity of dairy sheep farms. The results of this work notably confirm the hypothesis that introducing HFAl had different consequences on the sustainability of a dairy sheep farm according to its initial configuration. It thus suggests that implementing AI without using HT should be associated (or not) with additional management changes depending on the farm's type of agriculture and season of reproduction.

Overall, the HFAl scenario had mostly negative impacts on the simulated sustainability indicators for the conventional farms, especially in *Early_conv* whose reproduction season was out of the ewe's natural season of sexual activity. It should however be noted that the HFAl scenario led to stopping HT use in the conventional farms which could be associated with positive impacts on other sustainability indicators. Indeed, indicators such as the animal welfare, or, GHG's emissions linked to the industrial production of HT were not studied here, but should be taken into consideration when evaluating the consequences of introducing HFAl. For the organic farms, HFAl had mostly neutral or positive impacts on the simulated indicators. That difference was because conventional farms had to go from HT use to a more variable oestrus induction/synchronisation practice which led to a series of col-

lateral negative consequences on the simulated sustainability indicators whereas organic farms did not change their oestrus induction/synchronisation practice. This suggests that changes in the farm management and organisation are needed in conventional farm to sustainably implement the HFAl practice whereas it is not necessarily the case for organic farms.

A 10-days extension of the milking period was introduced in the conventional farms to compensate for the expected staggering of milking starts when implementing the HFAl strategy while keeping the same reproduction periods as in conventional management (Laclef et al., 2023b). Although this extension did not lead to a higher flock milk production compared to the HAI, it did increase flock milk production sufficiently to achieve a better GM in the *Late_conv* farm. Therefore, the extension of the milking period could be a way to ensure a significant lactating period for all ewes and therefore to introduce HFAl in dairy sheep farms while keeping a good milk production level and sustain the farm's economy. However, the extension of the milking period also led to higher GHG emission and water consumption as well as a higher workload. Moreover, in practice, a milking period extension in a dairy sheep farm of the RB could only be implemented if accepted by the dairy collectors. It should also be noted that extending the milking period should be associated with an equivalent adjustment of the feeding periods of the flock. It could therefore lead to extend the duration of the grazing period which could be a challenge depending on the season, especially in Mediterranean regions such as the RB in which grass production and availability is more and more affected by climate change (Iglesias et al., 2012). The milking period extension did not however compensate for the low fertility results in the *Early_conv* farm suggesting that for this type of farm, solution should be found to avoid a too big reduction of the fertility rate and the associated biotechnical performances of the flock. One solution to improve fertility results in conventional farms could be to combine the use of the ME with other HF practices such as photoperiod protocols to try to improve oestrus induction in the flock (O'Callaghan et al., 1991; Pellicer-Rubio et al., 2019) especially for young ewes in "early" type farms. Another solution to increase reproductive performances of the young ewes in the "early" farms could be to delay the age at which they are first put into reproduction so that they could be mated or inseminated during their natural reproduction season. Extending the length of the direct mating period (and thus the reproduction period) could also be considered so that ewes that did not express oestrus in the spring (or in early summer for "late" farms) have a chance to do so later as the natural breeding season approaches. However, delaying the age at first reproduction as well as extending the reproduction period of the flock might disrupt the milking schedules of the farms. Introducing such changes in the reproduction management of the flocks should thus be discussed on a larger scale, with all stakeholders of the dairy industry, because, if all farms in the RB decide to modify their flock's reproduction schedules, it could disrupt the milk collect operations at a regional level.

As expected, results also shown opposite patterns between conventional and organic farms for the evolution of the AI rates and proportion of ewes born from AI into the flock. They increased in organic farms whereas they decreased in conventional farms. Still, the simulated HFAl protocol seems like a good way to keep AI and thus a high genetic background in the flock. The AI rate could be improved by increasing the number of AI days. However, it could lead to an increase in the workload during the reproduction period (to detect oestrus and do additional days of AI) and create additional financial costs. Using automated oestrus detection devices could simplify the process of AI, thereby lessening the workload for farmers during the reproduction season. Nonetheless, as these devices are relatively novel, it remains uncertain whether they will be exclusively adopted on farms by farmers themselves or also

managed by insemination centres as part of their service offerings. Ultimately, one of the fear of implementing HFAl was that it would ultimately increase the workload during lambing (Lurette et al., 2016), to an even greater extent than HFM. Simulation results showed that this is not necessarily the case. In fact, in the *Late* farm, HFAl did not lead to more work suggesting that for this type of farms HFAl could be implemented without disrupting the current farm functioning. It should be noted however that in this work, a perfect level of oestrus detection was simulated in HFAl suggesting that reliable tools such as an electronic estrus detector (Menassol et al., 2023) are needed to have a level of performance equivalent to that simulated.

The results of this study thus highlight the complexity to maintain all sustainability indicators to their current level when introducing an HFAl alternative scenario. It suggests that compromises should be made to sustainably implement such reproduction management depending on farmer's main objectives for their production systems.

Conclusion

This simulation work confirmed the hypothesis that the consequences on the sustainability of a dairy sheep farm, of introducing an HFAl reproduction management strategy, should differ according to the initial farm configuration and the related farming system practices. The conventional farms modelled were indeed more affected by the HFAl scenario than organic ones regarding key sustainability indicators of the farm functioning (biotechnical, economic, environmental and workload). Differences due to the complexity to induce oestrus out of the natural reproduction season ("Early") were also observed, as the impacts were more important in "Early" farms, compared to those practicing reproduction in the natural season ("Late"). Additional modifications of associated management practices (e.g. extension of the milking period and/or changes in the flock's feeding programme), to complete the changes in the reproduction management, should thus be targeted and adjusted to each farm context. The results of this work provide better understandings to the complex relationships between the management of the reproduction and the rest of farm's components, functioning and sustainability key pillars. It offers insights into changes to expect in the first five production cycles with HFAl, but further validation through simulating additional cycles is necessary to confirm these trends. Overall, this study's findings hold the potential to facilitate constructive discussions with stakeholders on redesigning a socially acceptable reproduction management system for the dairy sheep sector, specifically in performing AI without HT.

Supplementary material

Supplementary material to this article can be found online at <https://doi.org/10.1016/j.animal.2024.101210>.

Ethics approval

Not applicable.

Data and model availability statement

The model script is openly available on the following repository: <https://github.com/elaclef/REPRINOV-model.git>.

The data used to model the farms and simulate the scenarios are available on request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used the Deep L online translator for English editing and grammatical correction in the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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E. Laclef: Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Conceptualization. **E. González-García:** Writing – review & editing, Validation. **N. Debus:** Writing – review & editing, Validation, Conceptualization. **P. Taillandier:** Writing – review & editing, Validation. **C. De Boissieu:** Validation, Resources. **E. Morin:** Validation, Resources. **A. Lurette:** Writing – review & editing, Validation, Funding acquisition, Conceptualization.

Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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