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J. Dairy Sci. 106
https://doi.org/10.3168/jds.2022-22080

Alternative hormone-free reproduction management of a dairy sheep flock disrupts the farm's annual feeding system calendar and its associated strategies

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ABSTRACT

Hormone-free (HF) reproduction in dairy sheep is a way to meet current societal demands, but it requires being prepared for collateral impacts on related system components. The efficiency of HF practices (e.g., using the male effect for estrus induction and synchronization) is uncertain compared with hormonal treatment (HT). For example, these practices can lead to higher variability in the flock physiological stage patterns throughout the year, which has direct consequences for feeding regimens. The objective of this work was to simulate the impacts of HF reproduction management, including artificial insemination (AI), on the temporal distribution of productive performance and nutritional requirements of a conventional dairy sheep flock. Using the REPROsheep2.0 model, 6 scenarios were compared over one typical production season for the same flock (n = 597 Lacaune ewes) intensively reared in the Roquefort region of France. These scenarios depicted reproduction with HT and AI in mid-May (Early); HT and AI in July (Summer Late); HT and AI in November (Autumn Late); and their HF versions (HF-Early; HF-Summer Late, and HF-Autumn Late, respectively). In all HF scenarios, a reduction in the number of ewes lambing and consequently in the annual milk production of the farm was observed (−1 to −7%). This affected annual performance with a subsequent decrease of total annual nutritional requirements (−2 to −6%). The HF scenarios resulted in a staggering of lambing events with a 7- to 14-d shift in the appearance of milk production peaks and related nutritional requirements compared with the HT scenarios. Transitioning from conventional to HF reproduction management, while preserving AI, would increase farm workload, lengthen milking period operations, and necessitate a readjustment of feeding management strategies with regard to available feed resources. Depending on the production season, the observed delay in the distribution of nutritional requirements could be either an attractive or an unfavorable outcome for farmers. The delay may be concordant, for example, with the recently observed impacts of climate change on seasonal forage availability in Mediterranean regions (less spring herbage production and warmer temperatures) that are affecting farmers' decision-making about the most efficient use of forage and feed resources.
Key words: dairy sheep, hormone-free reproduction, agent-based model, feeding management

INTRODUCTION

In the conventional livestock farming industry, breeding strategies including AI often depend on the use of hormonal treatment (**HT**) for estrus synchronization. However, this practice is increasingly questioned by society worldwide, leading to higher consumer demand for healthier products originating from farming systems that minimize the use of HT and follow practices that do not compromise animal welfare (Martin et al., 2004). Some alternatives to HT have already been developed in sheep farming (Scaramuzzi and Martin, 2008). For instance, the male effect is a hormone-free (**HF**) breeding practice that stimulates ewe ovulation and concentrates the peaks of parturition in the flock (Rosa and Bryant, 2002; Pellicer-Rubio et al., 2019). This effect involves a sexually active male being able via sensory signals to induce and synchronize heats and ovulations in a group of anovulatory (i.e., sexually resting or uncycled) females by increasing the activity

Received March 14, 2022.
Accepted November 14, 2022.
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of their hypothalamic-pituitary axis, leading to ovulations and the resumption of estrous cycles (Thimonier et al., 2000; Delgadillo et al., 2009). Combining this practice with an electronic device solution to precisely detect estrus enables using AI without HT (Debus et al., 2019). However, the success of synchronization with the male effect technique may vary according to farming system conditions and the related zootechnical parameters, such as the age of the ewe, her BCS, the milk production level (Rosa and Bryant, 2002; Debus et al., 2022), and the time between drying-off and mating (Tournadre et al., 2009). Therefore, AI without HT is still complicated to implement. Furthermore, the uncertain effects on flock performance and associated management practices at both flock and farm levels are limiting factors for the wide adoption of these alternatives.

Among the most sensitive associated farming management practices, the feeding system is particularly prominent. Indeed, the performance of the herd depends on the feeding, which constitutes more than 70% of the total cost of the enterprise (Makkar, 2018). Overall, feeding strategies are mainly based on combining the management of the nutritional requirements of the flock over time, which are determined by the progression of the animals through different physiological stages, and the efficient use of the available feed and forage resources. The current global context of climate change affects forage autonomy of livestock farming systems, as farms are increasingly subject to fluctuations in the availability and quality of grazing, forages, and roughage resources. Therefore, proper management of the available land is required because grasslands can be a significant feed resource with a low unit cost when well matched to the flock requirements (Wilkinson and Lee, 2018). This is the case for pastoral systems in Mediterranean regions, such as the dairy sheep farming systems of the Roquefort region of France. These tradition-based grazing systems include rules for managing flocks with daily grazing sessions as soon as the meteorological conditions allow for them (INAO, 2017).

The aim of the current study was to simulate the impacts of establishing an alternative HF reproduction management in a flock belonging to a representative conventional semi-intensive dairy sheep farming system. We simulated and evaluated the effects of this management on both the annual and dynamic temporal distributions of the flock's reproduction and milk production performances, as well as the related repartition of nutritional requirements over time. We then assessed the direct consequences of these factors on the management of the flock feeding system.

MATERIALS AND METHODS

The study was carried out using available information, experiences, and the historical database related to the management of a flock belonging to one representative dairy sheep farming system in the Roquefort region of France. Specifically, it was located in the INRAE (French National Research Institute for Agriculture, Food and Environment) experimental unit La Fage, in the region of the Causses du Larzac (43°55′05″N 3°05′40″E, ~800 m above sea level). In this in silico experiment, a dynamic agent-based model was used to evaluate several alternative scenarios of reproduction management. Because no human or animal subjects were used, this analysis did not require approval by an Institutional Animal Care and Use Committee or Institutional Review Board.

Conventional Reproductive Management in Dairy Sheep Farming Systems of the Roquefort Region

In terms of reproductive management, dairy sheep farms can be distinguished by whether or not they use HT to synchronize ovulations and can thus easily perform AI. Conventional farms are usually characterized by the systematic use of AI (in part or all of the flock), after synchronizing ovulations using HT. In addition, in the Roquefort area, dairy sheep farms are divided into 2 main groups: the so-called early and late mating systems. In early mating systems, farmers mate their ewes in spring, with lactations scheduled between November and August. In late mating systems, the ewes are mated in midsummer, close to the natural mating season for sheep (i.e., autumn), which induces lactations between January and October. In response to the industry demand in this large dairy sheep production basin, a system of spreading production by splitting the mating periods between farms has been developed. This strategy allows year-round milk production and collection by the dairies in the region (Lagriffoul et al., 2016). Such diversity of mating period schedules was considered in the design of the scenarios tested in the current study.

Description of the Dairy Sheep Flock Model

The dairy sheep flock model was implemented with the GAMA open-source agent-based simulation platform (Taillandier et al., 2019). The source code for the model can be accessed at https://github.com/elaclef/REPROsheep2.0_ABM.git.

Baseline Model. The structure of the model relies on a previous agent-based flock model developed by our team (i.e., REPROsheep; Laclef et al., 2021), which was designed to simulate the reproductive dynamics of a dairy sheep flock composed of dairy Lacaune ewes and managed under an HF regimen. Briefly, the model presents 2 main types of agents (or entities): (1) a decision-making or human entity, the farmer, and (2) biotechnical animal entities (individual sheep) that are subdivided as ewes and rams. REPROsheep was designed to simulate a reproduction season followed by a milk production period with a time step of 12 h. The model is composed of biotechnical process submodels (i.e., to model individual reproduction and lactation biotechnical steps) and management submodels (i.e., to model farmer's decisions). Each simulation starts on the first day of the reproduction process (i.e., date of the male effect or first day for HT) during year n and culminates the day after the last day of the milking period of year $n + 1$. Therefore, the main processes represented in the model occur during this period, called the production season, which allows the succession of the physiological stages to be depicted over time for each ewe.

In the current work, REPROsheep was revisited. The progression of the individual BCS, as well as the net energy and digestible protein requirements of the animals, were added to the modules of the previous version (Laclef et al., 2021) to generate the new version of the model used here (REPROsheep2.0). Based on daily updates of ewes' physiological stages, a daily calculation of requirements in net energy [using the forage unit for lactation (**FUL**) system] and digestible protein [using the protein digestible in the intestine (**PDI**) system] (Jarrige, 1989) of each ewe was integrated, based on the INRAE feeding system and the equations for estimating nutritional requirements (Hassoun and Bocquier, 2010).

Reproduction and Lactation Submodels. The representation of the reproduction biotechnical process was adapted from Laclef et al. (2021), and it is functional in either HT or HF contexts practicing AI. In an HT context, a fixed probability of synchronization success is assigned and determines if the ewe is sexually receptive (in heat or in estrus) (Figure 1). In an HF context, the probabilities of being in estrus are determined by the probability of a ewe being cyclic (**P_C**; i.e., spontaneously ovulating and showing estrus) and, if not cyclic, by the probability of responding to the male effect. In this revised version of the model, the P_C differs according to the reproduction season considered. When reproduction occurs during the spring (i.e., outside the natural reproduction season of the ewes), the P_C is a function of the age, BCS, and milk production level of each ewe, as defined by Laclef et al. (2021) for Lacaune ewes. However, when reproduction occurs during the full natural reproduction season of ewes (i.e., autumn) or close to it (i.e., summer), the P_C for a ewe is high (Chemineau et al., 1992; Chanvallon et al., 2011). To our knowledge, very few recent studies report the natural seasonality of the dairy Lacaune breed, so the P_C in the current study was arbitrarily set to 0.8 when reproduction occurs in summer and to 1.0 when it occurs in autumn, leaving less room for the male effect to affect the reproductive response of the ewes. The male effect can only induce the resumption of cyclicity for anovulatory ewes (Delgadillo et al., 2009); therefore, during the natural season of reproduction, when most ewes are spontaneously cyclic, the male effect impact is basically null. Based on previous accumulated experience, collected information, and available databases, a probability coefficient of AI success was also added to determine whether AI would effectively lead to a pregnancy event. The pregnancy rate following an AI service depends on several factors such as farming system, ewes' health or parity, the insemination technique, and other environmental factors (Anel et al., 2005). For dairy Lacaune ewes, the pregnancy rate is usually between 65 and 71% in adult ewes (David et al., 2008). In the current study, the lactation process was modeled in the same way as reported by Laclef et al. (2021), using predictive equations for individual lactation curves for dairy Lacaune ewes proposed by Lagriffoul et al. (2003). However, a probability for a ewe to present health issues after its suckling period was added, including the probability of a decision being made to stop the lactation of that given ewe.

Reproduction Management Submodel. The reproduction management submodel was also modified from the previous REPROsheep version to include different reproduction management possibilities considering whether or not HT with an adapted AI protocol was used. The use of HT involves one AI day for adult ewes and one AI day for young ewes. For each of these batches, the day of AI occurs after 16 d of HT. In the HF context, we chose to represent a reproduction management protocol including the use of the male effect followed by AI only on adult ewes because young ewes usually respond poorly to the male effect, mainly owing to stress and lack of sexual experience (Chanvallon et al., 2010). In addition, in the HF context, the AI protocol differed according to the reproduction season considered. Outside the natural reproduction season, the response to the male effect has been found to induce the resumption of cyclicity in ewes, with peaks of estrus activity between 18 and 20 d and between 24 and 26 d after the male introduction for the male effect (Thimonier et al., 2000; Rosa and Bryant, 2002). Thus, in this case, 6 d of AI were scheduled around these days. However, during the full natural reproduction

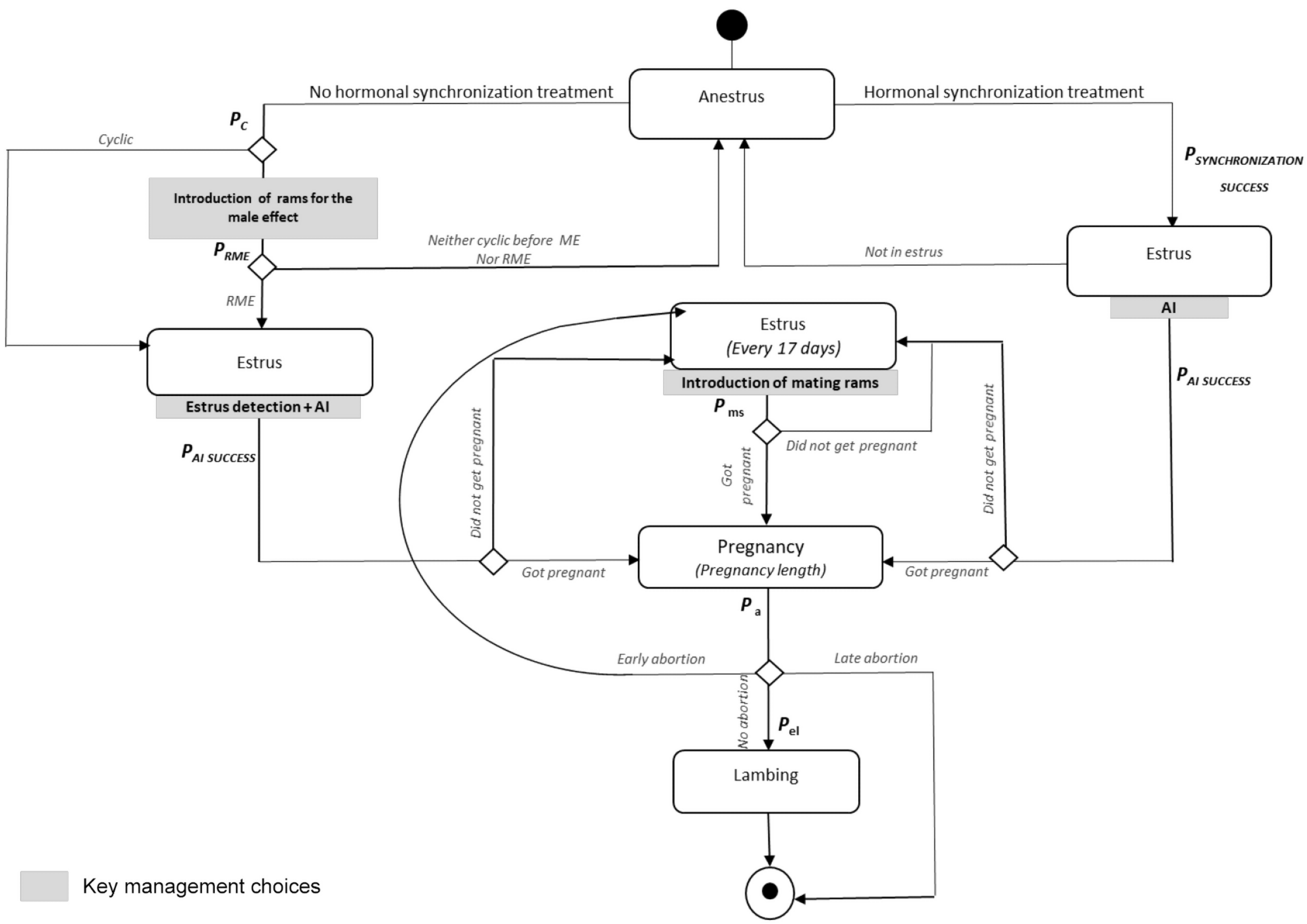

Figure 1. The individual ewe's reproduction phases modeled in REPROsheep 2.0 (Laclef et al., 2021), according to the sequence of physiological or biotechnical steps, or both, including farmer decisions in the context of reproduction practicing AI. Reproduction starts with an ewe in seasonal anestrus and ends at lambing. ME = male effect; RME = response to male effect; P_a = probability of abortion; P_C = probability to be cyclic; P_{el} = probability of easy lambing (i.e., lambing without health complications); P_{ms} = probability of mating success; P_{RME} = probability to respond to male effect.

season (or close to it), most ewes show estrus spontaneously (Chanvallon et al., 2011). Therefore, in the case of a seasonal HF reproduction, 6 consecutive days of AI were arbitrarily scheduled between 17 and 22 d after the male effect.

Whether reproductive management was conducted with or without hormones, the insemination period was followed by a mating period. In the HT context, this period was set to start 15 d after AI. In the HF context, the mating period started 6 d after the last day of AI for adult ewes. Then, about 1 mo after the start of the mating period for adult ewes, mating started for young ewes. Table 1 summarizes the different reproduction management strategies.

Simulation Initialization. All simulations were initialized using the characteristics and performance during a typical year for the management of sheep flock at La Fage experimental farm, starting from the first day of reproduction. Therefore, the modeled flock was initially composed of 11 Lacaune rams, 160 Lacaune ewe lambs (i.e., young ewes, nulliparous), and 437 adult Lacaune ewes (i.e., ewes with at least one lambing at the start simulations). In total, the flock had 597 ewes in reproduction. For each female represented, information on several individual characteristics were available (Tables 2 and 3). At this farm, reproduction usually takes place during summer (between July and September) and 2 groups of females are managed separately until milking starts, with adult ewes starting the reproduction process 42 d earlier than the young primiparous ewes. The programmed milking period of this farm (i.e., the period set by the farmer during

Table 1. Description of the principal steps of the different reproduction management modeled using REPROsheep2.0

Reproduction management	Reproduction season	Estrus synchronization protocol	AI	Mating
With hormones	All year	14-d hormonal treatment (vaginal fluoro-gestone acetate sponge + pregnant mare serum gonadotropin injection)	55 h after sponge removal, AI is performed in all ewes	15 d after AI rams are introduced for mating during 32 d
Without hormones	Spring	Male effect during 14 d on adult ewes	Each day between 18 and 20 d and between 24 and 26 d after male introduction, AI is performed on ewes detected in heat	6 d after the last AI date, rams are introduced for mating of adult ewes during 32 d. Then, 1 mo later, mating of ewe lambs during 32 d.
Without hormones	Summer and autumn	Male effect during 14 d on adult ewes	Each day between 17 and 22 d after male introduction, AI is performed on ewes detected in heat	6 d after the last AI date, rams are introduced for mating of adult ewes during 32 d. Then, 1 mo later, mating of ewe lambs during 32 d.

which the flock produces milk for sale in agreement with dairy sector in the region) has a total duration of 210 d (between late December and late July) and each lactating ewe enters milking after weaning their lambs, with an average 32-d suckling period (i.e., from lambing to weaning). The initial values for other attributes and parameters were chosen from data available in the literature and are provided in Tables 2 and 3.

Model Outputs

The outputs (i.e., indicators calculated by the model) were classified as annual (n = 5) or dynamic (n = 4). The 5 annual outputs simulated were the total number of ewes lambing and milking, the total milk production of the flock, and the total requirements in energy and digestible protein for the all females under reproduction in the flock (in FUL and grams of PDI, respectively). The 4 dynamic outputs were the daily number of ewes lambing, the daily milk production of the flock (in liters produced by all ewes at milking), and the average daily energy (in FUL per day) and digestible protein requirements (in grams of PDI per day) of all ewes in reproduction present in the flock.

Description of the Studied Scenarios

From the reference management of the La Fage farm, 6 different reproduction management scenarios were built for the same flock (i.e., with the same individuals, n = 597) (Figure 2): an early reproduction scenario with HT followed by AI in mid-May (Early); a late reproduction scenario with HT followed by AI in July (Summer Late), corresponding to the current reproduction management of the La Fage farm; a late reproduction scenario with HT followed by AI in November (Autumn Late); and the HF version of these 3 scenarios (HF-Early, HF-Summer Late, and HF-Autumn Late, respectively). They differed based on (1) the use of HT to synchronize ovulation before AI and (2) the mating dates and, thus, the consequent reproduction periods. The use of the male effect to try to synchronize estrus events in the flock is currently common in the mandatory regulations of organic farms in the Roquefort region (which applies HF practices), without any distinction of the season. Therefore, we chose to include the use of the male effect in all HF scenarios, and the AI of adult ewes only was implemented in these scenarios following the protocol described in the Reproduction Management Submodel section. The Early and Summer Late scenarios correspond to the current main mating periods practiced in the Roquefort region, whereas the others represent probable but more theoretical mating periods (Autumn Late) or alternative reproduction strategies (HF-Autumn Late, HF-Early, and HF-Summer Late, respectively). In the HF scenarios, the number of rams was set to 24 to be sufficient to perform an effective male effect on adult ewes and mating of all ewes. To complete a full production season, each simulation started arbitrarily on the

Table 2. Attributes and state variables of the agents of the model (i.e., ewes, rams, and farmer)

Attributes and state variables	Definition	Notation or abbreviation	Type	Initial value or range of values	Source
Age of the ewes	—	Age	Integer[1]	0–7 yr	Data from La Fage experimental farm
Age of the rams	—	Age	Integer	2–4 yr	
Ewe's body condition score	Score of 0–5, based on the level of muscling and fat deposition around the ewe's loin region (Russel et al., 1969)	BCS	Float	1–5	
Initial daily milk yield (for ewes >1 yr old)[2]	Daily milk production of an adult ewe on first day of milking after the suckling period	$IDMY_e$	Float[3]	1–4.5 L	
Initial daily milk yield (for ewe lambs <1 yr old)[2]	Daily milk production of a young ewe (<1 yr) on first day of milking after the suckling period	$IDMY_{el}$	Float	1–4.5 L	
Last daily milk yield monitoring (of previous lactation)	Last milk yield monitoring (during ewe's previous lactation). Usually, monitoring of ewe's milk yield occurs every 1–2 mo during the milking period of the flock.	LDMY	Float	0–993 mL	
Last total milk yield[2]	Total milk yield produced during the last lactation of the ewe	LTMY	Float	0–450 L	
Lactation number	Number of lactations performed by the ewe since the beginning of its productive life	$Lact_{num}$	Integer	0–7	
Mean live weight of ewes	Mean live weight of adult ewes at starting date (i.e., first day of reproduction process)	—	Float	75 kg	
Mean live weight of ewe lambs	Mean live weight of ewe lambs at starting date (i.e., first day of reproduction process)	—	Float	47 kg	
Lambing to reproduction interval[2]	Days between last lambing date and the hormonal treatment or the date of rams' introduction for male effect	LMEI	Integer	0–235 d	
Pregnancy length[2]	—	PL	Integer	145–157 d	Expert
Hormonal treatment	Whether reproduction strategy of the farmer includes hormonal treatment	—	Boolean[4]	True	—
Anestrus	Ewe at sexual rest and no estrus behavior (mating acceptance or heats) is observed	—	Boolean	True	
Cyclic before male effect	Ewe in estrus before rams' arrivals into the flock	CBME	Boolean	False	
Responding to male effect	Ewe that was not cyclic before male effect and became sexually receptive (in heat or in estrus) due to the 15 d of male effect	RME	Boolean	False	

Continued

Table 2 (Continued). Attributes and state variables of the agents of the model (i.e., ewes, rams, and farmer)

Attributes and state variables	Definition	Notation or abbreviation	Type	Initial value or range of values	Source
Show first estrus	First ewe's estrus after an anestrus period	—	Boolean	False	
In estrus	Ewe in estrus	—	Boolean	False	
Pregnant	Ewe pregnant	—	Boolean	False	
Abortion	Ewe aborts	—	Boolean	False	
Lambing	Ewe gives birth	—	Boolean	False	
Lactating	Ewe produces milk (i.e., during suckling and milking)	—	Boolean	False	
Active for mating	Ram has the possibility to mate with ewes	—	Boolean	False	

[1]Integer = whole numbers.

[2]Set randomly by a normal distribution whose mean and standard deviation are taken from the corresponding source.

[3]Float = values that have potential decimal places.

[4]Boolean = statement that can only be equal to yes or no.

first day of the reproduction process (date of the male effect or first day of HT depending on the scenario) and ended on the day after the end of the milking period, arbitrarily set by the farmer agent in each scenario. Based on the reference management of the La Fage farm, for each scenario the average length of the ewes suckling period was set at the realistic 32 d and the programmed milking period of the flock (i.e., days between the first day and the last day of the programmed milking period) was set to 210 d.

Statistical and Descriptive Analysis of Simulation Outputs

Scenario results are expressed as means of 75 simulation repetitions, the threshold value that allowed management of the stochasticity of this model, as reported by Laclef et al. (2021). All statistical analyses were carried out using the R 3.6.2 software (R Core Team, 2019).

Total Number of Ewes Lambing and Milking, Total Milk Production of the Flock, and Total Nutritional Requirements for the Ewes. One-factor ANOVA were performed to study the scenarios' effects on the total number of ewes lambing and milking, the total milk production of the flock, and the total nutritional requirements of the flock.

Progression of Number of Ewes Lambing, Milk Production, and Nutritional Requirements Over Time. The daily number of ewes lambing and the evolution curves of milk production, average energy requirement, and average digestible protein requirement of the flock over time (i.e., one production season) were plotted to perform a descriptive analysis of these dynamic simulation outputs.

RESULTS AND DISCUSSION

Total Number of Ewes Lambing and Milking, Total Milk Production of the Flock, and Total Nutritional Requirements for Ewes

For the annual outputs, a significant difference ($P < 0.05$) was observed in the comparison of the HT scenarios and their HF equivalents (Table 4). Indeed, in the HF scenarios, significantly lower annual numbers of ewes lambing and milking were observed. These lower values were the consequence of adopting an HF reproduction strategy while maintaining the same mating and milking time schedules, which resulted in a lower number of ewes lambing per year. This outcome could be explained by the fact that applying the male effect to trigger and synchronize ewes' ovulations outside their natural reproduction season, as in the HF-Early scenario, led to a more variable result than when using HT (Martin and Kadokawa, 2006). In fact, success in applying the male effect on anestrus ewes depends on several different types of parameters being combined at the same time (i.e., related to the ewes, to the rams, or to the management adopted by the farmer; Rosa and Bryant, 2002; Debus et al., 2021). Moreover, the use of the male effect is only effective on ewes in anestrus (Delgadillo et al., 2009). Thus, when reproduction occurs during the natural reproduction season (or close to it), such as in the Summer Late and Autumn Late scenarios, even though the number of ewes being cyclic will be high, the ovulations are not as synchronized around farmer-defined reproduction dates as they would be if the ewes received HT. Therefore, in all HF scenarios, the number of ewes in estrus on AI days and during the mating period is more variable than in HT scenarios. In addition, the simulated scenarios were de-

Table 3. Main global parameters of the model

Parameter	Definition	Notation or abbreviation	Type	Initial value or range of values[1]	Source
Starting date of the simulation	—	—	Date	Jun. 19, n	Data from La Fage experimental farm
Ending date of the simulation	—	—	Date	July 29, $n + 1$	
Starting date of hormonal treatment for adult ewes	—	—	Date	Jun. 19, n	
Starting date of hormonal treatment for ewe lambs	—	—	Date	Jul. 31, n	
Ram introduction date for male effect	Date on which the farmer introduces rams into the flock and leaves them for 15 d (without the possibility to mate) to stimulate the ovarian cycle of ewes in hormone-free context	—	Date	—	
Ram introduction date for the mating of adult ewes	Date on which the farmer introduces rams to mate the adult ewes that did not get pregnant following AI	—	Date	Jul. 20, n	
Ram introduction date for the mating of ewe lambs and adult latecomers	Date on which the farmer introduces rams to mate young ewes (<1 yr old) and the adult ewes that did not get pregnant during the previous mating periods	—	Date	Aug. 8, n	
Dry-off date	Limit date set by the farmer to dry off all ewes of the flock that are still milking	—	Date	Jul. 28, $n + 1$	
Minimum milk yield accepted at milking	Daily milk production value below which the farmer decides to dry off the ewe	MMYA	Float[2]	0.45 L/d	
Probability of abortion	Probability for a pregnant ewe to lose the fetus(es) before term	P_a	Float	0.003	
Milk fat content at milking start	Mean fat content of the flock's milk at the start of milking	—	Float	60.7 g/L	
Milk protein content at milking start	Mean protein content of the flock's milk at the start of milking	—	Float	45.9 g/L	
Probability of an easy lambing	Probability to lamb without complications preventing the milking or leading to a health problem	P_{el}	Float	0.94	
Probability of synchronization rate	Probability for a ewe (or a ewe lamb) to start ovulating following hormonal treatment	$P_{\text{SYNCHRONIZATION SUCCESS}}$	Float	1.0	
Detection rate	Heat detection rate in hormone-free scenarios	—	Float	100%	
Probability of AI success for ewes	Probability for a ewe to be pregnant following AI	$P_{\text{AI SUCCESS}}$	Float	0.67	
Probability of AI success for ewe lambs	Probability for a ewe lamb to be pregnant following AI	$P_{\text{AI SUCCESS}}$	Float	0.78	
Ewes' AI rate	Percentage of ewes inseminated	—	Float	100%	
Ewe lambs' AI rate	Percentage of ewe lambs inseminated	—	Float	100%	
Male/female ratio for the adult ewes batch	—	—	Float	1/40	
Male/female ratio for the ewe lambs batch	—	—	Float	1/15	
Probability of health problem	Probability for a ewe to have health problem preventing milking (e.g., mastitis)	P_{hp}	Float	0.06	
Theoretical litter size	—	Tls	Integer[3]	1	
Probability for the ewe to expect a twin litter	—	P_{L2}	Float	0.5	
Probability for the ewe to expect a multiple litter (≥3 lambs)	—	P_{L3}	Float	0.1	

Continued

Table 3 (Continued). Main global parameters of the model

Parameter	Definition	Notation or abbreviation	Type	Initial value or range of values[1]	Source
Selected culling age	Age after which a ewe is considered by the farmer for culling	—	Integer	6 yr	
Selected free mating duration	Period set by the farmer during which rams can mate freely with ewes	—	Integer	32 d	
Mean suckling length	From lambing to weaning; minimum period during which the ewes must suckle their newborns	SL	Integer	32 d	
Selected turnover rate	Percentage of ewes to be renewed each year to keep a constant flock population	—	Float	25%	
Probability to be in estrus during season[4]	Probability that the ewe is in a spontaneous period of heat and will accept mating	P_{so}	Float	0.8	Adapted from Chanvallon et al. (2011)
Probability for a successful mating	Probability for a ewe to become pregnant after mating	P_{ms}	Float	0.5	Expert

[1]n = year of the period considered.

[2]Float = values that have potential decimal places.

[3]Integer = whole numbers.

[4]Probability to be in seasonal estrus (i.e., period during which a female spontaneously accepts mating). This probability ranges from 0.8 during summer to 1.0 in autumn (i.e., the full natural reproduction season of ewes).

signed to keep the same mating and milking schedules as those currently practiced at the La Fage farm (i.e., those adapted to the milk collection as defined by the regional dairy sector). Therefore, to limit the decrease in annual performance associated with the use of male effect instead of HT to induce estrus in the flock, an extension of the mating period might be necessary so that ewes whose estrus was not induced by the male effect have a chance to come into heat spontaneously and be covered later. This could also be associated with a longer milking period, as a longer reproduction period could lead to some ewes entering in the milking parlor later on.

Furthermore, the ewe's average annual individual milk production (in liters per ewe per year; Table 4) was rather similar between HF and HT reproduction management, suggesting that introducing HF reproduction management does not lead to a reduction in the individual milk production level. The average individual milk production level in the flock was even slightly increased in HF-Early (+4 L/ewe per yr; Table 4) and HF-Summer Late (+2 L/ewe per yr; Table 3), which could be explained by the fact that ewes that better respond to the male effect also have good annual milk production level (Laclef et al., 2021; Debus et al., 2022). Still at the flock level, the reduction in the number of ewes milked led to a significant decrease in the milk production of the flock in the HF reproduction management scenarios. Overall, the annual reproductive and milking simulated performances of the flock were significantly lower in the HF scenarios compared with their HT equivalents ($P < 0.05$; Table 4), but the differences between the performances of each HF scenario and its HT equivalent remained relatively small (between −1% and −7%; Table 4).

As a consequence of these lower performances, the annual nutritional requirements of the flock were also negatively affected owing to their strong correlation with the production level of the flock. This outcome suggests that the potentially reduced farm incomes due to reduced annual milk and lamb production (and thus sales) in the HF context could be less severe or even compensated by the reduced nutritional requirements of the flock (i.e., the costs for feeding would be lower).

A significant difference also existed between the simulated performances and nutritional requirements of the various HF scenarios ($P < 0.05$; Table 4). Indeed, the differences were higher as the reproduction was closer to the natural reproduction season of the ewes (i.e., autumn). This consequence arises from the spontaneous cyclicity and therefore spontaneous ovulatory activity of ewes increasing closer to their natural reproduction season (Chanvallon et al., 2011). Thus, use of the male effect to induce and synchronize ovulations in the HF-Early scenario does not seem to compensate for the lower spontaneous ovulatory activity at this time, affecting the flock performances.

Number of Ewes Lambing Per Day

Throughout the year, lambing events were more spread out in the HF scenarios and thus distributed differently compared with the HT equivalents (Figure 3).

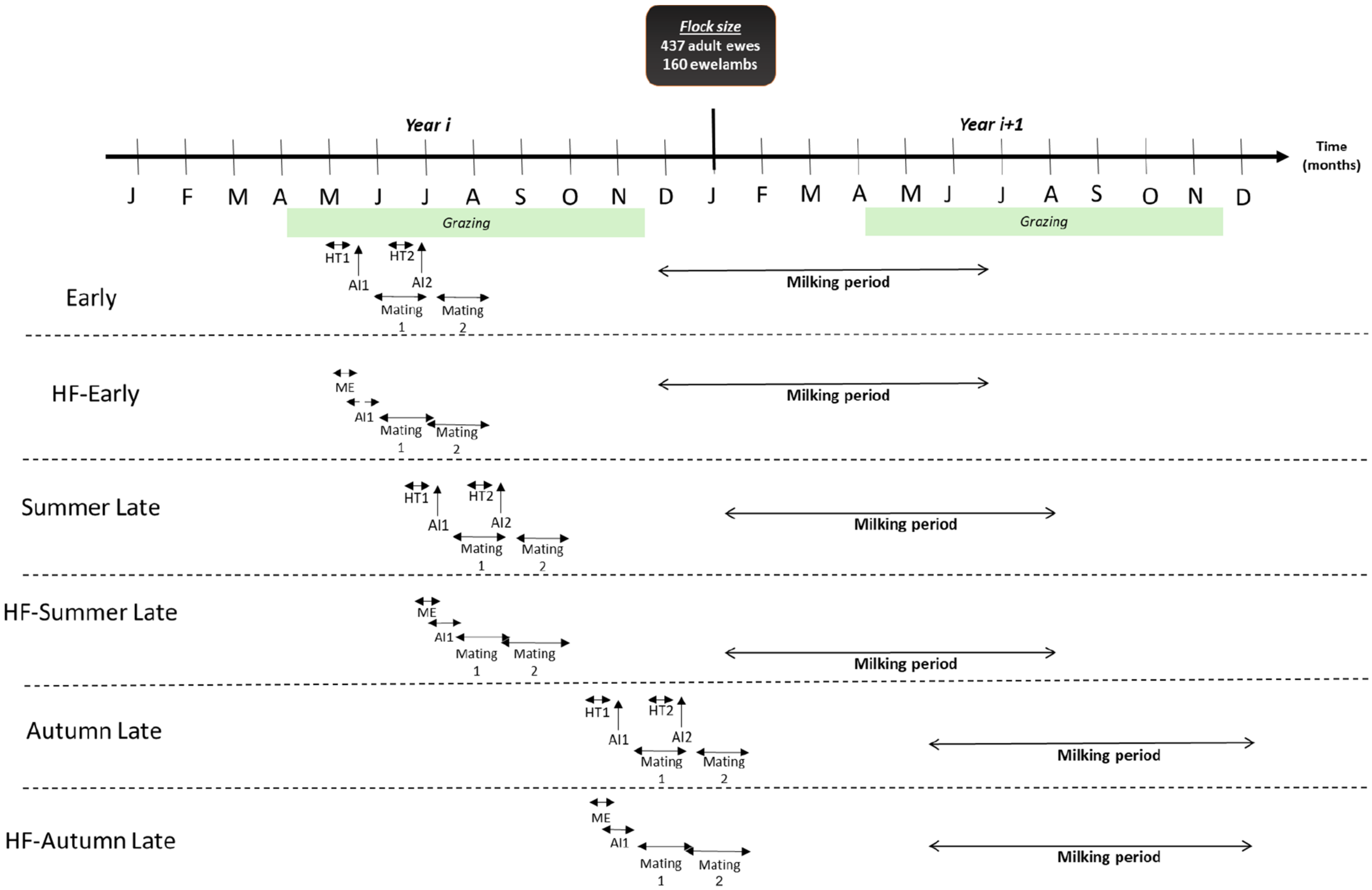

Figure 2. Main steps of the reproduction and lactation management over the simulated production season. Ref = current management context in the intensive dairy sheep reference farming system; AI1 = artificial insemination of adult ewes; AI2 = artificial insemination of ewe lambs; Early = early reproduction scenario; HF = hormone-free; HT1 = hormonal treatment of adult ewes; HT2 = hormonal treatment of ewe lambs; Late = late reproduction scenarios; Mating 1 = mating of adult ewes; Mating 2 = mating of ewe lambs; ME = male effect.

Consequently, the peaks of daily lambing events were less pronounced and staggered in time among ewes submitted to the HF regimen. In the HT scenarios, the maximum number of ewes lambing per day occurred on the first day of the lambing period, with 114 or 115 ewes lambing in one day, depending on the scenario. In contrast, in the HF scenarios, the maximum number of ewes lambing per day was not observed until 12 to 24 d after the start of the lambing period, with a maximum of 20 to 22 ewes lambing in one day, depending on the scenario. This staggering of lambing events is a consequence of the lesser synchronization of ovulation provided by the male effect with HF reproduction management. For instance, fertility after AI for adult ewes (percentage of ewes lambing following AI) ranged from 13 to 20% versus 63% (in HF with male effect and HT scenarios, respectively). At the farm level, this outcome would imply significant changes with regard to work organization and management of batches in the flock. It also implies a staggering of lambing events that would lead to greater diversity in the physiological stages present in the flock at the same time. For example, at the beginning of the milking period programmed by the farmer (i.e., as a function of the conventional reproduction management scheme), instead of having a large batch of ewes starting milking at the same time, the farmer would have to manage staggered milking starts with ewes arriving progressively and indistinctly, in a less programmed manner. This situation would imply the farmer adopting a more operational day-to-day decision-making routine to manage, for example, the feeding of ewes at different physiological stages at the same time (e.g., pregnant, suckling, and milking). Moreover, during the lactation period, ewes' energy and protein requirements are traditionally calculated by adding daily nutritional requirements for milk production to their daily nutritional requirements for maintenance. The daily nutritional requirement for milk production is a function of daily milk quantity and composition (i.e., fat and protein content; Bocquier

Table 4. Milking performances and nutritional requirements (annual accumulated values) of a Lacaune dairy sheep flock (n = 597 ewes), under 6 contrasting reproductive management scenarios

	Scenario[1,2]					
Item	Early	HF-Early	Summer Late (Ref)	HF-Summer Late	Autumn Late	HF-Autumn Late
Simulations per scenario	75					
Reproduction period[3]	May 1, i, to Aug. 12, i		Jun. 19, i, to Sep. 30, i		Oct. 15, i, to Dec. 26, i	
Milking period	Nov. 11, i, to Jun. 9, i + 1		Dec. 30, i, to Jul. 28, i + 1		Apr. 27, i + 1, to Nov. 23, i + 1	
Total number of ewes lambing (mean ± SD)	560 (±6)^{d}	519 (±8)^{a}	560 (±6)^{d}	530 (±7)^{b}	560 (±6)^{d}	554 (±7)^{c}
Annual number of milked ewes (mean ± SD)	527 (±7)^{d}	483 (±8)^{a}	526 (±8)^{d}	498(±9)^{b}	526 (±8)^{d}	520 (±8)^{c}
Diff[4] (%)		7		5		1
Total milk production[5] (mean ± SD)	151,096 (±2,510)^{d}	140,495 (±2,911)^{a}	150,716 (±2,352)^{d}	143,773 (±2,619)^{b}	151,079 (±2,698)^{d}	149,183 (±2,971)^{c}
Diff[4] (%)		7		5		1
Average annual individual milk production (L/ewe per yr)	287	291	287	289	287	287
Total energy requirement[5] (mean ± SD)	383,943 (±2,664)^{d}	363,077 (±3,456)^{a}	384,005 (±2,454)^{d}	368,961 (±3,084)^{b}	384,023 (±3,145)^{d}	377,213 (±2,928)^{c}
Total energy requirement/ewe (mean)	643	608	643	618	643	632
Diff[4] (%)		5		4		2
Total protein requirement[5] (mean ± SD)	37,753,735 (±273,642)^{d}	35,491,037 (±376,059)^{a}	37,741,711 (±255,387)^{d}	36,116,910 (±340,288)^{b}	37,755,637 (±326,051)^{d}	37,071,959 (±316,688)^{c}
Total protein requirement/ewe (mean)	63,239	59,449	63,219	60,497	63,242	62,097
Diff[4] (%)		6		4		2

$^{a-d}$Values in the same row with different superscripts differ at $P < 0.05$.

[1]Ref = current management context in the intensive dairy sheep reference farming system.

[2]Early = early reproduction scenario; Late = late reproduction scenarios; HF = hormone-free.

[3]i = year of the period considered.

[4]Diff (%) = absolute difference value between each scenario and its HF equivalent.

[5]Total milk production of the flock (L); total energy requirement of the flock, in FUL (forage unit for lactation, 1 FUL being equivalent to the average energy produced by 1 kg of standard barley); total protein requirement of the flock, in grams of PDI (protein undegraded in the rumen that is digestible in the intestine).

et al., 1993). Therefore, because the evolution of milk production follows an exponential path with maximum production occurring at the beginning of lactation (Lagriffoul et al., 2003), an ewe's nutritional requirements to cover milk production are well known to be higher at the beginning of lactation and to decrease as the lactation progresses. A staggering in milking starts will thus force the farmer to simultaneously manage different feed requirements for the several different stages of lactation (early, mid, late), as well as different "subbatches" of lactating ewes that have arrived to the milking parlor at different times.

The farms of the Roquefort region currently manage the feeding system of dairy ewes according to the largest and most homogeneous batches of animals (in terms of physiological stage) present in the flock. The strategy is based on adjusting the individual daily DMI as a function of the average energy and protein requirements of the flock (i.e., ad libitum, covering more than 100% of overall requirements; De Boissieu et al., 2019). In this context, Bocquier et al. (1995) showed that on average around 17% of the ewes of the flock (the most productive) are at risk of being underfed during milking, whereas more than 50% of the flock (the least productive) are probably being overfed. Therefore, in the case of HF reproduction management, if the farmer decides to keep a small number of batches, a greater disparity may exist between the expected individual feed intakes based on the average requirements of a functional category (e.g., late pregnancy or early milking) and the actual requirements of the individuals. For example, ewes in mid or late lactation will be fed according to the same regimen as ewes at the very beginning of lactation and will therefore potentially be overfed. One solution might be to group animals by stage as much as possible. This may be planned by physically separating the ewes in different places in the shed facility based on their category, but this practice may be complicated with a larger number of batches. However, it may also be planned virtually, for example, by using precision feeding equipment such as an automatic dispenser for concentrates (i.e., the most expensive feed component

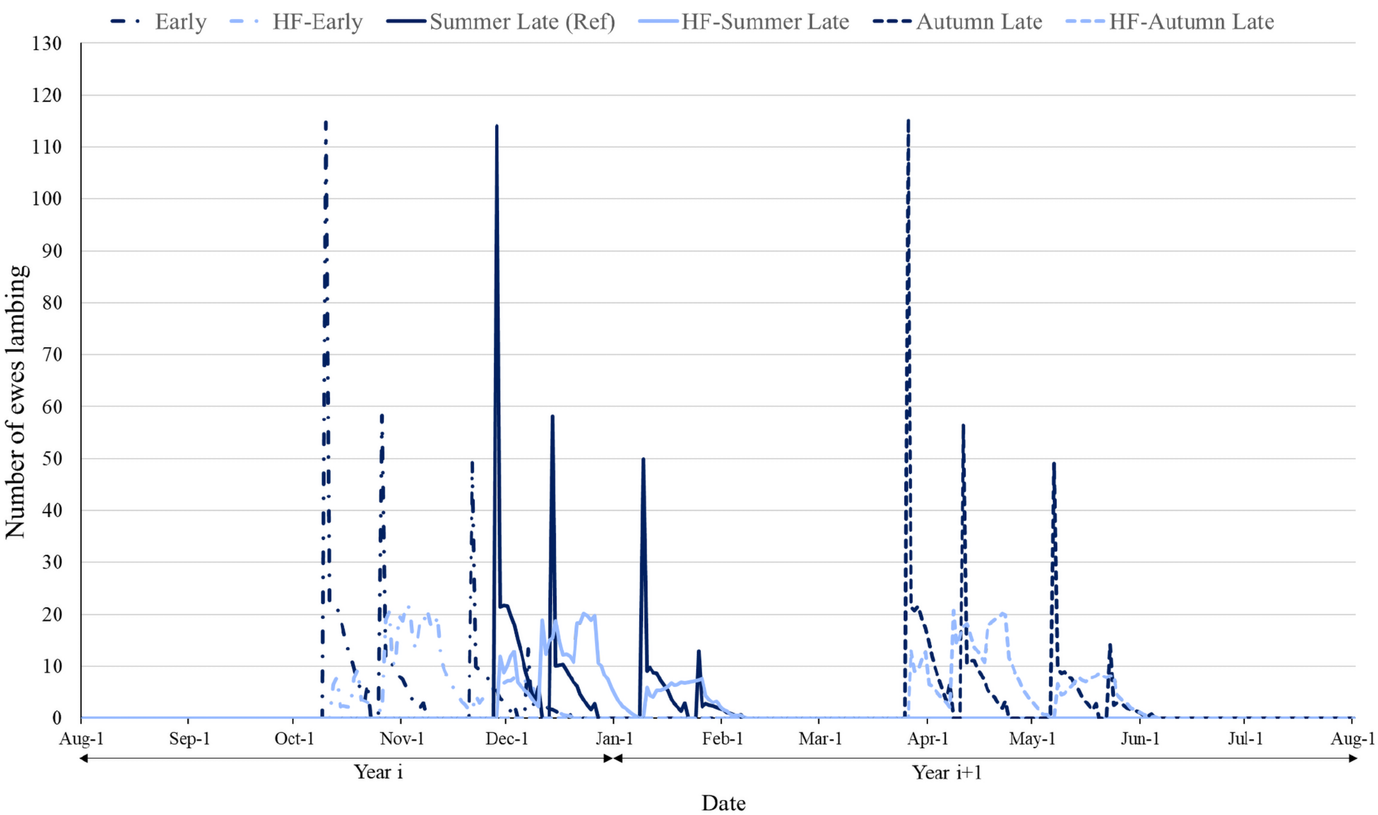

Figure 3. Daily number of ewes lambing for each scenario over the simulated production season. Ref = current management context in the intensive dairy sheep reference farming system; Early = early reproduction scenario; Late = late reproduction scenarios; HF = hormone-free.

of the diet) to fix their daily distribution as a function of specific individual requirements (with the help of individual electronic identification). Such an approach may contribute to better meeting ewes' individual nutritional requirements (Hassoun et al., 2018). However, saving concentrate, when planning more than 3 batches in a flock like that of La Fage farm, has been found to be inconsequential, while creating a practical constraint owing to a considerable increase in the workload and thus labor demand (Bocquier et al., 1995). Nevertheless, improving batch conformation, especially to account for specific requirements (e.g., as a function of parity), is still a necessary practice to maintain good trade-offs between performances at the flock level, the farm economy, and a reasonable workload for the farmer (De Boissieu et al., 2021). Indeed, under HF management, some adult ewes get pregnant later in the year than others, with lambing occurring around the same time as ewe lambs. Thus, they would have higher milk production level and therefore higher nutritional requirements than primiparous ewes, even though they belong to the same batch. However, primiparous ewes have specific nutritional requirements because they are still growing while starting their productive life. These 2 categories of ewes should thus not be fed in the same way, regardless of the reproduction scenario adopted.

In addition, it should be noted that the level of estrus detection was considered to be at 100% in the HF scenarios, which is possible if an automated estrus detector is used (Alhamada et al., 2016). This means that all the ewes that were in estrus on insemination days were effectively covered. In situations in which the level of detection would be more variable (e.g., with a visual heat detection made by the farmer), the staggering of lambing events could thus be even more pronounced than in the situation simulated here.

Milk Production and Nutritional Requirement Progression Over Time

Overall, for all breeding periods, the progression of the flock's milk production as well as the inherent reproductive female's nutritional requirements throughout a typical full production season, differed between the HT and HF scenarios.

Effects on Milk Production Dynamics. As shown by the flock's daily milk production evolution curves plotted in Figure 4A, the HF scenarios resulted in a 10- to 14-d shift in the occurrence of the production peaks, regardless of the reproduction season. This result is a direct consequence of the staggering of lambing events in these scenarios, which led to a change in the pattern of milking entries and therefore a shift in the peaks of daily milk production of the flock. In addition, due to the staggered lambing events, the daily milk production at the end of the second month of the milking period (i.e., according with the conventional milking period of 210 d traditionally programmed in the La Fage farm) was observed to be consistently higher in all HF scenarios (HF-Early, HF-Summer Late, and HF-Autumn Late, respectively), in comparison with their HT equivalents (Early, Summer Late, and Autumn Late, respectively). The bigger difference was observed during the last month of the milking period (+103, +88, and +102 L/d on average for the HF-Early, HF-Summer Late, and HF-Autumn Late, respectively). Indeed, as expected, the synchronization of milking entries dates was better with HT. Therefore, in the last month of this programmed milking period, the batches of ewes at milking were homogeneous in terms of physiological stages, and the ewes that lambed during the first lambing phase (i.e., the largest proportion of the flock) were naturally already in the last part of the lactation curve (i.e., close to the dry-off). In contrast, in the HF scenarios, the batches of ewes being milked were more heterogeneous due to the staggering of milking starts. The number of ewes already dried was therefore lower and more ewes were still being milked at the end of the programmed milking period, with some of them still having a high daily production. This result would imply a prolongation of milking activities, allowing continued milking of the ewes that arrived to the milking parlor later, with a progressive decrease in the rhythm of drying-off planning. Further, the issue of labor demand and workload would once again arise. Moreover, in farms that sell their milk exclusively to dairies, the replanning of the milking schedule could be a challenge because the dairy usually sets the milking period according to demand and the farmer has less flexibility in selecting dates for the milking period during the year. Therefore, organizing collective brainstorming at the regional scale would be needed to reach agreements and decisions that accord with the different interests and objectives of each stakeholder involved in the value chain of the dairy sheep sector.

In addition, ewes with high milk production levels close to the programmed date of introduction of rams for inducing the male effect tend to have fewer spontaneous ovarian cycles with a concomitant lower response to the male effect (Debus et al., 2021). Therefore, if the same reproduction schedule is being kept, the higher number of ewes still being milked at the end of the programmed milking period in the HF scenarios could have a negative influence on the reproductive performances of the following production season, which would also accentuate the staggering of lambing events observed in HF contexts including the use of the male effect.

Effects on the Dynamics of Nutritional Requirements in the Reproductive Flock. In agreement with the shifts in the peaks of the flock's milk production observed in the HF scenarios, effects on the flock's associated nutritional requirements progression over the production season were also observed. Indeed, the distribution curves of the average daily energy (Figure 4B) and protein (Figure 4C) requirements of La Fage farm's flock showed delays of 7 to 10 d and 10 to 13 d in the peaks of daily energy and protein requirements, respectively, in the HF scenarios compared with their equivalent HT scenarios. Indeed, the largest part of the total nutritional requirements is known to be associated with the milk production trait. Thus, a shift in the peak of daily milk production accordingly induces a shift in the peak of nutritional requirements during the year. Moreover, during the last months of the programmed milking period, the daily nutritional requirements, especially the protein requirements (Figure 4C), tended to be higher in all HF scenarios as a consequence of the higher milk production at this time for a proportion of the flock. For HF scenarios, the end of the programmed milking period thus appears to be a period during which the adaptation of the feeding system will be a major factor. In the case of an off-season breeding scheme such as the Early scenario, most of the milking phase occurs under 100% confinement with a passive feeding regimen (i.e., 100% of the diet distributed). Therefore, the feeding management becomes somewhat easier for making the required adjustments as a function of the progression of physiological stages. In contrast, in the Late scenario, it may be necessary to redefine and revisit other direct or indirect components of the farming system, such as the use of arable land destined to be used for grazing, to better match the biomass availability and quality of grass and forage resources with the flock requirements in a more complex and operational manner. This process would include the management of milk production peaks, especially for the farms that have their peak in summer (June and July), as in the Autumn Late scenario. In addition, in an HF context, the number of ewes still in production during the last month of the programmed milking period is higher, and they must have access to the milking parlor. If the last months of milking are during the grazing period, the implication is that they would have to graze on areas close to the farm. In HT scenarios, however, the ewes would have been dried-off at the same period of the year for the most part and

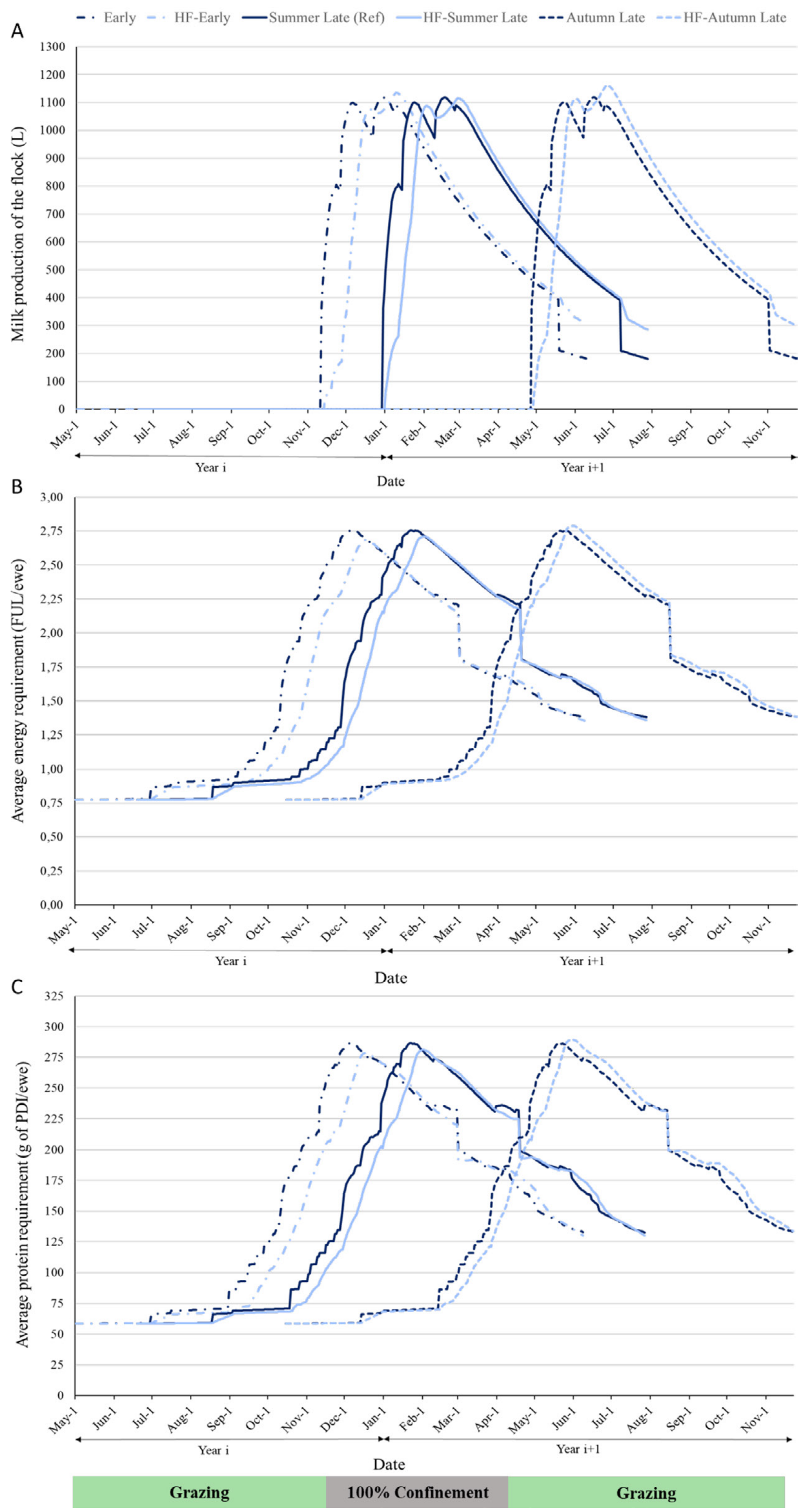

Figure 4. (A) Daily milk production (in L/d), (B) daily average energy requirements (in FUL/ewe per d), and (C) daily average protein requirement (g of PDI/ewe per d) of the flock throughout one full production season, for each simulated scenario. During one reproductive season, the ewes pass from a period of 100% confinement, with an indoor feeding system (i.e., distribution at the feeding trough), to a period including grazing that increases with time according to the availability of biomass in the farm. Ref = current management context in the intensive dairy sheep reference farming system; Early = early reproduction scenario; FUL = forage unit for lactation; HF = hormone-free; Late = late reproduction scenarios; PDI = protein digestible in the intestine.

could be sent to graze independently of the proximity of the milking parlor or facility to the grazing paddock.

Depending on the production season chosen, the changes in the evolution curves for the nutritional requirements simulated here could be either an attractive or an unfavorable outcome. In the current context of climate change, reliance on grazing to feed local dairy sheep flocks seems to be increasing, yet a delay in biomass availability also appears to be occurring compared with historical patterns in Mediterranean regions such as Roquefort. This situation causes farmers to delay the start of grazing periods for their flocks during the spring (Iglesias et al., 2012; Aguilera et al., 2020). Thus, paradoxically, dairy sheep farmers of the region could add value from the observed shift in the curve of nutritional requirements as an adaptation response to climatic change challenges affecting the availability of pasture. However, in the HF-Autumn Late scenario, the daily requirements of the flock are higher compared with those observed in the equivalent HT scenario (i.e., Autumn Late) between the peak of nutritional requirements (in early June) and the end of milking (in late November). Indeed, in this HF-Autumn scenario, in which the majority of the milking period occurs during the summer, the number of ewes milked is almost the same as in the Autumn Late scenario; consequently, the peak of production, and therefore that of nutritional requirements, is equivalent but delayed. Therefore, the HF-Autumn scenario leads to higher daily nutritional requirements in summer in comparison with the equivalent HT scenario. This could present a challenge because summers have been getting warmer, leading to less grazing land being available in summer, especially in Mediterranean regions (Iglesias et al., 2012).

Within a more systemic perspective, we can expect that a modification in the reproduction management approach could also induce a chain of modifications in other farming system components (Bellon et al., 2007). Outcomes from this study demonstrated the consequences of a change only in the reproduction management strategy (with or without hormone) of the farm. However, as discussed above, changing the reproduction strategy to introduce HF synchronization of estrus followed by AI will have other impacts, with complex domino effects that could more or less lead to having to change management practices affecting other aspects of the flock and overall farm performances. It should also be noted that only one production season was simulated here. Therefore, to make solid and holistic interpretations in time, additional simulations are needed to analyze several successive production seasons following the introduction of HF reproduction with AI in dairy sheep farms. This work would contribute to corroborating the tendencies observed in the current study and thus provide a more complex and long-term dynamic perspective. It would also allow observing other important differences linked to those changes in the reproduction strategies, especially the effects on flock breeding policies and the performances throughout several successive production seasons.

CONCLUSIONS

The simulated transition to HF reproduction for a conventional dairy sheep flock using HT resulted in a disruption of the annual lambing events repartition over time, followed by a shift in milk production peaks and related flock nutritional requirements through the year. A reduction of the flock's annual milk performances was also observed. This suggests necessary readjustments of the overall farm management, starting with the feeding system, which include revisiting allocation policies of available feed resources and decision making for the efficient use of farmland for grazing and forage production. Therefore, changing toward HF reproduction management implies that subsequent and significant changes in feed resource planning and management at the farm level should be taken into consideration. Further simulations on several production cycles are warranted to confirm tendencies observed here and to explore the consequences of such readjustments in the overall farming system and beyond (e.g., in industry).

ACKNOWLEDGMENTS

This work was supported by the French National Research Agency (Paris, France) under the Investments for the Future Program, referred to as ANR-16-CONV-0004, and by a PhD scholarship provided by the INRAE PHASE Department (Paris, France). The authors are grateful to La Fage experimental farm (Saint-Jean-et-Saint-Paul, France) for providing the data used to build the simulated scenarios. The authors have not stated any conflicts of interest.

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