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Simulation et évaluation de scénarios de pratiques alternatives pour une reproduction sans hormones dans les exploitations ovines laitières

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Résumé

En élevage ovin laitier (OVL), la gestion de la reproduction sans hormones de synchronisation des cycles ovariens est un levier à mobiliser pour répondre aux enjeux de l'agroécologie et à l'évolution des demandes sociétales. Dans les grands bassins de production, comme le Bassin Nord Occitanie (BNO), le développement d'alternatives aux traitements hormonaux (TH) de synchronisation, tout en conservant la possibilité de faire de l'insémination artificielle (IA), est nécessaire pour pouvoir continuer à diffuser les schémas de sélection de manière efficace. L'effet mâle, qui consiste à mettre un bélier dans un groupe de femelles après un temps de séparation, est une pratique alternative possible pour induire et synchroniser les chaleurs des brebis. Elle ne permet cependant pas de grouper ces dernières aussi efficacement que l'utilisation de TH et doit être accompagnée d'une détection précise de ces dernières pour permettre de réaliser l'IA au moment adéquat. L'utilisation de cette pratique alternative implique ainsi des changements au niveau de la conduite de la reproduction, mais aussi au niveau d'autres composantes associées (ex : la gestion de l'alimentation du troupeau) avec de potentielles conséquences sur le fonctionnement global de l'exploitation ; lesquelles sont encore peu connues à ce jour. L'objectif de ce travail était donc d'évaluer l'impact « ex-ante » des méthodes alternatives aux TH sur les performances zootechniques, économiques et environnementales de l'exploitation ainsi que sur la charge de travail de l'éleveur. Ceci afin d'identifier des pistes durables pour introduire des pratiques de gestion de la reproduction alternatives aux TH dans les élevages OVL du BNO. Pour ce faire, le modèle multi-agent REPRIN'OV a été développé et implémenté sur la plateforme de modélisation GAMA. Il simule des effets de ces changements de pratiques sur différents indicateurs annuels et dynamiques (quotidiens ou hebdomadaires) de la durabilité du fonctionnement d'exploitations OVL. La construction de ce modèle s'est faite par étapes. Un premier modèle dynamique de troupeau OVL (REPROsheep), a été développé afin de représenter le fonctionnement d'un troupeau OVL dans un contexte de gestion sans TH en tenant compte de la variabilité individuelle de réponse à la méthode de synchronisation des chaleurs utilisée. Il représente les processus individuels de reproduction et de lactation en tenant compte du lien entre certaines caractéristiques individuelles des brebis, telles que leur âge, leur note d'état corporel ou leur rendement laitier, et les réponses individuelles ainsi que les performances globales de reproduction et de production du troupeau. Le modèle REPROsheep a ensuite été complexifié pour aboutir au modèle REPRIN'OV qui permet de simuler le fonctionnement dynamique global d'une exploitation OVL, dans le cadre de scénarios contrastés de gestion de la reproduction (avec ou sans TH). Le modèle a été conçu et paramétré à partir de données expérimentales et techniques, puis validé à partir de données de terrains et de la littérature. REPRIN'OV a ensuite été utilisé pour simuler des scénarios de gestion de la reproduction sans TH dans quatre cas-types d'exploitations OVL du BNO. La comparaison des résultats de simulation obtenus pour cinq campagnes de production successives a montré des résultats contrastés selon les exploitations. Ils ont notamment différé selon la saison de reproduction (« hâtive » ou « tardive ») et selon le type d'agriculture (conventionnelle-AC ou biologique-AB) des exploitations simulées. Les résultats de ce travail de thèse donnent ainsi des éléments pour mieux comprendre les enjeux consécutifs à l'introduction d'alternatives aux TH pour le fonctionnement de l'ensemble d'un système de production OVL et contribuent à accompagner et à faciliter la réflexion autour de la reconception des systèmes OVL en vue de l'introduction d'alternatives durables aux TH.

Mots-clés : Brebis laitières ; Reproduction sans hormones ; Simulation ; Élevage innovant ; Modèle multi-agent

Abstract

In dairy sheep farming, the management of reproduction without the use of hormonal treatments (**HT**) to induce and synchronize ovarian cycles represent an opportunity and a disrupting lever to achieve agro-ecological transition goals while meeting societal demands. In large production basins, such as the North Occitania Basin, the development of alternatives to **HT** for induction and synchronization while maintaining the possibility of the artificial insemination (**AI**) practice, is necessary to continue providing efficient genetic selection schemes. The male effect, which consists in adding a ram in the flock after it has been separated from ewes, is an alternative to induce and synchronize heats. However, in practice, the male effect may not be as effective as the conventional use of TH, therefore requiring to be accompanied by accurate additional heat detection tools allowing AI to be performed at the right time. The use of this alternative practice implies changes in reproductive management but also in other associated components such as the flock feeding management, with potential consequences at the farm level. To date, the consequences on the global functioning of the farm is still unknown. The objective of this work was thus to evaluate the "ex-ante" impact of alternative methods to HT on the zootechnical, economic and environmental performance of the farm as well as on the farmer workload. All to identify sustainable ways to introduce alternative reproductive management practices to HT in dairy sheep farms. For this purpose, the multi-agent model REPRIN'OV was developed and implemented on the GAMA modelling platform. It simulates the effect of introducing alternative reproduction management practices on different annual and dynamic (daily or weekly) indicators of the sustainability of the operation of dairy sheep farms. The construction of this model was done in different steps. A first dynamic flock model (REPROsheep) was developed to represent the functioning of a flock in a context of hormone-free management (**HF**), taking into account the individual variability of response to the estrus synchronization method used. It represents individual reproductive and lactation processes by taking into account the link between certain individual ewe traits, such as age, body condition score (**BCS**) or milk yield, as well as the overall reproductive and production performance of the flock. This REPROsheep model was then enriched to build the REPRIN'OV model, which simulates the global and dynamic functioning of a dairy farm over time, under contrasting reproductive management scenarios (with or without HT). The model was designed and parameterized from experimental and technical data, then validated using field collected and literature data. REPRIN'OV was then used to simulate HF reproduction management scenarios in four dairy sheep farms, representative of the North Occitania Basin. Simulations of farm performances during five consecutive production seasons showed contrasting results and trends. Specifically, results were affected by reproduction season (“early” or “late”) and the agricultural system (conventional or organic) of the simulated farms. The outcomes of this thesis provide elements for a better understanding of impacts on the functioning of the whole dairy sheep production system, after introducing alternatives to HT. They also provide new insights contributing for accompanying the various stakeholder brainstorming around the redesign of dairy sheep sector in a free-hormone context.

Keywords: Dairy sheep; Hormone-free reproduction; Simulation; Innovative reproduction; Multi-agent model

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Table des matières

RESUME **2**

ABSTRACT **3**

REMERCIEMENTS **4**

PREAMBULE **6**

LISTES DES FIGURES **10**

LISTES DES TABLEAUX **11**

LISTE DES ABREVIATIONS **12**

INTRODUCTION GENERALE ET OBJECTIFS DU TRAVAIL DE THESE **14**

CHAPITRE I- ÉTATS DES CONNAISSANCES **18**

I-1. LA FILIERE OVINE LAITIERE DANS LE CONTEXTE ACTUEL ET LES ENJEUX POUR LA GESTION DE LA REPRODUCTION 18

I-2. CARACTERISTIQUES DE LA GESTION DE LA REPRODUCTION D'UN TROUPEAU D'OVINS LAITIERS . 20

I-2.1. Fondements de la physiologie de la reproduction ovine *20*

I-2.2. Saisonnalité de la reproduction et conséquences en termes de gestion de la reproduction *21*

I-2.3. Grandes stratégies de gestion de la reproduction et importance des traitements hormonaux dans les schémas actuels *23*

I-3. ÉTATS DES LIEUX DES METHODES ALTERNATIVES AUX TRAITEMENTS HORMONAUX DE SYNCHRONISATION DES CYCLES OVARIENS 26

I-3.1. Préparation du troupeau à la reproduction *26*

I-3.2. L'effet mâle : pratique alternative privilégiée en élevage ovin *27*

I-3.2.1. Principe de l'effet mâle 27

I-3.2.2. Facteurs influençant la réponse à l'effet mâle à « contre-saison » 28

I-3.3. Les traitements lumineux (ou photopériodiques) *30*

I-3.4. De nouveaux outils pour réaliser l'IA sans hormones *31*

I-3.5. Adoption des alternatives développées dans les élevages d'ovins laitiers : Leviers et verrous *32*

I-4. MODELISER LE FONCTIONNEMENT GLOBAL DES EXPLOITATIONS POUR ACCOMPAGNER LA RECONCEPTION DES SYSTEMES D'ELEVAGE OVIN LAITIER 33

I-4.1. La modélisation : un outil pertinent pour accompagner l'adoption d'innovations et la reconception des systèmes agricoles *33*

I-4.2. Cas particulier de la modélisation de systèmes d'élevage *34*

I-4.3. Modèles d'élevage ovin existants et représentations de la reproduction *35*

CHAPITRE II- DEMARCHE METHODOLOGIQUE GENERALE **38**

II-1. PRESENTATION DE LA ZONE D'ETUDE 40

II-2. METHODE DE MODELISATION ET ETAPES DE CONCEPTION DU MODELE DE SIMULATION 42

II-3. DONNEES UTILISEES ET SCENARIOS SIMULES 43

II-3.1. Données expérimentales pour la modélisation du processus individuel de reproduction des brebis *43*

II-3.2. Données pour modéliser la gestion du troupeau et de l'exploitation par l'éleveur *44*

II-3.3. Choix des scénarios et données utilisées pour les simuler *45*

CHAPITRE III- MODELISATION DU PROCESSUS DE REPRODUCTION ET SIMULATION DES PERFORMANCES D'UN TROUPEAU OVIN LAITIER DANS UN CONTEXTE DE GESTION SANS HORMONES UTILISANT L'EFFET MALE **49**

III-1. INTRODUCTION DU CHAPITRE 49

III-2. ARTICLE 1: REPROSHEEP: A MODEL THAT INTEGRATES INDIVIDUAL VARIABILITY TO OPTIMISE HORMONE-FREE REPRODUCTION MANAGEMENT STRATEGIES FOR A DAIRY SHEEP FLOCK 50
III-3. CONCLUSION DU CHAPITRE 66

CHAPITRE IV- SIMULATION DES CONSEQUENCES DE L'UTILISATION D'ALTERNATIVES AUX HORMONES SUR LA GESTION DE L'ALIMENTATION DU TROUPEAU 68

IV-1. INTRODUCTION DU CHAPITRE 68
IV-2. ARTICLE 2: ALTERNATIVE HORMONE FREE REPRODUCTION MANAGEMENT OF A DAIRY SHEEP FLOCK DISRUPTS THE FARM'S ANNUAL FEEDING SYSTEM CALENDAR AND ITS ASSOCIATED STRATEGIES 69
IV-3. CONCLUSION DU CHAPITRE 92

CHAPITRE V- MODELISATION DES CONSEQUENCES A LONG TERME DE LA MISE EN ŒUVRE D'UNE GESTION DE LA REPRODUCTION SANS HORMONES SUR LA DURABILITE D'UNE EXPLOITATION OVINE LAITIERE 95

V-1. INTRODUCTION DU CHAPITRE 95
V-2. ARTICLE 3: MODELLING THE LONG-TERM CONSEQUENCES OF IMPLEMENTING HORMONE-FREE REPRODUCTIVE MANAGEMENT ON THE SUSTAINABILITY OF A DAIRY SHEEP FARM 96
V-3. CONCLUSION DU CHAPITRE 130

CHAPITRE VI- ÉTUDE DE SCENARIOS D'INTRODUCTION DE NOUVELLES CONDUITES DE LA REPRODUCTION SANS HORMONES DANS UNE DIVERSITE D'EXPLOITATIONS OVINES LAITIERES DU BASSIN NORD OCCITANIE 133

VI-1. INTRODUCTION DU CHAPITRE 133
VI-2. ESTABLISHING HORMONE-FREE REPRODUCTION STRATEGIES IN DAIRY SHEEP FARMS: A DIVERSITY OF CONSEQUENCES ON FARM'S LONG-TERM SUSTAINABILITY DEPENDING ON THE PRODUCTION SYSTEM TYPE 134
VI-2.1. Description of the scenarios 134
VI-2.2. Statistical analysis methods 138
VI-2.3. Simulation results 138
VI-2.4. Discussion: Consequences of introducing new hormone-free reproduction strategies for a diversity of dairy sheep farms in the Roquefort Basin 146
VI-3. CONCLUSION DU CHAPITRE 152

CHAPITRE VII- DISCUSSION GENERALE 155

VII-1. DEMARCHE GENERALE 155
VII-2. ORIGINALITES DU MODELE REPRIN'OV 162
VII-3. PRINCIPAUX APPORTS DES RESULTATS DE SIMULATION DANS LE CADRE DE LA REFLEXION AUTOUR DE L'INTRODUCTION D'ALTERNATIVES A L'UTILISATION DE TRAITEMENTS HORMONAUX DANS LE BASSIN NORD OCCITANIE 166

CONCLUSIONS ET PERSPECTIVES 174

REFERENCES BIBLIOGRAPHIQUES 177

ANNEXES 187

Listes des figures

Figure I.1. Evolution des concentrations hormonales au cours du cycle sexuel de la brebis (Dudouet, 2003). 21
Figure I. 2. Moment et durée de la saison anoestrale (nombre de jours entre le début et la fin de l'anoestrus) chez quatre races de moutons français. D'après Chanvallon et al. (2011). 23
Figure I.3. Représentation schématique de la réponse ovulatoire et œstrale à l'effet mâle. D'après Thimonier et al. (2000). 27
Figure I. 4. Détecteur électronique de chevauchement porté par le mâle (crédit photo INRAE). 32
Figure II. 1. Schéma de la démarche méthodologique générale du travail de thèse et liens avec les différents chapitres du manuscrit. 39
Figure II.2. Carte de répartition des IA ovines réalisées en 2018 (IDELE, 2018a). 41
Figure IV. 1. The individual ewe's reproduction phases modelled in REPROSheep 2.0, according to the sequence of physiological and/or biotechnical steps, including farmer decisions' makings in a context of reproduction practicing artificial insemination. Reproduction starts with an ewe in seasonal anestrus and ends at lambing. 74
Figure IV. 2. Main steps of the reproduction and lactation management scheduled followed over the simulated production season. 81
Figure IV. 3. Daily number of ewes lambing for each scenario over the simulated production season... 86
Figure IV. 4. A: Daily milk production (in L/day), B: Daily average energy requirements (in FUL/ewe/day), and C: Daily average protein requirement (in g of PDI/ewe/day) of the flock throughout one full production season, for each simulated scenario. 91
Figure V. 1. Principal steps of the modelled reproduction management strategy from the start of the synchronization protocol until the start of mating for the adult batch in both hormonal and non-hormonal contexts (including AI or not). 107
Figure V. 2. Distribution of the average daily number of ewes lambing in each scenario (n= 75 repetition of simulations *per* scenario) during the first (N1) and the fifth (N5) production cycles, including the number of ewes lambing from AI in (HAI and HFAI scenarios). 115
Figure V. 3. Theoretical progression of the percentage of the flock born from AI for the simulated conventional flock (i.e. initially composed of 405 ewes all born from AI) with a 27 % renewal rate. This evolution was plotted over five consecutive production cycles and for each scenario based on the average percentage of ewes of the renewal batch born from AI simulated in this study, assuming that all culled ewes were from the initial flock (i.e. from AI). 116
Figure V. 4. Average milk production of the flock (L/ewe) for each scenario (n= 75 repetitions of simulations *per* scenario) over the successive simulated production cycles. 117
Figure V. 5. Progression of (A) the daily milk production and (B) the cumulative milk production of the flock in each scenario, during the first (N1) and the fifth (N5) simulated production cycle. 120
Figure V. 6. Comparison of the radar diagrams of the main sustainability indicators of the farm functioning, according to each scenario; in the first (N1) and fifth production cycles (N5). Each indicator value of the HAI baseline scenario corresponds to 100 % on the radar scale. 129
Figure VI. 1. Main steps of the modelled reproduction management strategy from the start of the synchronization protocol until the end of mating in both hormonal and non-hormonal contexts (including AI or not). The direct mating periods illustrated here are specific to each of the farms modelled. 137
Figure VI. 2. Radar diagrams of the main farm's functioning sustainability indicators values (mean over five successive production cycles), according to each scenario. For each farm, each indicator value in the baseline scenario corresponds to 100 % on the radar scale. 139
Figure VI. 3. Average daily number of ewes lambing (including the number of ewes lambing from AI) for each scenario in each farm (n= 75 repetition of simulations *per* scenario) during the first (N1) and fifth (N5) production cycles. 141
Figure VI. 4. Average daily daily milk production of the flock for each scenario in each farm (n= 75 repetition of simulations *per* scenario) during the first (N1) and fifth (N5) production cycles. 144
Figure VII. 1. Schématisation de la quantité de changements de pratiques à introduire pour mettre en place une conduite alternative de la reproduction sans perturber le fonctionnement actuel de l'exploitation en fonction du type d'agriculture et de la saison de reproduction des différents cas-types d'exploitations OVL simulées dans la thèse. 168

Listes des tableaux

Table I.1. Caractéristique de la production de lait de brebis des régions de la Méditerranée et de la mer Noire appartenant à l'Union Européenne. 19
Table II.1. Descriptif des exploitations OVL types modélisées (d'après INOSYS-Réseaux d'élevage ; IDELE, 2018b ; De Boissieu et Morin, 2022). 47
Table IV. 1. Description of the principal steps of the different reproduction management modelled using REPROsheep2.0. 76
Table IV. 2a. Attributes and state variables of the agents of the model (i.e. ewes, rams and farmer). 77
Table IV. 3. Milking performances and nutritional requirements (annual accumulated values) of a Lacaune dairy sheep flock (n= 597 ewes), under six contrasting reproductive management scenarios. 84
Table V. 1. Main processes and/or farming activities considered in the REPRIN'OV model (in bold the additional processes modelled in comparison to the REPROsheep flock model; Chapitre III). 102
Table V. 2. Flock and farm performance outputs, and sustainability indicator outcomes, evaluated with the REPRIN'OV model. 110
Table V. 3. Main features of the simulated dairy sheep farming system for each scenario under assessment. 112
Table V. 4. Mean values (± SD) of the evaluated farm sustainability indicators at each simulated production cycle (mean of 75 repetitions of simulations *per* scenario). 126
Table V. 5. Mean values (± SD) of the sustainability indicators of the farm functioning over the five production cycles (i.e. mean and SD of the 5 × 75 repetitions of simulations *per* scenario). 127
Table VI. 1. Characteristics of the simulated farms in each scenario. 136
Table VI. 2. Mean values of the simulated farms sustainability indicators at the first (N1) and fifth (N5) production cycles (mean of 75 repetitions of simulations *per* scenario). 140
Table A2. 1. Description of the main attributes and state variables of the agents represented in the REPRIN'OV model 199
Table A2. 2. Main parameters used in the REPRIN'OV model 201
Table A4 1. Values of the main parameters used to model the ewe's individual reproduction process in REPRIN'OV for each farm. 209
Table A5. 1. Mean values of the simulated sustainability indicators of the farms functioning over the five production cycles following the introduction of a HF reproduction management strategy (i.e. mean of the 5 × 75 repetitions of simulations *per* scenario). 210
Table A5. 2. Indicators of each farm's daily milk production and lambing distribution over time *per* scenario. 211

Liste des abréviations

Abréviations françaises :

AB : Agriculture Biologique

AC : Agriculture Conventionnelle

BNO : Bassin Nord Occitanie

CIA : Centre d'Insémination Artificielle

DAC : Distributeur Automatique de Concentrés

FGA : Acétate de Fluorogestone

GES : Gaz à Effet(s) de Serre(s)

IA : Insémination Artificielle

IDELE : Institut De l' Élevage français

INRAE : Institut National français pour la Recherche en Agronomie, Alimentation et Environnement

NEC : Note d' État Corporel

OVL : Ovin(s) lait(s)/Ovin(s) laitier(s)

TH : Traitement(s) Hormonal(aux)

Abréviations anglaises :

AI: Artificial Insemination

BCS: Body Condition Score

GHG: Greenhouse Gaz(es)

HF: Hormone-Free

HT: Hormonal Treatment(s)

ME: Male Effect

PMSG: Pregnant Mare Serum Gonadotrophine

Introduction générale
et
objectifs du travail de thèse

Introduction générale et objectifs du travail de thèse

La filière ovin lait (**OVL**) produit aujourd'hui 2 % de la production laitière totale de l'Union Européenne (**UE**) et la demande en produits issus de lait de brebis est en constante augmentation (IDELE, 2020). L'évolution des systèmes d'élevage OVL montre des exigences de performances économiques de plus en plus élevées dans les exploitations agricoles ainsi qu'une volonté croissante de répondre aux attentes de la société tout en travaillant sur les enjeux agroécologiques et environnementaux. Ceci implique une bonne maîtrise de la conduite de la reproduction, notamment chez des espèces saisonnées telles que les ovins, afin de permettre une adaptation rapide aux aléas du contexte, sans mettre en péril la viabilité économique du système de production et de la filière. Les traitements hormonaux (**TH**) de synchronisation des cycles ovariens sont utilisés pour gérer la reproduction dans beaucoup d'exploitations des grands pays producteurs de lait de brebis tels que la France. En effet, la synchronisation hormonale présente l'avantage de permettre à la fois une mise à la reproduction à contre-saison et un groupage des mises bas par monte naturelle ou par insémination artificielle (**IA**) chez les petits ruminants (Pellicer-Rubio et al., 2009). De plus, ces TH facilitent la mise en place et le développement des schémas d'amélioration génétique (Fatet et al., 2008).

Cependant, l'utilisation de TH de synchronisation des cycles ovariens dans les élevages est aujourd'hui remise en cause par la société pour son inadéquation avec les problématiques actuelles de bien-être animal et de santé publique. L'origine des hormones utilisées ainsi que les inconnues concernant leur devenir dans les produits de consommation humaine et dans l'environnement sont notamment pointées du doigt, comme en témoigne la couverture médiatique très vive à ce sujet (*France Télévision 18/07/2018 - LCI 25/07/2018- Libération 21/11/2021*). Face à cette remise en question, plusieurs travaux visant à maîtriser techniquement la reproduction des petits ruminants sans TH d'induction/synchronisation sont menés depuis plusieurs années (Pellicer-Rubio et al., 2019). De nouvelles approches pour induire et synchroniser les chaleurs et ovulations hors saison sexuelle, en alternative à l'utilisation d'hormones sont développées, tant pour l'agriculture conventionnelle (**AC**) que pour l'agriculture biologique (**AB**) (ex : effet mâle et traitements photopériodiques) et d'autres travaux sont en cours de développement (ex : phéromones de synthèse). Pourtant, des freins à l'adoption de ces nouvelles alternatives subsistent. Parmi les principaux, on retrouve le manque de vision concernant les conséquences associées à l'introduction de ces alternatives à l'échelle de l'exploitation voire du territoire (Lurette et al., 2016). Afin d'accompagner le processus de diffusion de ces innovations pour la gestion de la reproduction en élevage OVL, il est intéressant d'étudier les stratégies d'introduction des nouveaux outils de gestion et

d'évaluer les conséquences associées à leur mise en place, sur les performances, mais aussi sur l'organisation des systèmes d'élevage dans leur territoire au regard des attentes des acteurs. La gestion de la reproduction dans les élevages OVL doit en effet être abordée dans le cadre de mécanismes qui garantissent la durabilité globale des exploitations (économique, environnementale et sociale).

La modélisation par simulation informatique apparaît ici comme un outil efficace pour appréhender les conséquences liées à l'introduction de ces nouveaux outils sur la gestion de la reproduction du troupeau et sur le fonctionnement plus général de l'exploitation, voire sur l'organisation de la filière à l'échelle du territoire. Il s'agit en effet d'un outil permettant d'analyser des systèmes complexes grâce à une simplification ciblée et réfléchie de la réalité. La modélisation est ainsi souvent utilisée comme outil de projection/prévision et de reconception de systèmes existant, voire de conception de nouveaux systèmes agricoles (Gouttenoire et al., 2011).

L'objectif général de cette thèse est de **concevoir un modèle de simulation du fonctionnement d'une exploitation OVL et de l'utiliser pour évaluer les effets des changements de pratiques associés à l'introduction de nouvelles conduites de la reproduction sur le fonctionnement global de l'exploitation**. Il s'agit de caractériser les mécanismes biotechniques et/ou changements de pratiques associés à l'emploi d'outils et de méthodes alternatifs aux TH dans les élevages OVL afin de représenter au mieux tous les processus décisionnels et biotechniques impliqués. L'analyse des sorties de simulation a ensuite pour but de fournir une évaluation ex-ante de l'impact de l'introduction de nouvelles conduites de la reproduction et vise à apporter des supports facilitant la réflexion sur les modalités de mise en œuvre de ces nouvelles conduites et leur faisabilité aux vues des attentes des acteurs de la filière. **Dans le cadre de cette étude, le Bassin Nord Occitanie (BNO), premier bassin de production OVL français, a été choisi comme zone d'étude.** Le simulateur est envisagé ici comme un outil de recherche, pour étudier ***comment concevoir des élevages ovins lait durables, utilisant des méthodes alternatives aux TH conventionnels de synchronisation dans leur gestion de la reproduction***. Son développement a ainsi été structuré par trois questions de recherche :

- *Comment représenter la variabilité interindividuelle de réponse à la conduite de la reproduction des brebis et son impact sur les performances d'un troupeau OVL, dans un contexte sans hormones ?*
- *Quelles sont les implications, en termes de modifications de pratiques en chaîne, de l'introduction de ces nouvelles conduites de la reproduction sur le*

fonctionnement des exploitations OVL conventionnelles et biologiques du BNO, à l'échelle du troupeau et de l'exploitation ?

- *Quels sont les scénarios les plus pertinents d'intégration des alternatives aux hormones dans les élevages OVL caractéristiques du BNO ?*

Ces questions de recherche détaillées reposent sur deux hypothèses de départ :

H1 : Les changements de pratiques associés à l'introduction de nouveaux outils/conduites diffèrent selon la structuration des exploitations et notamment selon leur type d'agriculture (conventionnelle ou biologique) et leur saison de reproduction.

H2 : L'introduction de nouvelles conduites de la reproduction relevant des principes de l'agroécologie (en réduisant notamment les intrants hormonaux) induit une modification globale du fonctionnement et de la cohérence des systèmes d'élevage OVL du BNO.

Le présent manuscrit s'organise en 7 chapitres. Le 1er chapitre fait état des connaissances aussi bien au sujet de la gestion de la reproduction ovine et des alternatives aux traitements hormonaux que des modèles d'élevages et de leur utilisation pour la conception de nouveaux systèmes d'élevage. Le 2ème chapitre décrit la démarche méthodologique mise en place pour répondre à l'objectif général et aux différentes questions de recherches précédemment énoncées. Les 3ème, 4ème, 5èmeet 6èmchapitres présentent les résultats obtenus sous format classique ou sous la forme d'articles publiés ou soumis dans des revues internationales à comité de lecture. Un 7ème chapitre présente la discussion générale des différents résultats obtenus. Enfin, une conclusion générale clôture le manuscrit en récapitulant les principaux résultats et en présentant quelques perspectives ouvertes par ce travail de thèse.

Chapitre I :
État des connaissances

Chapitre I- États des connaissances

I-1. La filière ovine laitière dans le contexte actuel et les enjeux pour la gestion de la reproduction

Les petits ruminants laitiers représentent environ 21 % de l'ensemble des ovins et caprins dans le monde, et contribuent à la production d'environ 3,5 % du lait mondial (Pulina et al., 2018). Sur le plan géographique, ces cheptels ovins laitiers se concentrent autour des régions de la Méditerranée et de la mer Noire. Dans ces régions du pourtour méditerranéen, les produits laitiers issus de la production laitière ovine ne sont généralement pas consommés directement. Ils sont utilisés dans la production d'aliments de niche (principalement fromages et yaourts) qui sont autoconsommés ou vendus sous la forme de produits laitiers qui font partie intégrante de la tradition culinaire de ces populations (Altomare et al., 2013). Au sein de l'UE, la Grèce est le principal pays producteur en termes de lait collecté par l'industrie, suivie par l'Espagne, l'Italie et la France. La Roumanie quant à elle, bien que détentrice du plus gros cheptel OVL de l'UE (Table I.1) et produisant plus de lait que la France, a une très faible portion de sa production collectée (IDELE, 2020a). Les systèmes d'élevage (race, dimension des cheptels ou encore systèmes d'alimentation) diffèrent fortement entre les quatre premiers pays européens collecteurs de lait de brebis (Table I.1). Cependant, les filières OVL de ces pays ont en commun un maintien d'approches traditionnelles et locales tout en développant des systèmes OVL modernes caractérisés par des races laitières spécialisées, des fermes techniquement avancées et des usines de transformation commerciales qui transforment la majeure partie du lait en fromage (>90 %) et en yaourt (Pulina et al., 2018). On observe également que les cheptels OVL sont concentrés dans quelques régions spécifiques de chacun de ces pays et sont basés sur des races ovines locales, croisées ou importées, qui sont caractérisées par la saisonnalité plus ou moins marquée de leur période de reproduction. Ces cheptels OVL sont principalement élevés dans des systèmes semi-intensifs à intensifs (IDELE, 2020a) et sont conduits en un agnelage par an, la durée de la gestation d'une brebis étant d'environ 5 mois (Intervet, 1997) et la traite pouvant aller jusqu'à 8 mois en élevage OVL (Pulina et al., 2018). Les fromages de brebis à appellation d'origine protégée (**AOP**) reconnus par l'UE (ex : le Manchego, le Roquefort ou encore le Pecorino) jouent un rôle majeur dans le commerce international du fromage au lait de brebis et ont un marché international en pleine expansion ; l'Italie étant le leader des exportations de fromage de lait de brebis avec 36 % de la part de marché, suivie par la France avec 20 % (Pulina et al., 2018).

Table I.1. Caractéristique de la production de lait de brebis des régions de la Méditerranée et de la mer Noire appartenant à l'Union Européenne.

Pays producteur	Taille du cheptel (millions de têtes)[1]	Races prédominantes pour la production de lait [2,3]	Part de la production mondiale (%)[2]	Rendement laitier moyen (L/brebis)[2,3]
Espagne	2.4	Latxa, Manchega, Lacaune, Churra	12.6	243
France	1.6	Lacaune, Manech, Corse	6.8	232
Italie	4.8	Sarda, Comisana, Valle del Bellice, Massesse	9.9	190
Grèce	6.2	Karagounico, Lesvou, Chios	16.6	106
Roumanie	7.8	Turcana, Tsigai, Lacaune	14.7	89

1 : (IDELE, 2020a).
2 : (Pulina et al., 2018).
3 : (ICAR, 2021) ; Les valeurs de rendements laitiers indiquées sont une moyenne de l'ensemble des races observées par l' « International Committee for Animal Recording » (ICAR) dans chaque pays.

La demande en fromages au lait de brebis est en constante augmentation depuis plusieurs années (+ 5,5 % de ventes entre 2019 et 2020 en France par exemple). Les systèmes d'élevage OVL européens doivent donc faire face à des exigences de production de plus en plus fortes. Pour y répondre, la majorité des stratégies mises en place visent à une augmentation de la production laitière totale et du rendement laitier individuel des brebis, mais aussi au prolongement des périodes de collecte de lait sur les territoires en diversifiant les saisons de production des élevages (notamment en France et en Espagne). Comme dans tout type d'élevage, la mise en œuvre de ce type de stratégies nécessite avant tout une bonne maîtrise de la reproduction puisqu'elle détermine, entre autres, le nombre d'animaux qui entrent en production, leur potentiel de production (selon les schémas d'accouplement mis en place) mais aussi la gestion de l'alimentation des troupeaux. Pour les élevages OVL européens, cela implique également une maîtrise de la saisonnalité de la reproduction caractéristique des races ovines européennes.

Les stratégies de reproduction mises en place doivent ainsi permettre de répondre à ces exigences de production tout en tenant compte d'autres enjeux économiques, sociétaux et environnementaux. En effet, la volatilité des prix du lait depuis la fin des quotas laitiers en 2015 ainsi que l'augmentation des prix des matières premières poussent beaucoup d'élevages à rechercher l'autonomie alimentaire, notamment en augmentant la part de pâturage et de fourrages locaux dans la ration afin de limiter leurs coûts de production (Thenard et al., 2018; De Boissieu et al., 2021). En parallèle, les élevages OVL méditerranéens doivent faire face à des changements climatiques notables avec en particulier des sécheresses récurrentes qui

limitent l'utilisation des surfaces fourragères l'été (Iglesias et al., 2012). Enfin, les stratégies de gestion de la reproduction doivent aussi s'organiser dans un contexte sociétal nouveau où l'on observe d'une part une volonté croissante des éleveurs d'améliorer leurs conditions de travail (Duval et al., 2021) et d'autre part un poids fort des attentes sociétales autour des conditions de production des produits alimentaires. Les consommateurs sont en effet demandeurs de systèmes d'élevage plus « green, clean and ethical » qui limitent le recours aux intrants (Martin et al., 2004). L'utilisation des TH et notamment de la choriogonadotropine équine (eCG, encore appelée PMSG) pour induire et synchroniser les chaleurs en élevage OVL est notamment remise en question depuis plusieurs années. En effet, la PMSG provient du sang de jument gravide dont les conditions d'exploitation sont de plus en plus dénoncées pour leur inadéquation avec les attentes actuelles en matière de bien-être animal (Rapport Européen 2016/2078(INI); Manteca Vilanova et al., 2019). Il y a également des questionnements en termes de santé publique vis-à-vis du devenir des hormones dans les produits de consommation humaine et dans l'environnement (González-Bulnes et al., 2020). Ainsi, des stratégies alternatives aux TH se développent pour gérer la reproduction des brebis (Pellicer-Rubio et al., 2019). Cependant, leur introduction dans les élevages OVL pourrait avoir des conséquences sur l'organisation de toute la filière, notamment dans les grands pays utilisateurs de TH de synchronisation comme la France.

Dans le contexte actuel, il est donc important que les alternatives aux hormones développées pour gérer la reproduction dans les élevages OVL soient abordées dans le cadre de mécanismes qui garantissent la durabilité globale des exploitations.

I-2. Caractéristiques de la gestion de la reproduction d'un troupeau d'ovins laitiers

I-2.1. Fondements de la physiologie de la reproduction ovine

Chez la brebis, comme chez beaucoup de mammifères, l'ovulation est nécessaire pour que la reproduction soit possible. Elle a lieu au cours du cycle ovarien (l'intervalle entre deux ovulations). Ce cycle dure 17 jours chez la brebis, mais peut varier entre 15 et 19 jours selon la race, l'âge et la saison de l'année (Thimonier et al., 2000). Chaque cycle se divise en deux phases : la phase folliculaire et la phase lutéale. La phase folliculaire correspond à la phase de croissance des follicules ovariens (structures ovariennes présentes dès la naissance et contenant les ovules). Pendant cette phase qui dure 3 à 4 jours, les follicules croissent sous l'effet d'hormones (hormone de stimulation des follicules : FSH et hormone lutéinisante : LH) provenant de la glande du cerveau appelée hypophyse et sécrètent une hormone appelée œstradiol qui entraîne l'apparition d'un comportement d'œstrus (ou chaleur). Chez la brebis, les chaleurs durent de 24 à 72 heures, pour une moyenne de 36 heures et l'ovulation, qui

correspond à la libération des ovules contenus dans les follicules matures, se produit entre 20 et 40 heures après le début des chaleurs, soit vers la fin de celles-ci (Castonguay, 2018). Les structures folliculaires ayant libéré des ovules se transforment alors en corps jaune qui sécrètent de la progestérone, hormone exerçant un rétrocontrôle négatif sur l'hypophyse, empêchant ainsi la croissance de nouveaux follicules. Durant 14 jours, correspondant à la phase lutéale, les corps jaunes sont actifs, le développement des follicules ralentit et l'ovulation impossible. Si la brebis n'est pas fécondée, le corps jaune dégénère pour permettre une reprise de l'activité ovarienne (Figure I.1).

Chez les ruminants, l'activité ovarienne débute au moment de la puberté et se poursuit toute la vie avec des interruptions au moment de la gestation, de la lactation, de la période postpartum ainsi que pendant l'anœstrus saisonnier (Castonguay, 2018).

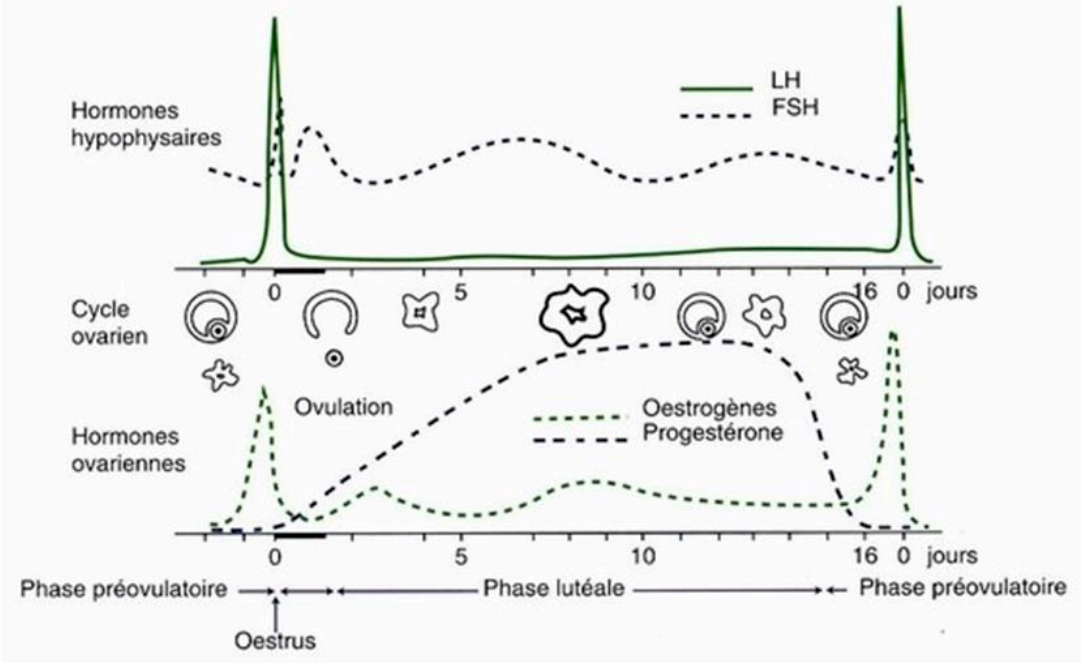

Figure I.1. Évolution des concentrations hormonales au cours du cycle sexuel de la brebis (Dudouet, 2003).

I-2.2. Saisonnalité de la reproduction et conséquences en termes de gestion de la reproduction

Comme tous les petits ruminants, la brebis est caractérisée par la saisonnalité de sa reproduction. Il s'agit en effet d'une espèce dite polyœstrienne saisonnière (Henderson et Robinson, 2007), ce qui signifie que pendant une période spécifique de l'année, elle présente une succession d'œstrus (période au cours de laquelle les femelles acceptent l'accouplement avec les mâles). C'est la durée d'éclairement journalière, aussi appelée photopériode, qui contrôle principalement les variations saisonnières de l'activité sexuelle chez les ovins. En effet, les informations photopériodiques, générées par les cycles lumière-obscurité quotidiens,

exercent des effets sur l'axe hypothalamus-hypophysaire du cerveau des brebis par le biais de la sécrétion de mélatonine, hormone produite par la glande pinéale du cerveau (Menassol et al., 2012). Il a été démontré que le schéma de sécrétion de cette hormone suit un rythme circadien avec une sécrétion importante se produisant uniquement la nuit, c'est-à-dire pendant la période sombre de la journée (Rosa et Bryant, 2003). Il a aussi été montré que des facteurs associés aux pratiques d'élevage peuvent participer à la régulation de la saisonnalité de la reproduction (Rosa et Bryant, 2003). La nutrition des brebis apparaît notamment comme un facteur pouvant influencer la saisonnalité de la reproduction en modulant de manière centrale l'interprétation de la photopériode pour affecter les transitions reproductives saisonnières chez certaines brebis (Menassol et al., 2012).

En Europe, pour la majorité des races ovines, la saison naturelle de reproduction s'étend ainsi de fin août à janvier, en période dite de « Jours Courts » (Chemineau et al., 1992) où la durée d'exposition à la lumière est réduite et la sécrétion de mélatonine en période sombre accrue. Le reste de l'année correspond à une période de repos sexuel (contre-saison sexuelle) durant laquelle les brebis sont dites en anœstrus saisonnier. On distingue l'anœstrus « profond » où il n'y a ni chaleur ni ovulation, et l'anœstrus « léger » (début et fin d'une saison sexuelle), où il y a ovulation sans œstrus (Oussaid et al., 1993). La « profondeur » de l'anœstrus varie selon les races (Figure I.2; Chanvallon et al., 2011). Chez la plupart des races méditerranéennes, par exemple, les schémas saisonniers d'activité de reproduction sont peu prononcés et il peut arriver que certaines brebis présentent des chaleurs pendant l'anœstrus. Il n'est pas rare non plus que chez certaines races du pourtour méditerranéen, des brebis en anœstrus saisonnier présentent des ovulations dites silencieuses, c'est-à-dire non associées à un comportement d'œstrus, à la fin du printemps (Thimonier et al., 2000). Que ce soit avec des races plus ou moins saisonnées, cette saisonnalité de la reproduction constitue une vraie contrainte pour les systèmes de production OVL dans le contexte économique et socio-environnemental actuel. En effet, la saisonnalité de la reproduction se traduit par une irrégularité de l'offre en lait et en agneaux au cours de l'année. Or, pour assurer leur revenu et pouvoir répondre à la demande des consommateurs, les producteurs et les industriels recherchent une régularité de la production et de sa qualité tout au long de l'année, voire une augmentation de la production à certains moments de l'année (Lurette et al., 2016). Les stratégies permettant de s'affranchir de la saisonnalité sont ainsi plébiscitées par la filière OVL car elles permettent d'adapter la production à la demande des marchés, de diversifier les périodes de production, mais aussi d'adapter la gestion de l'alimentation du troupeau aux ressources disponibles selon le contexte pédoclimatique.

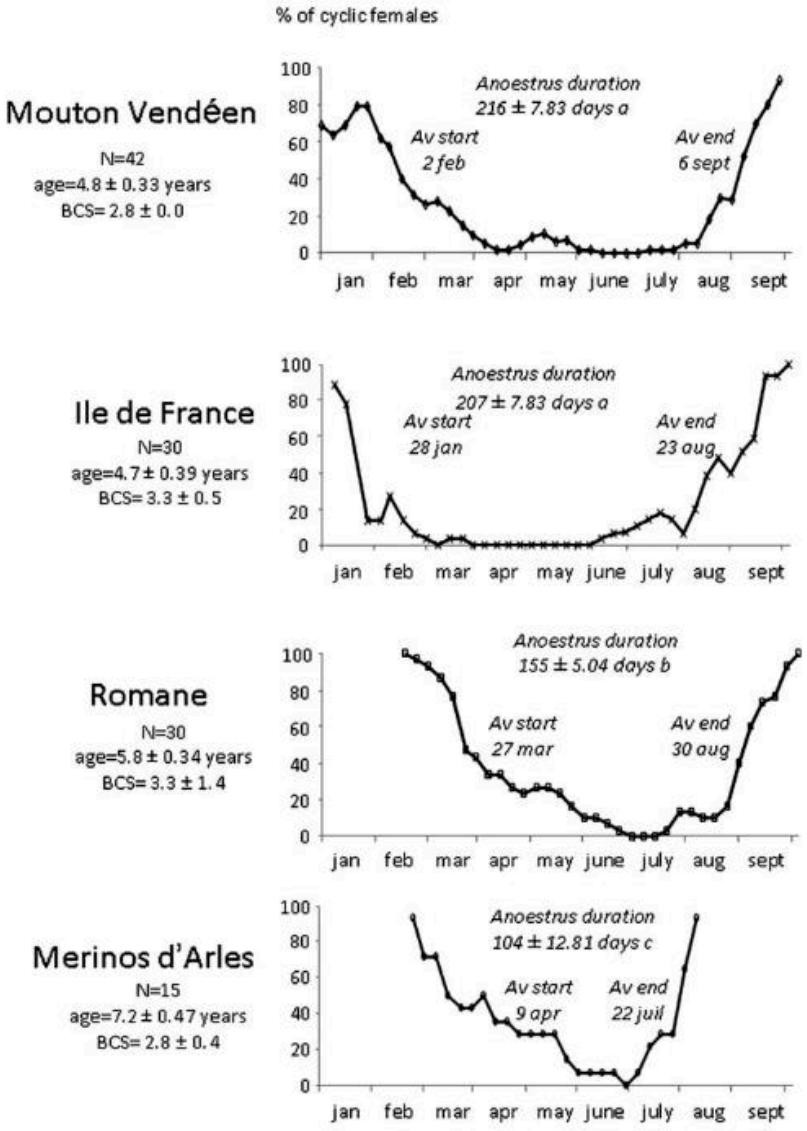

Figure I. 2. Moment et durée de la saison anoestrale (nombre de jours entre le début et la fin de l'anoestrus) chez quatre races de moutons français. D'après Chanvallon et al. (2011).

I-2.3. Grandes stratégies de gestion de la reproduction et importance des traitements hormonaux dans les schémas actuels

Afin de s'affranchir de la saisonnalité de la reproduction caractéristique des petits ruminants, la recherche de méthodes permettant de dessaisonner les périodes de reproduction et diversifier les périodes de production s'est donc accentuée dès le milieu du 20ème siècle. Il a ainsi été découvert que l'utilisation de TH était un moyen très efficace de dessaisonner et d'induire les cycles ovariens chez les petits ruminants (Robinson, 1950; Haresign, 1990; Ungerfeld et Rubianes, 1999). Dès lors, l'utilisation de ces TH s'est démocratisée dans beaucoup d'élevages OVL conventionnels.

Les TH classiquement utilisés consistent à administrer une progestagène de synthèse, via l'introduction d'une éponge vaginale imprégnée d'acétate de fluorogestone (**FGA**),

pendant 14 jours afin de mimer la phase lutéale du cycle ovarien, puis à réaliser une injection de PMSG le jour du retrait de l'éponge pour déclencher l'ovulation en augmentant la concentration d'œstradiols dans le sang. Cela permet aux brebis de présenter un œstrus environ 48 heures après le retrait de l'éponge, et ce, même en dehors de leur saison naturelle de reproduction (Abecia et al., 2012), et induit la possibilité de réaliser une IA 55 heures après le retrait des éponges sur l'ensemble du lot traité. Il existe également un autre type de traitement hormonal qui consiste à déposer en sous-cutané, à la base de l'oreille des brebis, un implant contenant de la mélatonine. L'implant permet de diffuser progressivement de la mélatonine dans l'organisme pendant 2 à 3 mois. Cela modifie la perception de la photopériode par l'organisme, en simulant l'arrivée de l'automne et permet une reprise de l'activité sexuelle 6 à 7 semaines après la pose de l'implant. Cette technique permet d'avancer la saison sexuelle de 4 à 6 semaines pour produire des agneaux à une période plus favorable, d'améliorer les performances de reproduction et de grouper les agnelages (Chanvallon, 2009). Souvent associé à la mise en place d'un protocole de traitement lumineux, ce type de TH est cependant moins utilisé que les TH par éponge vaginale + injection de PMSG en élevage OVL (Lurette et al., 2016) car, s'il permet de désaisonner les brebis, il ne permet pas d'obtenir une synchronisation du moment de l'ovulation des brebis suffisante pour faire une IA à date fixe sur l'ensemble d'un lot.

Ces TH d'induction et de synchronisation des cycles ovariens permettent ainsi de s'affranchir de la saisonnalité de la reproduction qui existe chez les petits ruminants et donc de réaliser une mise à la reproduction dite « à contre-saison », tout en rendant possible le groupement des mises-bas du troupeau à des périodes choisies, ce qui facilite également la gestion des lots d'animaux et le travail des éleveurs (notamment dans la gestion de l'alimentation, de la traite et de la prophylaxie). Outre la possibilité d'une reproduction dite « à contre-saison » et la facilitation de l'organisation du travail pour l'éleveur, l'utilisation de TH de synchronisation des cycles ovariens permet également de faciliter la pratique de l'IA ou de la monte en main, puisqu'elle permet la sélection et le contrôle des accouplements à l'avance. Cette possibilité de prévoir à l'avance le moment d'entrée en chaleur des femelles apportée par les TH est d'autant plus importante à la pratique de l'IA ovine puisqu'elle ne peut aujourd'hui se faire qu'avec de la semence fraîche de bélier ; le délai d'utilisation de la semence fraîche après prélèvement sur le bélier étant d'environ 10 heures selon la méthode de conservation (Druart et al., 2009). Dans les grands bassins européens de production OVL et plus particulièrement en France, le développement de l'IA favorisé par la généralisation de l'utilisation des TH dans les élevages a permis la mise en place et la diffusion de schémas de sélection performants, tout en limitant les risques sanitaires pour le troupeau (grâce à la

réduction des échanges de béliers entre élevages pour les saillies) (Fatet et al., 2008). Le schéma de sélection le plus efficace et le plus répandu pour les principales races locales européennes est basé sur une gestion pyramidale de la population (Carta et al., 2009). Au sommet, on retrouve les élevages des troupeaux « noyaux », où le suivit du pedigree, le contrôle laitier officiel (**CLO ;** ensemble de mesures quantitatives (matière protéique, matière grasse, numérations cellulaires, etc.) et qualitatives du lait selon des protocoles précis), l'IA (ou l'accouplement contrôlé) et l'estimation de valeurs de reproduction, sont effectués pour générer un progrès génétique. Ce progrès génétique est ensuite transféré aux troupeaux commerciaux par le biais de l'IA principalement ou de l'accouplement naturel de béliers sélectionnés (Carta et al., 2009). En France, le développement du schéma de sélection pour la race Lacaune via l'IA a permis un gain génétique laitier de l'ordre de 5 à 7 litres/an sur la quantité et la qualité du lait, mais aussi sur des paramètres sanitaires (ex : résistance à la maladie de la tremblante du mouton) ainsi que sur d'autres caractères fonctionnels (ex : morphologie de la mamelle ou encore résistance aux mammites) (Barillet et al., 2001). Par rapport à une reproduction par monte naturelle avec des béliers sélectionnés, l'utilisation de l'IA permet d'accélérer le progrès génétique d'au moins 2 ans (durée moyenne entre la conception d'un agneau mâle sélectionné et son utilisation en tant que bélier reproducteur).

Dans les élevages européens en AB, l'utilisation de TH est interdite par le cahier des charges AB (règlements 2007/834/CE et 2008/889/CE). Les éleveurs en AB ont donc souvent recours à d'autres méthodes non hormonales pour gérer la saisonnalité de la reproduction de leur troupeau. Cependant, ces méthodes sont moins efficaces qu'un TH, notamment en ce qui concerne la synchronisation des chaleurs. De fait, beaucoup d'élevages en AB ne pratiquent pas l'IA. Ils ne peuvent alors profiter du progrès génétique apporté par les schémas de sélections que via l'utilisation de béliers sélectionnés. Ainsi, la diffusion du progrès génétique pour les races sélectionnées est beaucoup plus lente dans les élevages en AB par rapport aux élevages en AC qui intègrent l'IA dans leur stratégie de reproduction.

En termes de gestion de la reproduction, les élevages OVL des grands bassins de production européens se distinguent donc aujourd'hui par le fait qu'ils utilisent ou non des TH pour synchroniser les ovulations dans le troupeau. En effet, il existe d'une part des élevages conventionnels, caractérisés par l'utilisation quasi systématique de TH pour synchroniser les ovulations dans le troupeau en vue de la réalisation d'IA sur tout ou partie du troupeau. Et d'autre part, il existe des élevages en AB où les TH sont interdits et qui ne font généralement pas d'IA. Ces schémas classiques de gestion de la reproduction sont aujourd'hui fortement remis en cause par les nouveaux questionnements autour de l'utilisation des TH d'induction et de synchronisation des cycles ovariens en élevage OVL.

Pour les élevages conventionnels utilisateurs de TH il s'agit de repenser les stratégies de gestion de la reproduction tout en conservant la possibilité de travailler sur les schémas de sélections génétiques via l'IA. Pour les élevages ovins en AB, en plein essor et qui pour la plupart ne pratiquent pas l'IA du fait de l'interdiction d'utiliser des TH, ces nouvelles questions sont aussi une opportunité de faire progresser les schémas d'amélioration génétique. Il y a donc un véritable enjeu socio-environnemental, mais aussi technique au développement d'alternatives aux TH qui permettraient notamment de conserver la pratique de l'IA pour la gestion de la reproduction des troupeaux OVL.

I-3. États des lieux des méthodes alternatives aux traitements hormonaux de synchronisation des cycles ovariens

I-3.1. Préparation du troupeau à la reproduction

L'état des brebis au moment de la reproduction influence leurs performances de reproduction. Ainsi, une préparation des brebis est généralement recommandée pour favoriser l'obtention de bons résultats de reproduction. L'alimentation est l'un des principaux facteurs influençant les performances reproductives des brebis, de l'apparition de la puberté au nombre total d'agneaux produits au cours de leur vie. L'état nutritionnel des brebis détermine, en effet, fortement leurs performances de reproduction, notamment le taux d'ovulation, la fertilité et la prolificité (Rassu et al., 2004). Ainsi, il convient d'assurer un bon état corporel des brebis avant la mise à la reproduction. La technique dite du *flushing* est un moyen d'assurer ce bon état corporel en permettant une reprise de poids et d'état adéquate. Elle consiste à améliorer de façon transitoire le niveau alimentaire des brebis avant la mise à la reproduction, par une distribution supplémentaire d'aliments généralement concentrés ou une amélioration des conditions de pâturage. Cette suralimentation débute habituellement un mois avant la mise à la reproduction et se poursuit pendant celle-ci (Chanvallon, 2009). Le *flushing* est souvent associé à d'autres techniques comme les TH ou l'effet mâle.

Un bon état sanitaire est aussi indispensable pour favoriser de bons résultats de reproduction. Ainsi il est recommandé d'établir un programme de vaccination du troupeau avant la mise à la reproduction, en fonction des risques sanitaires de l'élevage. Il est également recommandé d'effectuer tous les traitements antiparasitaires du troupeau avant la mise à la reproduction (traditionnellement, un mois avant). Enfin, afin d'éviter tout stress et tous mouvements brusques des brebis au moment de la reproduction, il est recommandé de réaliser toutes les diverses opérations de tonte ou de parage des pieds avant la mise à la reproduction (IDELE/CIRPO, 2018).

I-3.2. L'effet mâle : pratique alternative privilégiée en élevage ovin

I-3.2.1. Principe de l'effet mâle

Dès le milieu des années 80, il a été observé que l'introduction d'un bélier dans un troupeau de brebis en anœstrus saisonnier permet de déclencher l'apparition de comportement d'œstrus ainsi que l'ovulation (Martin et al., 1986). En effet, l'introduction, de béliers en nombre suffisant (au moins 1 pour 30 brebis) dans un troupeau de brebis en état d'anœstrus saisonnier, après un temps de séparation d'au moins 2 mois, induit une augmentation quasi immédiate de la sécrétion de l'hormone lutéinisante (LH) menant à l'ovulation et à la reprise des cycles ovariens (Thimonier et al., 2000). Cette technique, appelée effet mâle (ou effet bélier) permet d'induire et de synchroniser sans traitement hormonal l'apparition des chaleurs chez des femelles en anœstrus. Chez la plupart des brebis, une ovulation dite silencieuse, car non associée à un comportement œstral, survient dans les 2 à 4 jours suivant l'introduction du bélier. Elle est ensuite suivie soit par un cycle ovulatoire de durée « normale » (17 jours) puis d'une nouvelle ovulation associée à un comportement œstral, soit par un cycle ovulatoire de durée courte, mais constante (6 jours) suivi d'une nouvelle ovulation silencieuse puis, après un cycle ovulatoire de durée normale, par une nouvelle ovulation associée à un comportement d'œstrus. Ceci entraîne deux pics d'apparition des chaleurs suite à un effet mâle : 18-20 jours et 24-26 jours après introduction des béliers, respectivement (Thimonier et al., 2000).

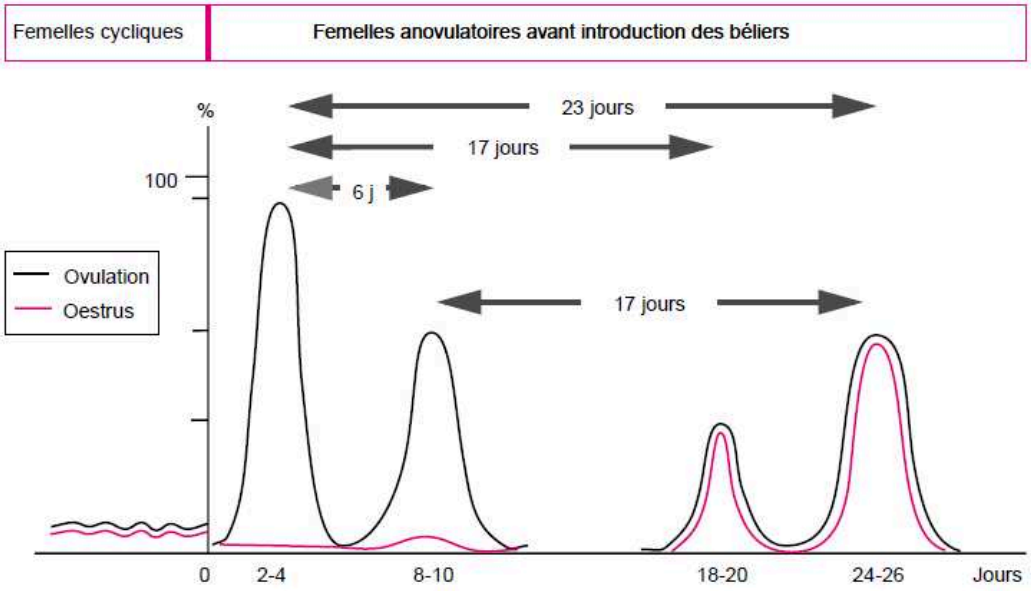

Figure I.3. Représentation schématique de la réponse ovulatoire et œstrale à l'effet mâle. D'après *Thimonier et al. (2000).*

Les différents travaux menés sur l'effet mâle permettent de dire avec certitude que l'effet mâle ne peut déclencher l'induction des cycles ovariens que chez des brebis qui sont en

anœstrus (Delgadillo et al., 2009). Ainsi, pendant la saison naturelle de reproduction, où la reprise des cycles ovariens est spontanée chez la plupart des brebis, l'effet mâle n'a pas d'effet direct sur l'induction des cycles ovariens dans un troupeau. En revanche, plusieurs travaux s'accordent pour dire que l'effet mâle peut affecter la dynamique du cycle œstral chez des brebis cycliques en avançant le début de la saison de reproduction ou encore en synchronisant la distribution des œstrus spontanés (Hawken et al., 2008; Delgadillo et al., 2009). Cependant, les mécanismes sous-jacents caractérisant la relation entre la réponse neuroendocrine à l'effet mâle, la dynamique du cycle œstral et la fertilité des brebis, pendant la saison naturelle de reproduction, sont encore peu connus, ce qui empêche le développement de méthodologies d'utilisation de l'effet mâle en saison naturelle de reproduction.

I-3.2.2. Facteurs influençant la réponse à l'effet mâle à « contre-saison »

La réponse à l'effet mâle d'une brebis en anœstrus saisonnier est variable. En effet, le succès d'une induction/synchronisation des cycles ovariens avec cette technique varie en fonction de plusieurs facteurs pouvant être associés aux brebis, aux béliers, mais aussi aux conditions d'élevage imposées par l'éleveur (Pellicer-Rubio et al., 2009).

Le principal facteur responsable de la variabilité de réponse des brebis à l'effet mâle est la « profondeur » de l'anœstrus des brebis. Cette profondeur dépend de la race de la brebis et du stade de l'anœstrus saisonnier dans lequel elle se trouve (Chanvallon et al., 2011), c'est-à-dire la période de l'année par rapport à sa saison naturelle de reproduction. Lorsque l'on considère la réponse ovarienne à l'effet mâle, deux paramètres principaux doivent donc être pris en compte : la proportion de femelles présentant une reprise spontanée de l'activité ovarienne avant l'introduction du bélier et la proportion de femelles présentant effectivement une reprise des cycles ovariens suite à l'effet mâle (Debus et al., 2021). Les relations entre ces deux paramètres sont relativement complexes. En effet, si une augmentation du nombre de femelles cycliques avant effet mâle entraîne une réduction du nombre de brebis répondant à l'effet mâle, il a aussi été montré que plus il y a de brebis spontanément cyclées dans le troupeau, meilleure sera la réponse des autres brebis du troupeau après un effet mâle (Folch et al., 2000; Rosa and Bryant, 2002). D'autres facteurs comme l'âge des brebis affectent la réponse à l'effet mâle (Thimonier et al., 2000). En effet, il a été montré que les brebis adultes multipares répondent plus à l'effet mâle que les jeunes agnelles (Notter, 2000; Rosa et Bryant, 2002). Ceci étant principalement lié au stress et au manque d'expérience sexuelle des agnelles (Chanvallon et al., 2010). L'état corporel des brebis au moment de l'effet mâle affecte aussi leur réponse à cette technique de synchronisation des chaleurs. En effet, les brebis en meilleur état corporel sont aussi celles qui répondent le mieux à l'effet mâle (Tournadre et al., 2009; Kenyon et al., 2014; Debus et al., 2021). Le moment de réalisation de

cette technique influence aussi la réponse à l'effet mâle puisque qu'il a été montré que plus le temps entre le sevrage et l'effet mâle est long, plus ce dernier est efficace (Rosa et Bryant, 2002; Tournadre et al., 2002). De plus, chez les races laitières, la production laitière des individus semble aussi impacter les performances de reproduction des brebis. En effet, il existe une période d'anœstrus de lactation chez les brebis laitières pendant laquelle les brebis ne présentent pas d'œstrus (Castonguay, 2018) et dont la force diminue au fil des mois de lactation selon les races. Il existe donc une interférence permanente entre anœstrus saisonnier et anœstrus de lactation chez les brebis laitières (Mauléon et al., 1965). Plusieurs travaux ont ainsi montré que plus la durée de lactation d'une brebis est élevée, plus le moment de la prochaine conception est éloigné (Kassem et al., 1989; Pollott et Gootwine, 2004). Pour les brebis Lacaune, David et al. 2008 ont également observé une corrélation génétique négative entre leur rendement laitier et leur fertilité à l'insémination animale. L'impact spécifique des performances laitières sur les performances de reproduction de brebis soumises à un effet mâle et non soumises à un TH reste cependant à préciser.

En outre, la réponse du troupeau à l'effet mâle peut être aussi influencée par des caractéristiques individuelles des béliers. L'âge et l'expérience sexuelle des béliers sont les facteurs répertoriés comme ayant une influence majeure sur cette réponse. En effet, un vieux bélier ayant de l'expérience stimule mieux le retour des cycles ovariens chez les femelles par rapport à un jeune bélier inexpérimenté (Ungerfeld et al., 2008). La race du bélier et la saisonnalité associée affectent aussi la capacité des béliers à stimuler l'ovulation des brebis, notamment « hors saison » (Rosa et Bryant, 2002). La libido des béliers influence également la réussite de l'effet mâle (Perkins et Fitzgerald, 1994). Il est de ce fait important de préparer les béliers avant la reproduction, tout comme les brebis, avec un *flushing*. En effet, un bon état nutritionnel des béliers est nécessaire pour assurer une libido optimale et favoriser les performances reproductives des béliers (Martin et Walkden-Brown, 1995; Mahouachi et al., 2011; Lassoued et al., 2013). Afin de limiter les contraintes liées aux caractéristiques individuelles des béliers, des travaux se mettent en place pour développer des phéromones des synthèses. L'effet mâle implique en effet des stimuli « olfactifs » et plusieurs études ont montré que le contact visuel ou physique entre les béliers et les brebis n'était pas obligatoirement nécessaire pour affecter l'activité sexuelle de ces dernières. En effet, l'exposition des brebis à la seule laine de bélier permet de reproduire partiellement l'effet mâle (Knight et Lynch, 1980; Cohen-Tannoudji et al., 1994). L'utilisation de molécules olfactives impliquées dans l'effet mâle pour induire et synchroniser les chaleurs et les ovulations à contre-saison apparaît donc comme une potentielle alternative supplémentaire aux TH. Comme chez beaucoup de mammifères, la perception olfactive des phéromones chez

la brebis se fait en premier lieu au niveau des voies aériennes de la muqueuse nasale avant que les signaux de ces phéromones ne soient transférés vers les centres olfactifs du cerveau et stimulent la région hypothalamo-hypophysaire pour qu'elle sécrète des hormones de reproduction (Murata et al., 2014). Dans ce contexte, il semblerait que la forme la plus efficace de diffusion des molécules des phéromones soient sous forme de spray aérosol, ce qui conduit la majorité des récents travaux autour de l'utilisation de phéromones en élevage ovin, à se tourner vers cette forme de diffusion (Lurette et al., 2016).

Aujourd'hui, bien qu'il n'existe pas encore de phéromones de synthèses utilisables en élevage ovin, et malgré des interrogations concernant les modalités d'application des phéromones en élevage ou encore les implications en termes d'organisation du travail, la filière ovine est globalement favorable au développement de ce type d'alternative aux TH (Lurette et al., 2016). L'utilisation de phéromones permettrait en effet de s'affranchir de plusieurs contraintes liées à la pratique de l'effet mâle physique en élevage. Elle permettrait notamment de limiter le nombre de béliers présents dans l'élevage (Hashem et González-Bulnes, 2021). Le recours aux béliers reste malgré tout nécessaire puisque la composante comportementale de l'effet mâle est un facteur clé de son fonctionnement (Rosa et Bryant, 2002). La réussite à l'effet mâle est en effet maximale lorsque les béliers sont placés directement avec les brebis et que les différents signaux émis par des béliers sont présents (contacts physiques, odeurs, sons ; Delgadillo et al., 2009; Hawken et Martin, 2012; Debus et al., 2018). Il s'agirait donc de développer les phéromones de synthèses comme outil à associer à la présence de béliers pour favoriser, voire améliorer la réponse à l'effet mâle dans un troupeau.

En définitive, les variations importantes de la « profondeur » de l'anœstrus selon les races et le moment de l'année, associées aux caractéristiques individuelles des brebis, des béliers et aux facteurs environnementaux, rendent complexe la prédiction de la réponse à l'effet mâle au sein d'un troupeau. Malgré tout, l'effet mâle est aujourd'hui la technique de synchronisation/induction non hormonale des cycles ovariens chez les ovins la plus étudiée, la plus documentée et la plus aboutie.

I-3.3. Les traitements lumineux (ou photopériodiques)

Le traitement lumineux (ou photopériodique) des femelles et/ou des mâles est un moyen complémentaire pour optimiser la réponse à l'effet mâle tout au long de l'anœstrus saisonnier (Pellicer-Rubio et al., 2009), notamment dans le cas des races très saisonnées pour qui l'effet mâle n'est pas assez efficace pour induire une reproduction à contre-saison. La manipulation de la photopériode via des protocoles de traitements lumineux, qui consistent à soumettre les animaux à une alternance de « Jours Longs » (inhibiteurs de la reproduction, équivalent à 16

h de lumière par jour) et de « Jours Courts » (stimulateurs de la reproduction, 8-12 h de lumière par jour) à des moments très précis de l'année (Chemineau et al., 1996; Pellicer-Rubio et al., 2019), permet en effet de maîtriser la saisonnalité et de rendre possible la reproduction en dehors de la saison sexuelle, aussi bien chez les mâles que chez les femelles. Ils peuvent également permettre de faciliter l'expression de l'œstrus et de l'ovulation chez les brebis ou encore de favoriser l'installation d'une cyclicité (3-4 cycles consécutifs) permettant aux femelles d'être fécondées aux retours de chaleurs dans le cas d'un échec de reproduction après une première mise à la reproduction (Pellicer-Rubio et al., 2009).

En pratique, dans les élevages, les traitements lumineux nécessitent un contrôle de la durée d'éclairement journalière des animaux en alternant des phases d'éclairement et des phases d'obscurité totale. Il est notamment impératif de ne pas éclairer, même momentanément, pendant les heures d'obscurité. Ainsi, aucune intervention de l'éleveur ne peut être réalisée pendant les phases d'obscurité, ce qui n'est pas toujours compatible avec les heures de traite et/ou chez des animaux sortant au pâturage (Pellicer-Rubio et al., 2009). Des traitements lumineux peuvent être facilement appliqués dans des bâtiments possédant des installations permettant de les rendre complètement étanches à la lumière, mais de telles installations sont coûteuses et les factures d'électricité associées à ce genre de traitements sont élevées. Dans les élevages conventionnels, il est aussi possible de remplacer les jours courts artificiels par des implants de mélatonine sur les brebis, mais cette pratique nécessite l'achat d'implants et représente donc des frais supplémentaires non négligeables pour l'élevage. Devant ces contraintes, l'utilisation de traitements lumineux en élevage ovin reste anecdotique (Lurette et al., 2016).

I-3.4. De nouveaux outils pour réaliser l'IA sans hormones

Les techniques de synchronisation non hormonales, quelles qu'elles soient, demeurent trop variables et ne permettent pas d'anticiper le niveau de synchronisation des chaleurs des brebis pour envisager l'IA sur tous les individus d'un troupeau donné à une date unique. Or, il est indispensable de pouvoir anticiper, autant que possible, le nombre de brebis en chaleur aux moments choisis pour l'insémination pour que les inséminateurs des Centres d'insémination animale (CIA) organisent leurs interventions dans les élevages. Face à ce besoin, il a été montré, dès les années 80, que l'IA sans hormones peut être envisagée, en associant une méthode de synchronisation des chaleurs telle que l'effet mâle, à une détection précise des brebis en chaleur, afin d'identifier individuellement les brebis à inséminer (Corke, 1980). Les manifestations d'œstrus chez la brebis étant très difficilement détectables, des outils et méthodes de détection de l'œstrus ont été développés ces dernières années pour permettre l'insémination sans hormones. Le seul indicateur qu'une brebis est en œstrus est

son acceptation du bélier lors de la monte. En se basant sur cet indicateur, la technique la plus largement utilisée pour identifier les brebis en œstrus consiste à utiliser un harnais marqueur fixé au niveau du sternum du bélier. Il s'agit classiquement d'un harnais muni d'un crayon de couleur permettant de marquer la croupe des brebis chevauchées (Radford et al., 1960). Ce dispositif permet de repérer les brebis en œstrus suite à un effet mâle et rend ainsi possible leur IA. Il demande cependant à l'éleveur une surveillance quotidienne accrue pour identifier les individus en état d'œstrus au sein du troupeau. Ainsi, pour faciliter la détection des brebis en œstrus un détecteur automatique de chevauchement a été développé (Figure I.4; Debus et al., 2019). Il s'agit d'un harnais connecté placé sur le bélier qui permet de suivre en temps réel le nombre de chevauchements des béliers pendant la saison de reproduction et donc de déduire précisément quelles sont les brebis en œstrus suite à l'effet mâle ainsi que le moment de chaque œstrus.

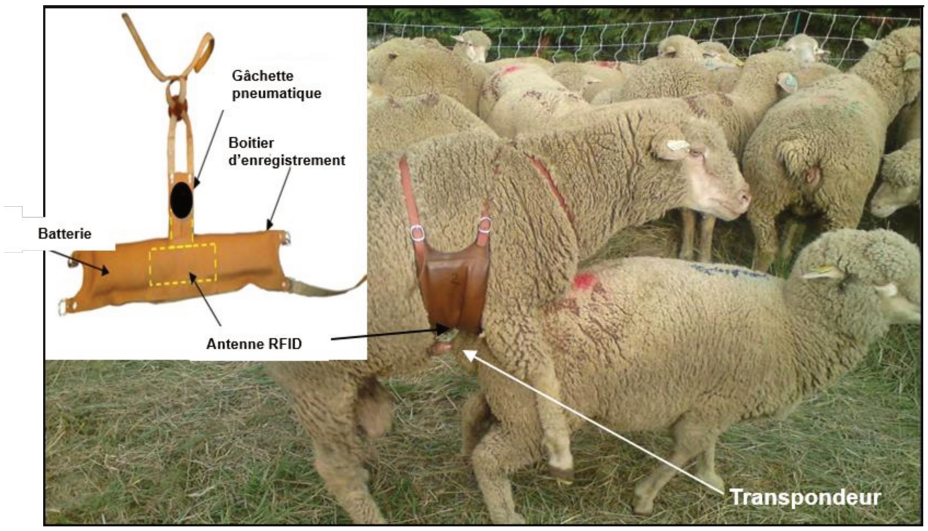

Figure I. 4. Détecteur électronique de chevauchement porté par le mâle (crédit photo INRAE).

I-3.5. Adoption des alternatives développées dans les élevages d'ovins laitiers : Leviers et verrous

Ces alternatives aux TH sont des innovations pour la gestion de la reproduction en élevage OVL, en particulier dans les zones où les TH sont très utilisés pour gérer la reproduction, comme dans le BNO, en France. De manière générale, le choix d'adopter ou non une innovation suit une rationalité en lien avec le contexte et les besoins socio-économiques d'une exploitation (Barrientos-Fuentes et Berg, 2013). En effet, si le bénéfice économique lié à la mise en place d'une innovation est souvent mis en avant dans la décision d'adoption, il n'est pas le seul élément pris en compte. Ainsi, une innovation incompatible avec les valeurs, les expériences passées et les besoins des utilisateurs sera difficilement adoptée. De même, une innovation qui n'est pas compatible avec les caractéristiques de la société ne sera pas acceptée dans cette dernière (Ingrand et al., 2014). Le contexte géopolitique peut aussi contribuer à précipiter l'adoption d'innovations. On constate ainsi que dans les élevages OVL

français du BNO l'utilisation d'alternatives aux TH est bien plus fréquente dans les élevages en AB pour qui l'usage de TH est interdit par la législation européenne. L'effet mâle qui est aujourd'hui la pratique alternative la plus diffusée en élevage OVL est même considéré comme relativement bien adapté à la conduite en AB (Lurette et al., 2016). Une grande proportion d'éleveurs ovins laitiers du BNO (majoritairement en AC) restent malgré tout réservés quant à l'adoption de techniques alternatives aux hormones pour conduire la reproduction de leurs troupeaux. En effet, outre la peur du changement ou de l'introduction d'innovations, ils disposent de peu d'informations sur les effets potentiels de l'introduction des alternatives aux TH proposées sur le fonctionnement global de leurs exploitations. Ils craignent par exemple que les nouveaux outils et les nouvelles méthodes de gestion de la reproduction perturbent fortement leur organisation du travail, soient en inadéquation avec la conduite des troupeaux au pâturage, ou encore que le coût de ces méthodes innovantes soit trop important (Lurette et al., 2016). L'introduction de nouveaux outils ou encore de nouvelles conduites dans les exploitations agricoles implique en effet des changements de pratiques (ou de conditions de mise en œuvre de certaines pratiques) qui peuvent, dans certains cas, bouleverser la cohérence du système en place et ainsi conduire à la nécessité de reconcevoir le système existant, voire de concevoir un nouveau système agricole. Or, comme l'évoquent Ingrand et al. (2014), l'apport d'une vision claire des avantages et inconvénients d'une innovation favorise son intégration dans un système d'élevage en donnant une meilleure perception de ce qu'elle peut leur apporter par rapport à leurs propres objectifs.

Jusqu'à maintenant, aucun des travaux visant à développer ces méthodes alternatives ne s'est intéressé à l'impact des changements de pratiques associées sur l'organisation et le fonctionnement de l'élevage à long terme. Une analyse à l'échelle de l'exploitation semble donc nécessaire afin de proposer des stratégies de maîtrise de la reproduction qui répondent à la fois aux objectifs socio-économiques et environnementaux des élevages, notamment dans une perspective de réduction, voire d'interdiction potentielle des TH de synchronisation des chaleurs. Plusieurs méthodes existent pour faire ce type d'analyse. Parmi elles, la modélisation.

I-4. Modéliser le fonctionnement global des exploitations pour accompagner la reconception des systèmes d'élevage ovin laitier

I-4.1. La modélisation : un outil pertinent pour accompagner l'adoption d'innovations et la reconception des systèmes agricoles

La modélisation est une méthode souvent utilisée pour concevoir/reconcevoir des systèmes agricoles car elle est basée sur une représentation schématique conceptuelle du système étudié. Il s'agit en effet d'un moyen efficace de comprendre le fonctionnement de

systèmes agricoles de manière générale, d'en avoir une compréhension partagée entre différents acteurs, d'identifier des lacunes dans les connaissances sur ces systèmes, de prédire leur évolution et d'accompagner les agriculteurs dans leurs processus de décisions (Malézieux et al., 2001). C'est aussi un moyen d'accompagner l'innovation en permettant de réaliser plus ou moins rapidement des évaluations multicritères de pratiques et de systèmes (Ingrand et al., 2014). L'implémentation des schémas conceptuels construits, via diverses plateformes informatiques, peut ensuite permettre de construire des outils de simulation (à visée de projection ou d'exploration) et/ou d'optimisation (visant à maximiser certaines performances d'un système sous un certain nombre de contraintes). Ces outils peuvent ainsi être utilisés pour tester virtuellement un grand nombre de combinaisons différentes entre les éléments représentés du système tout en limitant l'emploi de méthodes coûteuses en argent et en temps (Bernard, 2010). Ils permettent également d'explorer des systèmes complexes qui ne peuvent être manipulés directement par des essais contrôlés mais aussi d'étudier le comportement d'un système sur de longues périodes de temps, ce qui est presque impossible avec les dispositifs expérimentaux classiques (Tichit et al., 2009).

I-4.2. Cas particulier de la modélisation de systèmes d'élevage

Un système d'élevage est par définition un ensemble d'entités en interaction dynamique gérées par l'homme pour transformer des ressources par l'intermédiaire d'animaux domestiques en divers produits (ex : lait, viande, laine ou encore matière organique) ou pour servir d'autres objectifs (Landais, 1992). Les systèmes d'élevage sont donc particulièrement complexes, dans la mesure où ils sont constitués d'entités animales mais aussi végétales, en interaction entre elles mais aussi avec leur environnement, et dont les cycles de production ne se réfèrent pas aux mêmes échelles de temps (ex : la campagne annuelle de production végétale et la durée de vie pluriannuelle d'un animal en production ; Gouttenoire et al., 2011). Compte tenu de cette nature particulière, les approches développées ces dernières années pour modéliser ces systèmes complexes consistent à les diviser en sous-systèmes décisionnels et biotechniques (Gibon et al., 1999; Dedieu et al., 2008). Les sous-systèmes décisionnels représentent souvent ce qu'on appelle l'entité humaine des systèmes modélisés, c'est-à-dire les éleveurs, leurs objectifs et pratiques d'élevage. Les sous-systèmes biotechniques représentent quant à eux les entités de production animales et végétales ainsi que leur fonctionnement au sein du système d'élevage. L'objectif est de considérer les composantes les plus importantes d'un système d'élevage (i.e. l'éleveur, les animaux et les ressources biologiques, économiques et sociales du système), leurs fonctionnements distincts, mais aussi les relations qui les lient, afin de pouvoir analyser le système d'élevage. Il ne s'agit pas de se focaliser sur l'analyse exhaustive et approfondie de tous les différents mécanismes mis en jeu

et de leurs multiples interactions, mais plutôt de se concentrer sur le fonctionnement global du système, en discernant les connaissances nécessaires pour répondre à une problématique donnée tout en acceptant la complexité irréductible des systèmes étudiés (Landais, 1992; Tichit et al., 2009). Ce type d'approche dite systémique permet ainsi d'explorer les synergies entre les différentes composantes du système d'élevage afin de quantifier les avantages et les compromis des interventions probables à l'échelle globale (Gouttenoire et al., 2013). Pour faire ce type d'analyse systémique et répondre ainsi aux questions de conception ou de reconception des systèmes d'élevage, certains auteurs ont souligné la nécessité de construire des modèles à l'échelle de l'exploitation (Dedieu et al., 2008). La modélisation à l'échelle de l'exploitation agricole est utile notamment dans les évaluations visant à reconcevoir des systèmes d'élevage et/ou à identifier des leviers « ex ante » d'adaptation humaines et biotechniques pour faire face aux différents changements qui touchent ces systèmes comme le changement climatique (Samsonstuen et al., 2019) ou dans le cadre de conversions vers des systèmes d'élevage plus durables (Gouttenoire et al., 2013; Villalba et al., 2019). Lorsque des stratégies de gestion sont modifiées, des compromis apparaissent en effet entre (et au sein de) les piliers de la durabilité d'un système.

I-4.3. Modèles d'élevage ovin existants et représentations de la reproduction

Dans les différentes revues de la littérature traitants des modèles destinés à étudier, analyser, concevoir ou reconcevoir des systèmes d'élevage, on constate que les modèles s'intéressant spécifiquement à l'élevage ovin sont peu nombreux comparativement aux modèles destinés à l'étude de systèmes d'élevage d'autres ruminants (Gouttenoire et al., 2011; Puillet, 2010; Van der Linden et al., 2020). Parmi les modèles traitant spécifiquement de l'élevage ovin, certains sont des modèles d'exploitation qui visent généralement à simuler une diversité d'indicateurs dans le cadre d'analyses multicritères [ex : le modèle de simulation ovin allaitant OSTRAL (Benoit et al., 2014), le modèle de simulation OVL BOUSSOLE (Lurette et al., 2018) ou encore le modèle d'optimisation OVL PASTOR-DSS (Villalba et al., 2019)]. Cependant, la plupart des modèles traitant de l'élevage ovin sont des modèles de fonctionnement de troupeaux qui s'intéressent à la performance du troupeau et se cantonnent donc essentiellement à une représentation de l'entité humaine décisionnelle et du troupeau, sans aller jusqu'à une représentation du fonctionnement global de l'exploitation, c'est-à-dire sans prendre en compte le fonctionnement des autres entités qui composent un système d'élevage (notamment les ressources fourragères et les pâtures). Cela peut s'expliquer d'une part par le fait que les modèles à l'échelle de l'exploitation sont plus complexes à développer car ils nécessitent un grand nombre d'informations, à différentes échelles. D'autre part, l'objectif final d'un modèle influence fortement son développement

(Tichit et al., 2009). De fait, selon les objectifs et les problématiques auxquels les modèles cherchent à répondre, ils vont se baser sur différentes représentations du système de production et des processus qui le gouvernent, en incluant ou non ses différentes composantes. Parmi tous les processus biotechniques qui caractérisent le fonctionnement d'un système d'élevage, le processus de reproduction des animaux et sa maîtrise par l'éleveur sont essentiels. En effet, pour qu'un élevage puisse fournir des produits et des services par l'intermédiaire d'animaux domestiques, il faut que ces animaux se reproduisent avec un certain niveau de performance. Du fait de ce caractère central de la reproduction dans le fonctionnement d'un élevage, son déroulement (en termes de processus biologiques) et sa gestion par l'entité décisionnelle à l'échelle du troupeau sont souvent représentés dans les modèles de systèmes d'élevage et de troupeaux ovins rencontrés dans la littérature scientifique. Cependant, sa représentation et son importance diffère entre les modèles. En effet, la modélisation du processus de reproduction se résume généralement à une représentation assez simple du passage de l'état « non fécondé » à « fécondé » où les performances de reproduction du troupeau sont simulées grâce à des relations déterministes. Ces relations impliquent généralement des taux de fertilité, fixés pour tout ou partie du troupeau, par saison de reproduction, par génotype ou par catégorie d'âge (Benoit, 1998; Lesnoff, 1999). En revanche, très peu de modèles de troupeaux ovins intègrent de l'individualité dans la représentation de la reproduction. Pourtant, afin d'évaluer précisément les performances d'un système d'élevage, il est nécessaire de tenir compte du fait qu'un élevage se compose d'un groupe d'animaux divers (ne serait-ce que par leur âge, leur état corporel ou encore leur patrimoine génétique). Cette diversité de caractéristiques est à l'origine d'une variabilité de réponse aux pratiques de gestion de la reproduction, ce qui peut affecter les performances globales du troupeau, notamment dans un contexte de gestion non hormonale de la reproduction. Cournut et Dedieu (2004) par exemple parviennent à illustrer avec leur modèle ovin allaitant les propriétés de régulation du système de troupeau en analysant entre autres la diversité des trajectoires productives individuelles des brebis. Ainsi, de plus en plus de modèles visant à optimiser les performances de systèmes d'élevage ovins s'attachent à représenter la variabilité de réponse à la méthode de reproduction modélisée (Villalba et al., 2019). **Dans ce travail, nous nous sommes donc attachés à modéliser la variabilité de réponse aux pratiques de gestions non hormonales de la reproduction** en supposant que la prise en compte de cette variabilité permet de mieux comprendre comment se construisent les performances d'un troupeau dans un contexte donné, mais aussi d'explorer des possibilités de régulation des performances du troupeau, voire de l'exploitation en jouant sur des caractéristiques des individus du troupeau.

Chapitre II :
Démarche méthodologique générale

Chapitre II- Démarche méthodologique générale

L'objectif de cette thèse est double. Il s'agit d'une part de conceptualiser et d'évaluer les conséquences des changements de pratiques associés à l'utilisation d'alternatives aux hormones de synchronisation en élevage OVL et d'autre part, d'identifier différents scénarios pertinents d'intégration d'alternatives pour le cas particulier des élevages OVL typiques du BNO. Ce chapitre présente la démarche méthodologique générale mise en place pour répondre aux objectifs du travail. Les différentes étapes de la démarche sont illustrées dans la Figure II.1. Dans un premier temps, le recueil et la **synthèse de connaissances** issues de la littérature, d'enquêtes et d'avis d'experts ont été nécessaires pour faciliter la bonne compréhension du système étudié. À partir de la synthèse des connaissances à l'échelle du troupeau, un **modèle multi-agent** représentant le fonctionnement dynamique d'un troupeau intégrant les spécificités de processus biotechniques liés à une gestion sans hormones de la reproduction OVL a été conçu. Ce modèle a ensuite été complexifié pour en faire un **modèle d'exploitation OVL** qui a été utilisé pour simuler des scénarios d'introduction d'alternatives aux hormones dans une diversité d'exploitations typiques du BNO. Les résultats des simulations ont ensuite servi à **dresser des pistes d'intégration durable d'alternatives** aux TH de synchronisation dans les systèmes élevages OVL du BNO.

Dans ce chapitre, un focus particulier est fait sur la **présentation de la zone d'étude choisie** (II-1). En effet, les caractéristiques de l'élevage OVL dans cette zone conditionnent l'organisation et donc la représentation qui est faite des exploitations OVL dans le modèle développé. Le paragraphe (II-2) décrit ensuite la méthode de modélisation privilégiée dans ce travail de thèse. Enfin, dans le dernier paragraphe de ce chapitre (II-3), les principaux jeux de données utilisés dans la conception et l'évaluation du modèle ainsi que dans l'élaboration des différents scénarios simulés sont présentés.

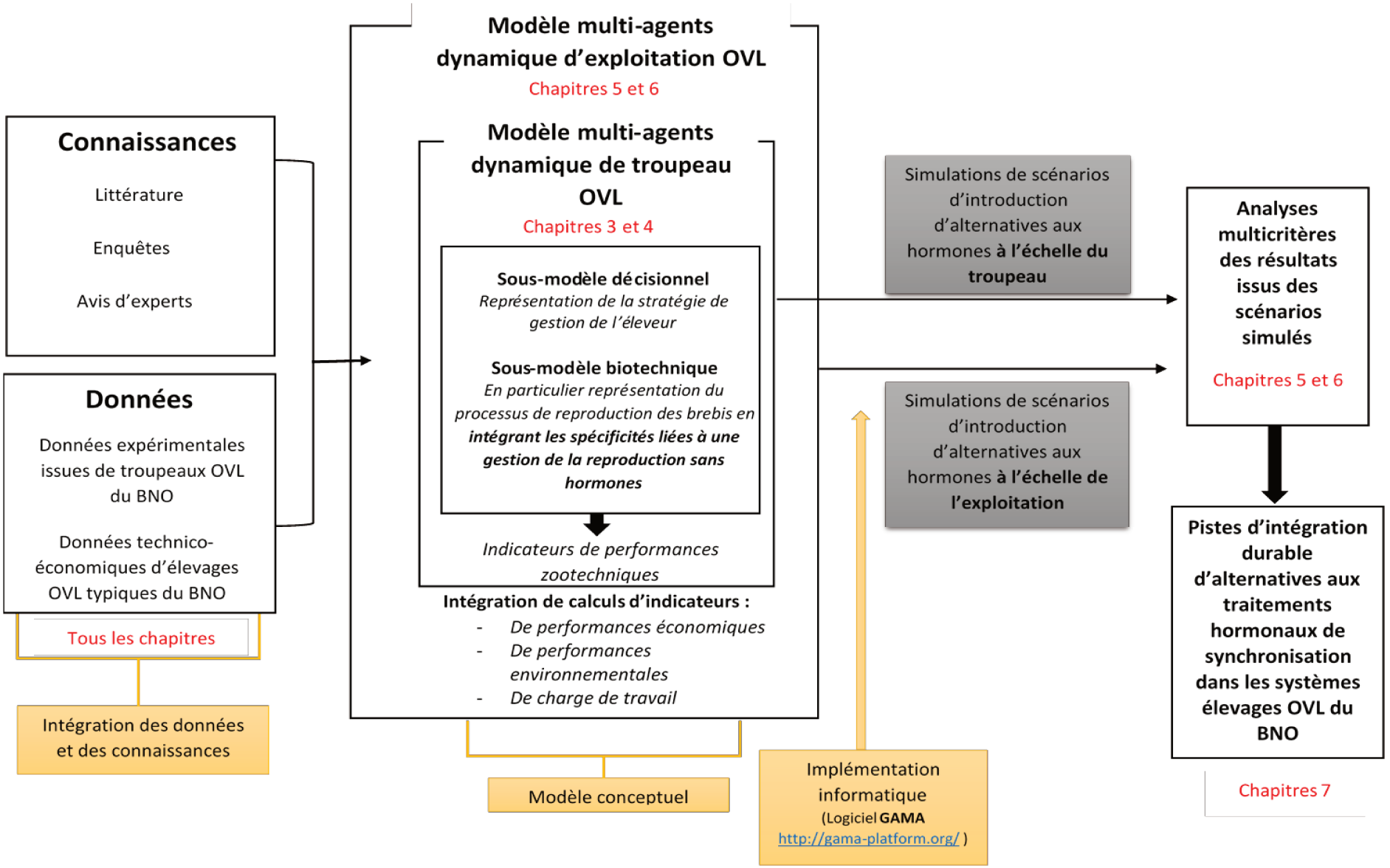

Figure II. 1. Schéma de la démarche méthodologique générale du travail de thèse et liens avec les différents chapitres du manuscrit.

II-1. Présentation de la zone d'étude

Le BNO, encore appelé « Bassin de Roquefort », a été choisi comme zone d'étude pour ce travail de thèse. Il s'agit en effet du premier bassin de production OVL français, principalement du fait de l'appartenance d'une grande partie de son territoire à l'aire d'appellation du fromage AOP *Roquefort* (Chambre d'agriculture Occitanie, 2021). Le BNO est également le plus grand bassin utilisateur de TH pour la gestion de la reproduction des brebis laitières. En effet, simultanément au développement des TH, le nombre d'IA dans les élevages OVL français a connu une forte progression à partir des années 1970. Ainsi, en 2018, la pratique de l'IA a concerné 42 % du cheptel français de brebis laitière (IDELE, 2018a) avec plus de la moitié de ces IA réalisées dans les départements des bassins laitiers du BNO (Figure II.2). En termes de race, la Lacaune lait, race très productive (330 L/brebis en moyenne pour cette race en France en 2019 ; IDELE, 2020b) mais aussi seule race autorisée pour la production de *Roquefort,* est la race majoritaire dans le BNO. C'est la première race utilisatrice d'IA en France avec plus de la moitié des IA françaises en 2018 (IDELE, 2018a). En France, la semence de bélier est prélevée dans des centres d'insémination artificielle (**CIA**) qui se trouvent hors de l'exploitation. Dans le BNO, il existe deux CIA : *le Service Elevage de la Confédération de Roquefort* et *Ovitest*. Ils travaillent en étroite collaboration avec les éleveurs et toute leur organisation repose aujourd'hui sur la possibilité de synchroniser efficacement les chaleurs dans les troupeaux du bassin. Ils fournissent ainsi les éleveurs en TH et travaillent avec eux en préparant les plans d'accouplement génétique, en effectuant l'IA, en fournissant des béliers sélectionnés, mais aussi en réalisant un suivi de la gestation et des performances laitières des brebis ou encore en fournissant des béliers sélectionnés dans les CIA. L'accès aux TH est donc à la base de tout le schéma organisationnel de la filière OVL dans le BNO.

Sur ce territoire du BNO, on observe la dichotomie classique entre élevages exclusivement conventionnels pratiquant un schéma de gestion de la reproduction basé sur l'utilisation de TH + IA et les élevages majoritairement en AB qui gèrent la reproduction sans TH et sans IA (Lurette et al., 2016). L'effet mâle est la pratique alternative aux TH la plus répandue pour dessaisonner et grouper les chaleurs dans les élevages OVL, notamment dans les élevages en AB (Lurette et al., 2016). **Ce travail de thèse se focalise ainsi sur l'utilisation de cette technique de l'effet mâle comme alternative aux TH pour l'induction et la synchronisation des chaleurs en élevage ovin.**

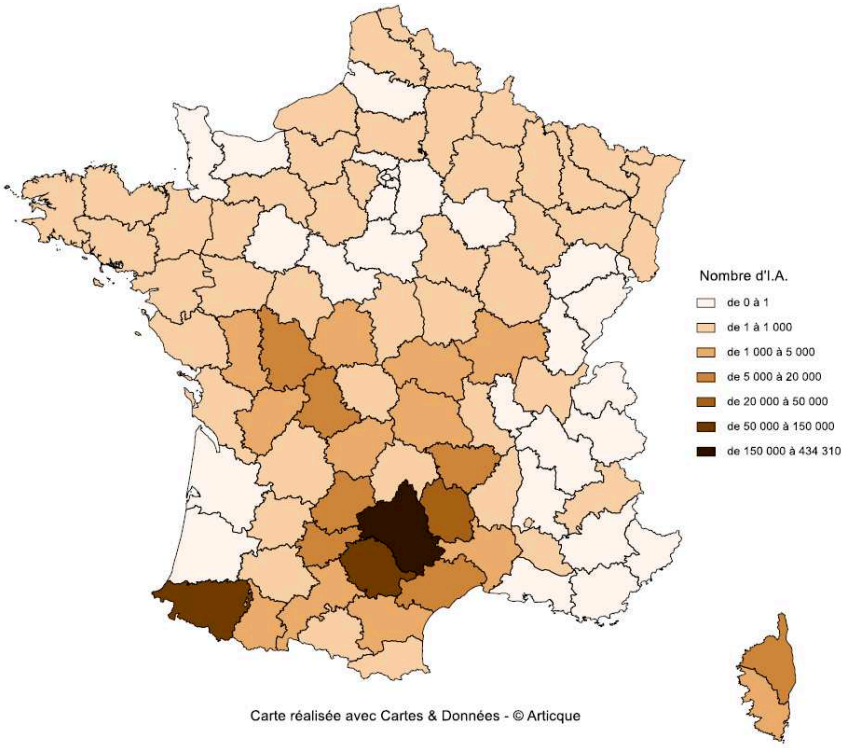

Figure II.2. Carte de répartition des IA ovines réalisées en 2018 (IDELE, 2018a).

En parallèle de la dichotomie observée entre gestion de la reproduction avec TH et gestion sans TH, les élevages OVL du BNO se divisent en deux grands groupes : les systèmes dits « hâtifs » dans lesquels les éleveurs luttent leurs brebis au printemps et produisent du lait entre novembre et août, et les systèmes dits « tardifs » dans lesquels les éleveurs luttent leurs brebis au milieu de l'été ou en début d'automne, proche de la période de reproduction naturelle des ovins (c'est-à-dire l'automne), et produisent du lait entre février et octobre. En effet, en réponse à la demande de l'industrie, l'étalement de la production par le fractionnement des périodes d'accouplement entre les exploitations, s'est développé dans ce grand bassin de production afin que le lait soit disponible toute l'année pour la collecte par les laiteries de la région (Lagriffoul et al., 2016). Des systèmes de production « hâtifs » et « tardifs » se retrouvent aussi bien dans les exploitations en AB que dans celles en AC.

En outre, les exploitations OVL du BNO sont de tailles moyenne à grande (entre 200 et 1000 brebis) et les brebis sont généralement conduites en un seul troupeau à la traite (au fur et à mesure des mises bas et après l'allaitement, les brebis sont regroupées dans un seul lot de traite). En règle générale, les systèmes de production sont considérés comme étant des systèmes plutôt semi-extensifs basés sur la valorisation de l'herbe (notamment l'herbe pâturée), la pratique du pâturage étant favorisée par l'obligation de pâturer pour les éleveurs qui fournissent du lait à l'AOP Roquefort (INAO, 2017). Dans ces systèmes, l'alimentation est généralement conduite en groupe, à l'échelle du troupeau sans ajustement individualisé

des apports aux besoins. L'objectif étant de satisfaire les besoins des brebis qui contribuent le plus à la production totale en couvrant environ 110 % des besoins énergétiques et 145 % des besoins azotés de la moyenne du troupeau (Lagriffoul et al., 2016). Depuis plusieurs années, de plus en plus d'élevages du BNO optimisent cependant leur stratégie d'alimentation en adaptant les rations des brebis à leur niveau de production. Ceci est possible grâce à l'utilisation de dispositifs de distribution automatisée de concentrés (DAC) qui permettent de faire des lots virtuels au sein du troupeau pour ajuster la distribution d'aliments concentrés aux besoins spécifiques des brebis en production (Hassoun et al., 2018). Les rations restent cependant construites de manière à couvrir au moins 100 % des besoins en énergie et en protéines pour chaque catégorie de brebis.

II-2. Méthode de modélisation et étapes de conception du modèle de simulation

Afin d'évaluer les conséquences des changements de pratiques associées à l'introduction d'alternatives aux TH sur l'organisation globale et le fonctionnement des exploitations OVL à long terme, nous avons choisi une **approche par modélisation informatique**. Cette approche permet en effet de créer un monde virtuel où l'on peut mener, rapidement et à moindre coût, des expériences *in-silico* qu'il ne serait pas possible de mener sur un système réel. Plus particulièrement, nous avons choisi d'utiliser la méthode de modélisation dite « multi-agent ». Il s'agit d'une méthode permettant de représenter le système étudié sous la forme d'une collection d'entités autonomes, appelées agents, qui interagissent entre elles. Cette méthode permet de représenter des systèmes au sein desquels plusieurs entités aux comportements hétérogènes et parfois complexes interagissent. Elle permet ainsi de tenir compte des processus de changements intervenant à différentes échelles et de simuler et de comprendre les propriétés émergentes qui résultent des interactions entre les individus d'un système et entre ceux-ci et l'environnement (Bousquet et al., 2002). L'utilisation de la modélisation multi-agent nous a donc semblé pertinente dans le cadre de ce travail de thèse afin de simuler au mieux les interactions entre les différentes entités qui composent une exploitation OVL dans un contexte de gestion de la reproduction sans hormones. Elle permet notamment de modéliser comment la réponse individuelle des brebis du troupeau dans un contexte de gestion de la reproduction sans TH peut affecter l'organisation de toute l'exploitation par des jeux d'interactions entre les différentes entités qui la composent (animales, végétales et humaines). Le but est de pouvoir utiliser le modèle développé pour explorer différents scénarios d'évolutions possibles pour des exploitations OVL typiques du BNO et proposer des pistes durables d'intégration des alternatives aux TH dans ces exploitations.

Le modèle de simulation a été construit en deux temps. Dans un premier temps, un modèle de fonctionnement de troupeau OVL de composition typique de celle que l'on retrouve dans le BNO a été développé en y intégrant les spécificités de la reproduction sans TH avec une synchronisation des cycles ovariens par effet mâle. Ainsi, la représentation du processus individuel de réponse physiologique des individus du troupeau à l'effet mâle a été modélisée. Dans le modèle de troupeau OVL développé, seules les entités décisionnelles (l'éleveur) et biotechniques (les brebis et les béliers) intervenant dans le fonctionnement du troupeau ont été représentées, afin d'explorer les conséquences de l'utilisation d'une méthode non hormonale de synchronisation des cycles ovariens (l'effet mâle dans notre cas) sur les performances du troupeau. Dans un deuxième temps, ce modèle de troupeau OVL a été complexifié pour obtenir un modèle dynamique d'exploitation OVL. Dans ce modèle d'exploitation, d'autres entités telles que les surfaces agricoles ainsi que leurs interactions avec les entités déjà représentées ont été modélisées afin de simuler, en sortie, différents indicateurs de la durabilité du fonctionnement de l'exploitation simulée. Une représentation de l'évolution au cours du temps des caractéristiques des différents agents représentés a aussi été intégrée afin de simuler les conséquences de l'introduction d'une méthode alternative aux hormones sur la durabilité de l'exploitation à long terme.

II-3. Données utilisées et scénarios simulés

Tout au long du développement du modèle de troupeau, puis du modèle d'exploitation, différents jeux de données ont été mobilisés pour les phases de conception et de validation ainsi que pour le choix et la mise en place des scénarios à simuler. Les principales données utilisées sont présentées succinctement dans ce paragraphe.

II-3.1. Données expérimentales pour la modélisation du processus individuel de reproduction des brebis

Le passage à une gestion sans hormones de la reproduction implique une expression accrue de la variabilité des réponses individuelles des brebis à la technique de synchronisation utilisée. Ainsi, il était important dans un premier temps de caractériser la réponse individuelle à l'effet mâle des brebis de race Lacaune (race majoritaire dans les exploitations OVL du BNO). Pour se faire, un jeu de données expérimentales issu d'une étude menée dans un élevage commercial français en AB du BNO, dans l'Aveyron, au sud de la France (44 387N, 2 9623E) a été analysé. Cette étude avait pour but d'étudier, sur le terrain et sur cinq années consécutives (2012 à 2016), les principaux paramètres affectant la réponse ovarienne précoce à l'effet bélier chez des brebis Lacaune lait en anœstrus saisonnier (Debus et al., 2022). Ainsi, pendant 5 ans, au moment de la reproduction qui a lieu au printemps

dans l'élevage observé (donc hors saison naturelle de reproduction pour les brebis) la réponse à l'effet mâle des brebis (n= 223 à 283 brebis selon les années) a été suivie grâce à des échantillons de sang prélevés sur les brebis à J-10, J0 et J+11 par rapport au jour d'introduction des béliers pour l'effet mâle. Les niveaux de progestérone dans les échantillons de sang ont ensuite été analysés afin de déterminer l'apparition de la cyclicité (c'est-à-dire une reprise de l'activité ovarienne) avant (J-10 et J0) et en réponse (J+11) à l'introduction des béliers. En parallèle, plusieurs caractéristiques des brebis ayant précédemment été identifiées dans la littérature comme ayant une influence sur la réponse ovarienne des brebis suite à l'effet mâle ont été suivies. Ainsi, la note d'état corporel (**NEC**, notée sur une échelle de 0 à 5 ; Russel et al., 1969) a été évaluée pour chaque brebis une semaine avant l'introduction des béliers par des techniciens formés. L'âge, le nombre de jours depuis l'agnelage précédent, la taille de la portée, le rendement laitier de la lactation précédente (production laitière totale ainsi que le rendement laitier au troisième et dernier contrôle laitier juste avant l'introduction des béliers) ont également été recueillis pour chaque brebis et pour chaque année.

Les données récoltées à l'issue de ces cinq années de suivi expérimental ont été analysées en parallèle du travail de thèse. L'analyse a consisté en la réalisation de régressions logistiques binaires pour chaque année et pour l'ensemble des années de suivi afin de déterminer la contribution des facteurs observés chez les brebis à la probabilité d'être cyclique avant l'effet mâle et à la probabilité de répondre à l'effet mâle. L'analyse complète est présentée en Annexe 1 sous la forme d'un article publié dans la revue *Animal* (DOI : 10.1016/j.animal.2022.100519). Les résultats obtenus ont permis de dresser deux équations de probabilités : 1) Probabilité pour une brebis d'être cyclique avant l'effet mâle et 2) Probabilité pour une brebis de répondre à l'effet mâle », qui sont toutes deux dépendantes de certaines caractéristiques individuelles des brebis. En particulier leur NEC, âge, rendement laitier et/ou nombre de jours entre leur dernier agnelage et l'effet mâle. Ces équations de probabilités ont ensuite été intégrées dans le modèle de fonctionnement de troupeau OVL afin de proposer une représentation de la variabilité de réponse à l'effet bélier chez les brebis Lacaune en anœstrus.

II-3.2. Données pour modéliser la gestion du troupeau et de l'exploitation par l'éleveur

La représentation de la gestion du troupeau s'est faite principalement sur la base de résultats de la littérature et de consultations d'experts (techniciens de CIA et de fermes expérimentales ou employés d'instituts techniques) afin de représenter au mieux les règles

de gestion de troupeaux et plus généralement des exploitations OVL dans le BNO. De même, la représentation de la gestion des autres ateliers s'est faite sur la base d'avis d'experts.
Tout au long de la construction des modèles de troupeau et d'exploitation OVL des allers-retours entre phases de construction et avis d'experts sur les sorties de simulations ont été réalisés afin de valider la modélisation faite des critères de la gestion du troupeau et de l'exploitation.

II-3.3. Choix des scénarios et données utilisées pour les simuler

À partir de la synthèse des connaissances issues de la littérature, mais aussi sur la base des données d'enquêtes recueillies lors de stages (Doumenge, 2016; Halzuet, 2021; Lautier, 2022), nous avons pu décider de scénarios d'introduction d'alternatives aux TH qui semblaient particulièrement pertinents à simuler. Dans ce travail de thèse, l'introduction de l'effet mâle a été choisie pour illustrer l'introduction de méthodes alternatives aux TH en élevage OVL. Cette technique a la particularité de permettre la réalisation de l'IA sans hormones. Deux possibilités s'offrent donc aux élevages OVL conventionnels, gérant leur reproduction avec TH+IA, en termes de transition vers une gestion non hormonale de la reproduction : 1) l'arrêt de l'utilisation de synchronisation hormonale avec conservation de l'IA ou 2) l'arrêt combiné de la synchronisation hormonale et de l'IA. Pour les élevages en AB qui sont déjà sans hormones, le développement de protocoles d'IA sans hormones est une opportunité d'introduire l'IA dans leur troupeau. Ainsi, nous avons décidé de simuler des scénarios de transitions vers deux types de conduites alternatives de la reproduction :

- ***Scénario Sans Hormones avec IA (SHIA) :*** Synchronisation des chaleurs par un effet mâle en conservant (pour les élevages en AC) ou en introduisant (pour les élevages en AB) l'IA pour les brebis adultes uniquement. En effet, la pratique de l'IA à la suite d'un effet mâle demande une identification précise des brebis en chaleur, qui est coûteuse en temps de travail pour l'éleveur (Lurette et al., 2016). Dans les élevages du BNO, la stratégie de renouvellement du troupeau consiste généralement à conserver les premières agnelles nées de chaque campagne de production (donc principalement celles nées du lot d'adultes) de manière à leur laisser le temps d'atteindre 7 à 8 mois avant leur première mise à la reproduction à la campagne de production suivante. Sachant par ailleurs que les agnelles répondent moins bien à l'effet mâle que les brebis adultes (cf. paragraphe I-3.2.2), les élevages du BNO pratiquant à ce jour l'IA sans hormones (à la suite d'un effet mâle) choisissent

généralement de n'inséminer qu'un lot de lutte : le premier, c'est-à-dire le lot des brebis adultes (Debus et al., 2022). Cela permet un compromis entre charge de travail et conservation de la pratique de l'IA.

- ***Scénario Sans Hormones avec monte naturelle uniquement (SHMN) :*** Synchronisation des chaleurs par un effet mâle et arrêt de l'IA dans le troupeau (uniquement pour les élevages en AC).

Une fois les scénarios de gestion de la reproduction à simuler définis, plusieurs jeux de données ont été mobilisés afin de modéliser au mieux les différents types de troupeaux et d'exploitations représentatifs du BNO et ainsi simuler l'introduction d'alternatives aux hormones dans cette diversité d'exploitations.

Dans un premier temps, afin de simuler et d'étudier les conséquences liées au passage à une conduite alternative de la reproduction sur les performances zootechniques d'un troupeau OVL en utilisant le modèle troupeau développé, des données historiques de suivi du troupeau OVL (suivis individuels de NEC, de performances laitières, d'âge ou encore de caractères génétiques) ainsi que des informations sur la gestion du troupeau OVL de l'unité expérimentale d'INRAE : la Fage ont été utilisées (cf. Chapitre IV). Cette unité expérimentale se situe dans la région des Causses du Larzac (43_54'54.5200N ; 3_05'38.110 0E ; ~800 m d'altitude), au cœur du BNO. Il s'agit d'un système en AC où la reproduction du troupeau est gérée par synchronisation hormonale suivie d'une IA sur la totalité du troupeau.

Dans un second temps, afin de modéliser l'exploitation dans son ensemble, la base de données technico-économiques issue du suivi pluriannuel d'exploitations OVL commerciales de l'observatoire INOSYS-Réseaux d'élevage de l'Institut de l'élevage (IDELE, 2018b) a été utilisée. Cette base de données répertorie régulièrement les informations permettant de comprendre le fonctionnement d'exploitations commerciales caractéristiques des types d'élevages les plus représentatifs des grands bassins de production français, y compris leurs résultats technico-économiques annuels. Dans cette base de données, sept cas-types illustrant les systèmes OVL en AC et deux cas-types illustrant les systèmes OVL en AB sont disponibles pour la région du BNO. Afin de représenter les grands types d'élevages OVL rencontrés dans le BNO en termes de gestion de la reproduction, nous avons choisi de simuler l'introduction d'alternatives aux hormones dans quatre de ces cas-types d'exploitations OVL. Ils se distinguent selon le type de système agricole (élevages en AC ou en AB) et selon leurs périodes de reproduction : « hâtive » (c'est-à-dire qui réalisent la reproduction du troupeau entre mars et mai) ou « tardive » d'été (c'est-à-dire qui réalisent la reproduction du troupeau entre juin et août). Deux exploitations en AC *(Roq 1.2 et Roq 6.2; De Boissieu et Morin, 2022)*

et deux exploitations AB (*Roq 8 et Roq 9 ; De Boissieu et Morin, 2022*) ont ainsi été modélisées afin de simuler et d'étudier les conséquences associées à l'introduction d'alternatives aux hormones dans cette diversité d'exploitations OVL (cf. Chapitre V et VI). La Table II.1 décrit les principales caractéristiques de ces exploitations modélisées.

Table II.1. Descriptif des exploitations OVL types modélisées (d'après INOSYS-Réseaux d'élevage ; IDELE, 2018b ; De Boissieu et Morin, 2022).

	Zone du BNO	**Type d'agriculture**	**Cheptel[1]**	**Période de reproduction**	**Méthode de reproduction[2]**	**Dates de traite**	**Dates de pâturage**
Roq 1.2	Zone herbagère	AC	370 brebis	Tardif été	TH+IA	15/12-20/07	01/03-15/11
Roq 6.2	Ségala	AC	415 brebis	Hâtif	TH+IA	20/11-15/07	15/03-10/09
Roq 8	Causses	AB	385 brebis	Tardif été	EM+MN	15/12-31/07	25/03-15/11
Roq 9	Lévezou	AB	491 brebis	Hâtif	EM+MN	05/11-15/06	15/03-30/09

1 : Effectif moyen présent dans le troupeau ; 2 : Méthode de reproduction adoptée pour le lot principal.
IA= Insémination artificielle ; EM= Effet mâle ; MN= Monte naturelle ; TH=Traitements hormonaux.

Chapitre III :

Modélisation du processus de reproduction et simulation des performances d'un troupeau ovin laitier dans un contexte de gestion sans hormones utilisant l'effet mâle

Chapitre III- Modélisation du processus de reproduction et simulation des performances d'un troupeau ovin laitier dans un contexte de gestion sans hormones utilisant l'effet mâle

Ce chapitre présente le développement du modèle REPROsheep, un modèle de simulation des performances d'un troupeau OVL géré sans hormones en utilisant l'effet mâle comme alternative pour induire et synchroniser les chaleurs dans le troupeau. L'objectif spécifique de ce travail est présenté dans ***la première partie de ce chapitre****. La description du modèle de troupeau OVL REPROsheep, son implémentation, sa validation et son utilisation sont présentées dans* ***la deuxième partie de ce chapitre*** *sous forme d'un article publié dans la revue Computers and Electronic in Agriculture (2021). Une* ***dernière partie*** *résume les conclusions principales du travail présenté dans ce chapitre.*

III-1. Introduction du chapitre

L'utilisation de TH de synchronisation dans la gestion de la reproduction ovine permet l'induction et la synchronisation des ovulations et des chaleurs à tout moment de l'année. Grâce à cette technique, l'éleveur peut s'affranchir de la saisonnalité de la reproduction des brebis. Cela lui permet ainsi de regrouper les moments d'ovulation et donc les agnelages ainsi que les périodes de lactation dans le troupeau. Passer d'une gestion de la reproduction avec TH à une gestion non hormonale de la reproduction suppose de laisser s'exprimer la variabilité individuelle de réponse à la méthode de synchronisation utilisée au sein du troupeau et donc une plus grande variabilité dans la dynamique des entrées en chaleurs des brebis du troupeau avec de potentielles conséquences sur les performances du troupeau. Cela est d'autant plus vrai à contre-saison (c.-à-d. au printemps) lorsque les brebis sont en anœstrus saisonnier. Ainsi, une des premières conséquences de l'abandon de l'utilisation d'hormones de synchronisation pour les éleveurs va être la nécessité de gérer la variabilité individuelle dans le troupeau en ce qui concerne l'entrée en chaleur des brebis.

L'objectif du travail présenté dans ce chapitre était de concevoir un modèle multi-agent de troupeau OVL qui intègre une représentation de la variabilité individuelle de réponse à l'effet mâle des brebis Lacaune lait. Le but est de pouvoir utiliser le modèle construit pour étudier les conséquences de cette variabilité sur les performances reproductives et laitières d'un troupeau de brebis Lacaune, ainsi que sur l'organisation de la reproduction du troupeau dans un contexte sans hormones. Le modèle développé vise également à une meilleure compréhension de l'interaction entre la variabilité des traits spécifiques des brebis, leurs performances reproductives individuelles et celles du troupeau dans le cadre d'une synchronisation des chaleurs par effet mâle. En effet, si l'on sait de par la littérature qu'il existe une variabilité de réponse à l'effet mâle liée à des caractéristiques biologiques de la brebis (âge et note d'état corporel notamment) et/ou à des pratiques d'élevage (Rosa et

Bryant, 2002), aucun auteur ne s'est intéressé jusqu'à présent aux conséquences de cette variabilité individuelle sur les performances (répartition des agnelages et production laitière) et sur l'organisation de la conduite du troupeau ovin lait.

III-2. Article 1: REPROsheep: A model that integrates individual variability to optimise hormone-free reproduction management strategies for a dairy sheep flock

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Original papers

REPROsheep: A model that integrates individual variability to optimise hormone-free reproduction management strategies for a dairy sheep flock

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ABSTRACT

Managing reproduction of a dairy sheep flock without using hormones for oestrus induction and synchronisation is an alternative method that complies with agroecological principles, animal welfare and public health concerns. However, shifting from conventional reproductive management to a hormone-free philosophy means leaving more room for individual intraflock variability in oestrus occurrence. The success of establishing alternative hormone-free reproduction systems relies on managing the variability of ewes' individual responses, which are themselves influenced by individual characteristics. Therefore, the so-called REPROsheep model was built to study the effects of individual ewes' characteristics, such as age, body condition score (BCS) or milk yield, on individual responses, as well as the overall productive and reproductive performances of the flock. This dynamic agent-based model (ABM) represents individual reproduction and lactation processes in a hormone-free management context. Outputs at the flock level were simulated using this model. Two dynamic outputs (weekly number of ewes lambing and weekly milk yield) and two punctual outputs (total number of ewes lambing and total milk yield) were simulated. Sensitivity analysis showed that the studied outputs were affected by ewe age, pre-mating BCS and milk-yield distributions in the flock. Increasing average age or pre-mating BCS by 0.5 from a starting point of 2.5 and average milk-yield by 50 L from a starting point of 195 L appeared to increase, for one breeding season, the number of ewes lambing, the concentration of those lambing events over one period, as well as total milk yield, whereas decreasing the average value of these factors by the same amount appeared to produce the opposite effect. Management strategies favouring an optimum age and pre-mating BCS, as well as good milk yield for the individuals of the flock, may thus be a lever for optimising performance, especially lambing distribution over time. Therefore, the REPROsheep model seems relevant to determine how a management strategy (affecting flock structure in terms of age, body condition or production potential) can impact the performance of a dairy sheep flock in the context of hormone-free reproduction.

1. Introduction

To achieve agroecological transition goals, French livestock farming systems are expected to maintain their productive performance while responding to a diversity of complex environmental, social and economic challenges. This implies a willingness to design farming systems based on biological regulations, adding value from interactions between the farming system components while enhancing autonomy and self-sufficiency in inputs (Thenard et al., 2014). Reproduction practices are among the practices to be revisited in such a paradigm shift, which is particularly challenging in seasonal species such as sheep. In this regard, alternative sheep farming systems have been conceived, taking into account the emergence of new and serious ethical issues related to animal welfare and public health concerns (Martin et al., 2004). Alternative solutions are investigated to limit hormonal treatments that have been conventionally used to induce and synchronise ovarian cycles in small ruminants (Pellicer-Rubio et al., 2019). The use of photoperiodic treatments or the so-called "male effect" technique are, in fact, functional alternatives to hormonal treatments for stimulation and synchronisation of ewe ovulatory activity (Lurette et al., 2016). However, these alternatives imply leaving more room for individual variability in oestrus occurrence, which suggests that the success of hormone-free

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reproduction at the flock level would rely on managing the variability of individual responses. These individual responses are related to intrinsic characteristics of the ewes as well as to the structure of the flock resulting from the management strategy of the farmer. Factors such as body condition score (BCS) (Russel et al., 1969; Kenyon et al., 2014), age (Fahmy, 1989; Notter, 2000) and production potential (Gootwine and Pollott, 2000) are known to be strongly related to reproductive performance in sheep. Therefore, heterogeneity in flock structure in terms of age distribution, BCS and/or individual production levels is expected to induce variability in individual responses to breeding practices, a key component for understanding flock function (Puillet et al., 2010b).

Flock simulation models are an interesting methodological resource to address this issue because they enable us to improve our ability to predict the responses of a flock to the management practices to which it is subjected (Tichit et al., 2009). The so-called agent-based modelling (ABM) method allows an interesting bottom-up approach in which the emphasis is placed on modelling the agents (entities, in our case sheep and farmer) and the interactions between them and their environment. The global performance of the modelled system then emerges from dynamic interactions between agents and/or their environments (Bruch and Atwell, 2015). We speculate that this agent-based approach will allow us to build a model to evaluate the impacts of individual variability in reproductive responses on the overall performance of a dairy sheep flock managed with alternative practices without hormones. For this, a detailed representation of ovine reproductive processes is required. Some models have been applied to dairy cattle herds (Oltenacu et al., 1980; Brun-Lafleur et al., 2013) to precisely represent both reproductive processes and individual variability. To our knowledge, there is a lack of this kind of model for sheep flocks, particularly for dairy sheep systems. However, some deterministic models are available. They usually represent hormonal management of reproduction and involve fertility rates, fixed for the totality or one part of the flock, by breeding season, by genotype or by age category (Benoit, 1998; Lesnoff, 1999).

A dynamic model incorporating the individuality of ewe reproduction is needed to conceive alternative dairy sheep farms based on new reproductive process management. Therefore, the aim of this work was to build an ABM to help evaluate the effects of using alternative hormone-free reproduction practices in dairy sheep flock management. The model would contribute to a better understanding of the interplay between the variability in the specific traits of individual ewes and their individual and whole flock reproductive performances.

2. Materials and methods

The model was built using GAMA software (Taillandier et al., 2019), which was designed for the development of ABM. The following description is given according to the rules of the O.D.D. protocol (Overview, Design concepts, Details), specifically created for the description of ABM (Grimm et al., 2010).

2.1. REPROsheep: A model to simulate the reproductive dynamics of a hormone-free dairy sheep flock

2.1.1. Purpose

The REPROsheep model was designed to represent the reproductive dynamics in a dairy sheep farm managed without hormonal treatments for induction and synchronisation of ewe oestrus. It took into account the individual variability of oestrus based on a detailed representation of the individual reproductive process. The objective was to understand the extent to which the number of ewes lambing and the milk production over one production season, at the flock level, are influenced by several individual characteristics of dairy ewes (e.g., age, BCS and milk yield level) and their distribution in the flock.

2.1.2. Model baseline and overview

To represent the mechanism of reproduction without hormones and to formalise the link between ewe characteristics and reproductive performance, data available from Debus et al. (2021) were used. This database reports the result of a 5 year experimental monitoring (from 2012 to 2016) of a flock composed of approximately 300 Lacaune ewes (ewe lambs and adult ewes) in an organic farm (i.e., without hormonal treatments) in the Roquefort basin (South France). The studied farm, known as “off-season”, was characterised by unseasonal breeding in spring (Fig. 1), different from conventional farms (seasonal) where the animals are bred in mid-summer or early autumn (during their natural breeding season). During the experimental monitoring, the “male effect” (ME) technique was used to induce and synchronise oestrus in the flock without hormonal treatment. This technique consists of introducing, after a separation time of at least one month, a sufficient number of rams into a flock of ewes under seasonal anoestrus (i.e., at sexual rest). This practice induces an almost immediate increase in luteinising hormone (LH) secretion, leading to ovulation and resumption of oestrus cycles within 15 days (Martin et al., 1986; Thimonier et al., 2000). The proportion of ewes responding to ME during anoestrus season have been shown to be highly variable, depending on time of use, breed (Rosa and Bryant, 2002; Chanvallon et al., 2011), age or nutritional status of rams and ewes (Ungerfeld et al., 2004; Maatoug-Ouzini et al., 2013; Alhamada et al., 2017). The depth of anoestrus (i.e the proportion of ewes showing spontaneous ovulation before any synchronisation technique) has also been found to influence the response to ME depending on the breed (Thimonier et al., 2000; Chanvallon et al., 2011). Overall, it has been demonstrated that the response to ME is highly variable and that this variability has many origins and underlying factors which have been studied generally one by one and usually in meat breeds as milking adds supplementary potential impact factors. Debus et al. (2021) studied the simultaneous link between some of the previously cited factors and short term ovarian response of milking Lacaune ewes to the male effect. The available database of their work provided access to individual ewe information concerning pre-mating BCS (BCS, scored one week before introducing the rams for ME), age at breeding time (Age), lactation number ($Lact_{num}$), interval (days) between last lambing and the male effect (LMEI), milk performance (third milk yield monitoring (TDMY, measured a few days before the male effect) and total milk yield from previous lactation (LTMY)) for each ewe (Table 1b), as well as the cyclicity status of each ewe before the male effect (CBME; i.e., in oestrus before the ram was introduced) and its response to the male effect (RME). This information was used to develop the equations used in the model to link all these characteristics of the ewes to their reproductive performance (Section 2.1.7.SM2).

The flock reproduction management that was modelled consisted of separate management strategies for two batches: the adult ewes batch (ewes that have completed at least one lactation) and the ewe lambs batch (young ewes that have never been mated). Only the adult ewes were subjected to off-season ME and were then naturally mated with rams. The ewe lambs were mated for the first time in mid-summer (i.e., close to the natural breeding season) so that ME was not necessary to stimulate their ovarian cycle. Adult ewes that did not respond to the ME in spring were added to the ewe lamb batch for mating in mid-summer without ME. With such management, the lambing period began in early autumn of year ‘n’, with the milk delivery period running from late October of the same year to August of year ‘n + 1’ (Fig. 1).

2.1.3. Entities, state variables and scales

***Entities*:** The model presented two main types of entities, i.e., (i) a decision-making or human entity: the farmer, and (ii) biotechnical animal entities: sheep divided into two subentities according to reproductive animal category (or sex): ewes and rams.

***State variables and attributes*:** Tables 1a and 1b describe the main model parameters, state variables and attributes. Fig. 2 provides an overview of the model structure in the form of a unified modelling

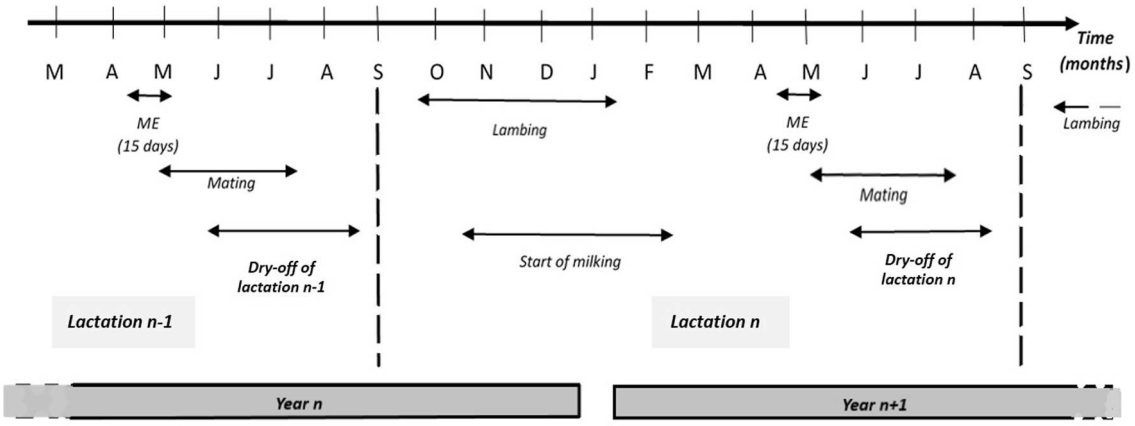

Fig. 1. Organisation of the main steps of reproduction and lactation management over one production season for off-season breeding with one lambing per year. ME: male effect.

Table 1a
Main parameters, attributes and state variables of the REPROsheep model.

Parameters	Definition	Notation	Type	Units	Initial value/ range of values in the model	Source
Starting date of the simulation	–	–	Date	–	04/17/(n)	–
Ending date of the simulation	–	–	Date	–	08/16/(n + 1)	–
Ram introduction date for male effect	Date on which the farmer introduces rams into the flock and leaves them for 15 days (without the possibility to mate) in order to stimulate the ovarian cycle of ewes	–	Date		04/17/(n)	*Experimental data of* Debus et al.(2021)
Probability to be in seasonal oestrus[1]	Probability that the ewe is in a period of heat and will accept mating	Pso	Float[2]	%	80	*Adapted from* Chemineau et al. (1992)
Minimum milk yield accepted at milking	Daily milk production value below which the farmer decides to dry up the ewe	MMYA	Float	L/ day	0.8	*Expert criteria*
Probability of abortion	Probability for a pregnant ewe to lose the foetus(es) before term	Pa	Float	%	2	
Probability of an easy lambing	Probability to lamb without complications preventing the milking or leading to a health problem	Pel	Float	%	96	
Probability for a successful mating	Probability for an ewe to become pregnant after mating	Pms	Float	%	50	
Rams introduction date for the mating of ewe lambs and adult latecomers	Date on which the farmer introduces rams to mate young ewes (<1 year old) and the adult ewes that did not get pregnant during the previous mating period	–	Date		07/15/(n)	
Dry-off date	Limit date set by the farmer to dry-off all ewes of the flock that are still milking	–	Date		08/15/(n + 1)	
Selected free mating duration	Period set by the farmer during which rams can mate freely with ewes	–	Integer[3]	days	60	
Selected culling age	Age after which a ewe is considered by the farmer for culling	–	Integer	years	5	
Theoretical litter size	–	Tls	Integer	–	1	
Probability for the ewe to expect a twin litter	–	P_{TL}	Float	%	40	
Age of ram	–	–	Integer	years	3	
Suckling length	From lambing to weaning. Period of time where the ewes suckle the newborns	SL	Integer	days	28	*Database from a previous research project (*IDELE, 2014*)*
Selected turnover rate	Percentage of ewes to be renewed each year to keep a constant flock population	–	Float	%	28	

[1] Oestrus = period during which a female will allow mating; 2: Float = values that have potential decimal places; 3: Integer = whole numbers.

language (UML) class diagram.

Temporal scale: For the development of the REPROsheep model, the time step chosen was half a day (i.e., 12 h). The model simulated a breeding period followed by its milk production period, which corresponds to approximately 16 months (i.e., a total of 972 time steps in the model).

2.1.4. Process scheduling

A simulation started with the introduction of the rams for the ME in the spring of year 'n' and ended the day after the last day of the milking period in the summer of year 'n + 1'. The main processes represented in the model therefore took place during this period, called the 'production campaign', and the different agents represented could be involved in one or more of these processes (Table 2).

2.1.5. Design concepts

The model is considered dynamic and stochastic. Indeed, several processes responding to probability laws ruled the modelled reproduction mechanism: cyclicity and response to the male effect of the ewes (Section 2.1.7.SM2). Mating, abortion, lambing without any complications, having a twin litter and being in seasonal anoestrus at time t are events that were also estimated using probabilities set at the beginning of the simulation (Table 1a and 1b) and based on accumulated expert knowledge and technical criteria from previous projects.

Table 1b
Attributes and state variables of the REPROsheep model.

Attributes and state variables	Definition	Notation	Type	Units	Initial value/ range of values in the model	Source
Initial daily milk yield (for ewes > 1 year old)[1]	Daily milk production of an adult ewe on first day of milking after the suckling period	$IDMY_e$	Float	L	1–5	*Experimental data of* Debus et al. (2021)
Initial daily milk yield (for ewe-lambs < 1 year old)[2]	Daily milk production of a young ewe (<1 year) on first day of milking after the suckling period	$IDMY_{el}$	Float	L	1–5	*Database from a previous research project (*IDELE, 2014*)*
Third daily milk yield monitoring (of previous lactation)	Third milk yield monitoring, made on 4/11/n (during ewe's previous lactation). Usually, there is monitoring of an ewe's milk yield every 1 to 2 months during the milking period of the flock	TDMY	Float	mL	0–1640	*Experimental data of* Debus et al. (2021)
Last total milk yield	Total milk yield produced during the last lactation of the ewe	LTMY	Float	L	0–390	
Age of the ewe	–	Age	Integer	years	0–7	
Pre-mating body condition score	Score of 0 to 5, based on the level of muscling and fat deposition around the ewe's loin region (Russel et al., 1969). Here, the score is assessed one week prior to ram introduction for male effect.	BCS	Float	–	1.75–3.5	
Lactation number	Number of lactations performed by the ewe since the beginning of its productive life	$Lact_{num}$	Integer	–	1–8	
Lambing to male effect interval	Days between last lambing date and the date of rams introduction for male effect	LMEI	Integer	days	0–211	
Pregnancy length	–	PL	Integer	days	145–155	
Anoestrus	Ewe is at sexual rest and no oestrus behaviour (mating acceptance or heats) is observed	–	Boolean[3]	–	True	–
Cyclic before male effect	Ewe in oestrus before rams arrivals into the flock	CBME	Boolean	–	False	–
Responding to male effect	Ewes that were not cyclic before male effect and started to enter oestrus thanks to the 15 days of male effect	RME	Boolean	–	False	–
Show first oestrus	First ewe's oestrus after an anoestrus period	–	Boolean	–	False	–
In oestrus	–	–	Boolean	–	False	–
Pregnant	–	–	Boolean	–	False	–
Abortion	–	–	Boolean	–	False	–
Lambing	–	–	Boolean	–	False	–
Lactating	–	–	Boolean	–	False	–
Mating	–	–	Boolean	–	False	–

[1] Set randomly by a normal distribution, bound between 1 and 5, whose mean = 2.5 and standard deviation = 0.9 (from corresponding source).
[2] Set randomly by a normal distribution, bound between 1 and 5, whose mean = 1.9 and standard deviation = 0.9 (from corresponding source); 3: Boolean = can only be equal to yes or no.

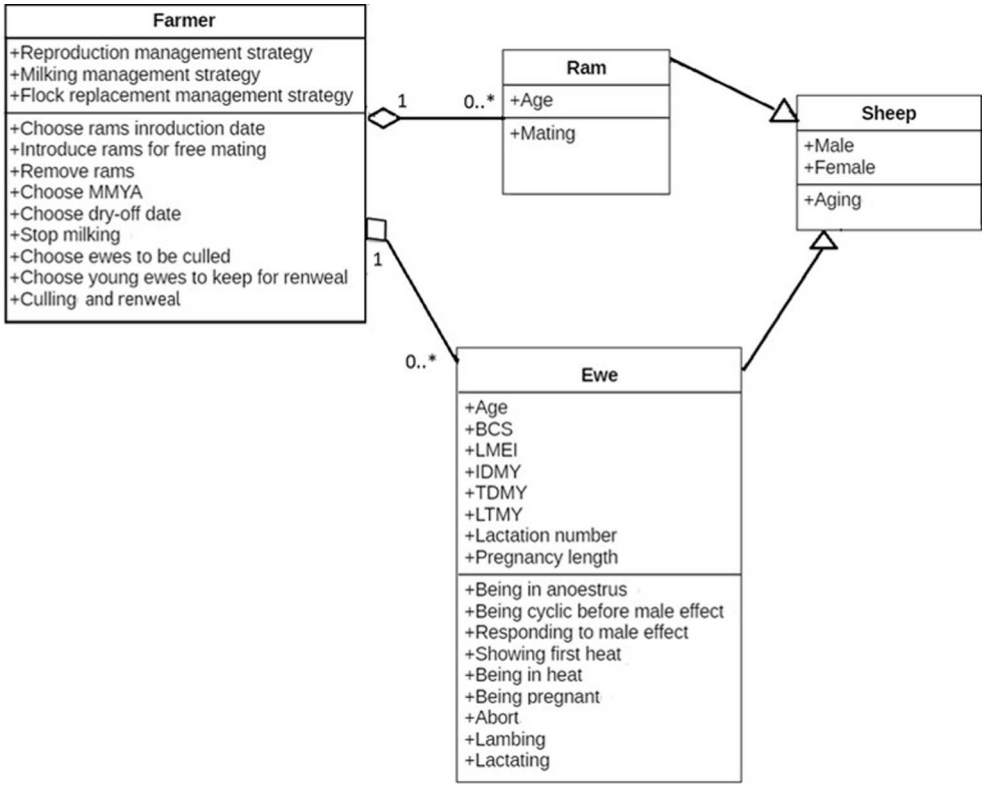

Fig. 2. Class diagram of entities in the REPROsheep model. Each block represents the model entities. The first portion of each block is the entity name, the second portion contains entity attributes and the third portion contains entities' principal actions.

Table 2
Main processes considered in the REPROsheep model.

Process	Agents implicated	Corresponding period	Sub-models
Reproduction management	Farmer	Mid-April (n) to mid-January (n + 1)	SM1
Reproduction activity	Ewes and Rams	Mid-April (n) to mid-January (n + 1)	SM2
Lactation	Ewes	October (n) to August (n + 1)	SM3
Milking management	Farmer	October (n) to August (n + 1)	SM4
Flock replacement management	Farmer	March (n + 1)	SM5

2.1.6. Initialisation

All simulations were initialised from the databases available in the literature and from the characteristics of the experimental flock monitored by Debus et al. (2021). To complete a full production campaign, each simulation started arbitrarily on April 17 of year 'n' (date of the ME) and ended on August 16 of year 'n + 1' (day after the end of milking arbitrarily set at August 15 of year 'n + 1'). The flock was initially composed of 51 Lacaune ewe lambs and 256 Lacaune ewes (i.e., 307 breeding reproductive females), for each of which we have pre-mating BCS, age, $Lact_{num}$, LMEI, TDMY and LTMY values for the year 'n'. (Table 1). The established ram:ewe ratio was 1 ram per 25 ewes (i.e., 12 rams in our case) so that the number of rams was sufficient for achieving the expected effective mating. The other main attributes and parameters of the model were fixed, and their initial values are provided in Tables 1a and 1b.

2.1.7. Submodels

The following paragraphs describe the different processes and actions represented in the model, as well as the modalities of the agents' action for each step:

Reproduction management: SM1

The main reproduction management actions or decision making executed by the farmer were as follows:

- *Choosing the date of ram introduction to achieve the ME:* The date of introduction of the rams for the ME was set arbitrarily by the farmer during the spring as it is commonly admitted in the Roquefort region that the Lacaune breed is not a strongly seasonal breed and therefore responds quite well to a ME in the spring. Once the rams were introduced in the flock, the male effect was considered to start on that date.
  All ewes were put to the ram as the modelled flock corresponds to a classic flock of the Roquefort basin area managed in such a way that the BCS pre-mating is acceptable for mating (i.e., BCS > 1.5; see range of values in Table 1b).
- *Introducing rams for free mating:* For adult ewes, the date of introduction of the rams for free mating was set by the farmer, each year, to be 15 days after the ME. For ewe lambs, by contrast, the date was arbitrarily chosen by the farmer to be close to the beginning of the natural sexual season (mid-summer). When this date was reached, the rams became active for mating.
- *Removing the free mating rams:* The duration of free mating was arbitrarily set by the farmer, and once ended, the rams were considered no longer active (without the possibility to mate with females).

Reproduction activity: SM2

The individual biological processes of reproduction correspond to a succession of transitions from one physiological stage to another over time. Such transitions are determined both by the technical management operations and decision making of the farmer (Fig. 1) and by other random events, including the particular individual features of the ewes. Debus et al. (2021) identified significant impacts of age, BCS pre-mating, milk yield observed in the previous lactation, and the last lambing date on the probability of being cyclic before the ME (i.e., in oestrus even before the rams are introduced) and on the quality of the response to the ME. These two events become critical during the off-season reproduction process when using the ME practice. Thus, they determined whether the transition from a seasonal anoestrus to an oestrus state, with oestrus appearance, should be expected (Fig. 3) and then followed by ovulations every 17 days (i.e., the length of a normal cycle in ewes) until fertilisation (Thimonier et al., 2000). Based on that, some probability equations were then considered for the events "Being cyclic before ME" (P_{CBME}) and "Responding to ME" (P_{RME}) (Table 3a). Ewe lambs started their mating season in mid-summer (close to the beginning of their natural breeding season) and started to be in oestrus spontaneously according to the probability of being in seasonal oestrus in mid-summer (Pso; Table 1a). Likewise, adult ewes that were not cyclic before ME and also did not respond to ME were mated again in mid-summer and subjected to Pso.

Once the ewe (ewe lamb or adult) was in oestrus, it was mated according to the farmer's strategy. Mated ewes were considered to be in the pregnancy stage based on the probability of success at mating (Pms). Once the pregnancy had started, a threshold of probability for abortion was considered (Pa), with two categories according to the timing of occurrence (i.e., early or late if the abortion occurs before or after the 45th day of pregnancy, respectively). In the 'early' cases, the ewe had the opportunity to return to oestrus, but if it was 'late', the ewe was not allowed to go back into oestrus and was separated from the breeding flock. At the end of pregnancy, without an abortion event, a probability to do an easy lambing (Pel), determined if the ewe was going to give birth or not. If the ewe was set to give birth normally, single or multiple litters were lambed, depending on the probability of lambing twins (P_{TL}). If the ewe turned out to have a difficult lambing, it was considered dead and no lambing took place.

Lactation: SM3

Lambing was followed by a 28-day suckling period (SL). At the end of this suckling period, lambs were weaned, and the ewe started to be milked. Individual milk yield during milking was calculated from an equation developed by Lagriffoul et al. (2003) for the Lacaune breed (Table 3b). This equation took into account the individual daily milk yield at the start of milking (IDMY) and the number of milking days, which was the difference in the number of days between the dry-off date and the start of milking date. IDMY values for each individual were randomly set using a normal distribution bound between 1 and 5 (i.e., the classic range of values for the milk production of a ewe in one day), whose mean and standard deviation were taken from previous research projects (Table 1b) and differed for adult ewes and ewe lambs. These mean and standard deviation values were considered to include differences in daily milk yield due to litter size and age.

Once started, milking ended either when the minimum acceptable daily milk yield set by the farmer was reached or upon the date defined by the farmer to end milk delivery (MMYA).

Milking management: SM4

A date for the end of milking was defined by the farmer. On this date, even if some ewes had not yet reached the minimum accepted production (MMYA), milking was stopped automatically, and the ewes were dried off.

Flock replacement management: SM5

For flock replacement, the main management decisions made by the farmer were as follows:

- *Culling ewes:* Once a year (on March 1st in this model), the farmer set a replacement rate and calculated the number of ewes to be culled, looking for a balance between the number of newborns and departures (so that the size of the flock remained more or less constant).

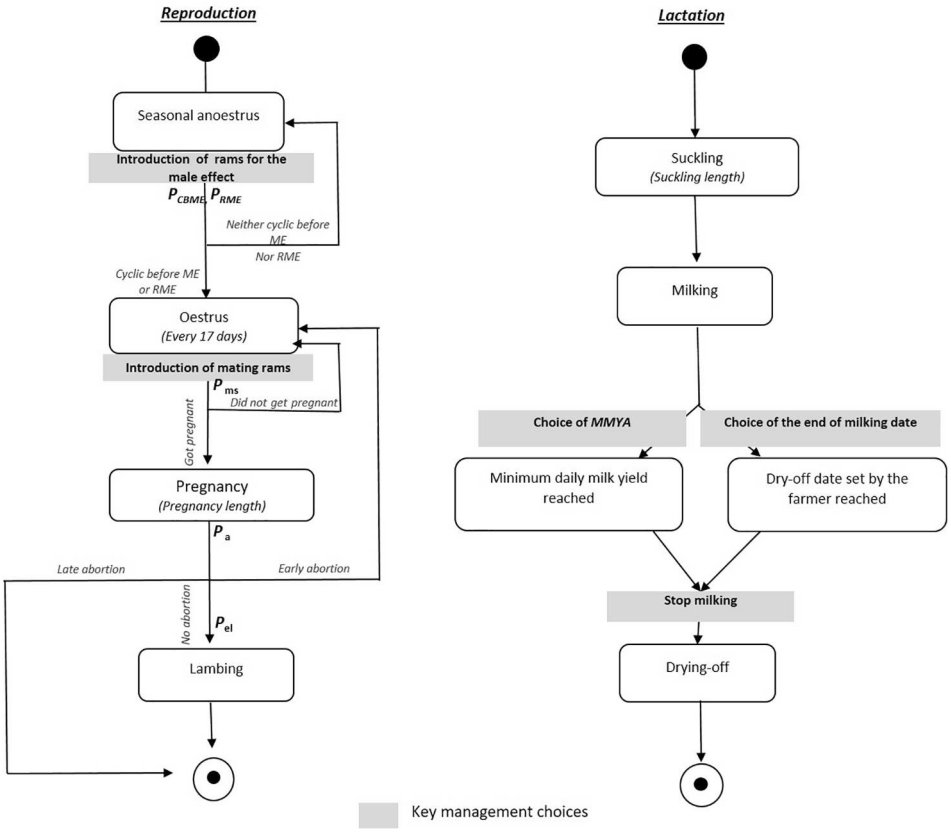

Fig. 3. The individual ewe reproduction and lactation phases were determined according to the sequence of physiological and/or biotechnical steps, including farmer decision making. Reproduction starts with an ewe in seasonal anoestrus and ends at lambing. Lactation starts just after lambing and ends with dry-off and includes subsequent phases, suckling (from lambing to weaning, for lamb rearing) and milking (from weaning to dry-off, for milk production purposes, without lamb presence).

Table 3a
Equations used for modelling individual reproductive processes.

Predictive equations[1]
Cyclicity before male effect (CBME):
$P_{CBME/BCS\leq 2} = exp(0.103*Age + 0.008*LMEI + 0.007*LTMY - 0.002*TDMY - 2.732)/(1 + exp(0.103*Age + 0.008*LMEI + 0.007*LTMY - 0.002*TDMY - 2.732))$
$P_{CBME/BCS\in]2-3]} = exp(0.592 + 0.103*Age + 0.008*LMEI + 0.007*LTMY - 0.002*TDMY - 2.732)/(1 + exp(0.592 + 0.103*Age + 0.008*LMEI + 0.007*LTMY - 0.002*TDMY - 2.732))$
$P_{CBME/BCS>3} = exp(1.212 + 0.103*Age + 0.008*LMEI + 0.007*LTMY - 0.002*TDMY - 2.732)/(1 + exp(1.212 + 0.103*Age + 0.008*LMEI + 0.007*LTMY - 0.002*TDMY - 2.732))$
Response to male effect (REM):
$P_{RME/BCS\leq 2} = exp(0.276*Age + 0.011*LTMY - 0.002*TDMY - 1.964)/(1 + exp(0.276*Age + 0.011*LTMY - 0.002*TDMY - 1.964))$
$P_{RME/BCS\in]2-3]} = exp(1.745 + 0.276*Age + 0.011*LTMY - 0.002*TDMY - 1.964)/(1+exp(1.745 + 0.276*Age + 0.011*LTMY - 0.002*TDMY - 1.964))$
$P_{RME/BCS>3} = exp(2.871 + 0.276*Age + 0.011*LTMY - 0.002*TDMY - 1.964)/(1+exp(2.871 + 0.276*Age + 0.011*LTMY - 0.002*TDMY - 1.964))$

[1] These logistic regression equations were developed from the experimental data set of Debus et al. (2021) to formalise the link between being cyclic before the male effect and the age, LTMY, TDMY and LMEI of each ewe and the link between responding to the male effect and the age, LTMY and TDMY of each ewe. BCS = pre-mating body condition score; LTMY = Last total milk yield; TDMY = Third daily milk yield; LMEI = Lambing to male effect interval; PCBME/BCS: Probability for an ewe to be cyclic before the male effect, as a function of its pre-mating BCS; PRME/BCS: Probability for an ewe to respond to the male effect, as a function of its pre-mating BCS.

Table 3b
Equations used for modelling individual lactation process.

Equations for calculating individual daily milk yield (L/day)[1]**:**
If ewe ($Lact_{num} \geq 1$) :
Daily milk yield = $IDMYe*exp(-[0.0028 + 0.0049*ln(IDMYe)]$ * *Number of milking days*
If ewe lamb ($Lact_{num} \leq 1$) :
Daily milk yield = $IDMYel*exp(-[0.0021 + 0.0052*ln(IDMYel)]$ * *Number of milking days*

IDMY = Initial daily milk yield.

[1] The coefficients of these daily milk yield equations come from the work of Lagriffoul et al. (2003).

Thus, the number of ewes culled was equal to the number of ewes × yearly replacement rate.

The ewes to be culled were chosen based on age (i.e., the oldest above the culling age set by the farmer) and those presenting difficulties at lambing. Old ewes to be culled were set to die on the day after the end of milking day and ewes presenting difficulties at lambing died at their lambing time.

- *Choosing ewe lambs for replacement:* At the same time, once a year (March 1st in this model), the farmer selected from all newborn females (<one year old) a percentage to be used to replace the culled ewes. The number of newborns to be retained to join the main flock was equal to the number of culled ewes.
- *Selling ewe lambs:* Once a year (on March 2nd in this model), ewe lambs that had not been chosen for replacement were sold.

For modelling purposes, farmer management practices have been deliberately simplified, and ewe lambs for replacement were selected randomly, considering that only one breeding campaign was simulated. However, it must be noted that in practice, there are other selection criteria, such as genetic index, health status or date of birth, that determine the number of ewes to be culled or retained.

2.2. Model outputs

At the end of each simulation, two dynamic outputs were observed: the distribution of the number of ewes lambing per week and the milk yield per week (in number of litres produced by all ewes at milking), as well as two punctual outputs: the total number of ewes lambing and the total milk yield of the flock, at the end of the campaign.

2.3. Stochasticity and choice of the number of repetitions for model analysis

As the REPROsheep model incorporated several stochastic processes, it was necessary to perform several replications for a given simulation. To determine the number of repetitions required for model validation and sensitivity analysis, an independent experiment was performed. The aim was to analyse the impact of the randomness of the simulations on the model outputs and find a threshold value of repetitions beyond which an increase in the number of repetitions would not imply a significant marginal decrease in the difference between the outputs. This exploration was carried out on the initial model described above (Section 2.1). Thus, the weekly number of ewes lambing, the weekly milk yield of the flock, the total number of ewes lambing and the total milk yield of the flock between the repetitions of a given simulation were compared. 150 replications of this simulation were performed and the variability between the outputs for 25, 50, 75, 100, 125 and 150 replications were compared.

Fig. 4, presents the median value by number of replicates over time for the outputs: weekly number of ewes lambing and weekly milk production of the flock. The results suggested that the increase in the number of repetitions beyond 25 did not have a significant impact on the overall trend of the weekly number of ewes lambing and weekly milk yield of the flock. Fig. 5A shows the box plots by number of repetitions of our two punctual outputs: total number of ewes lambing and total milk yield of the flock. From 75 repetitions, the median value of the total number of ewes lambing stabilised at approximately 267 ewes, and the median value of the total milk yield of the flock stabilised at approximately 60,500 L. It also appeared that beyond 75 repetitions, there were more “extreme” values, especially for total milk yield. Indeed, at 100 and 150 replicates, two total milk yield values were observed below 56,000 L. Moreover, Fig. 5B shows that from 75 repetitions, the standard deviation (sd) and thus the variance between the results of the repetitions for these two outputs seemed to be stable.

It was therefore decided to set the number of simulation repetitions required at 75 to minimise the calculation time required while trying to maintain realistic statistical properties, especially the appearance of extreme results.

2.4. Model validation

The model was validated using data from two commercial farms of

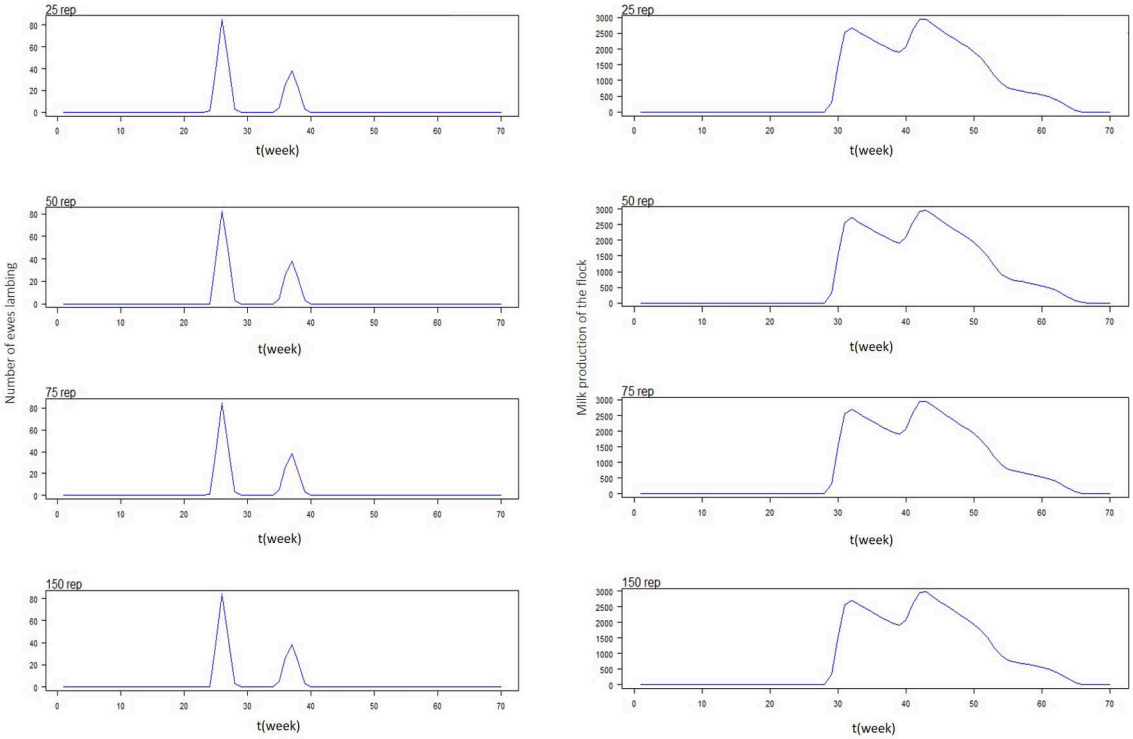

Fig. 4. Median of the number of ewes lambing and the milk production of the flock, per week, for 25, 50, 75 and 150 different repetitions.

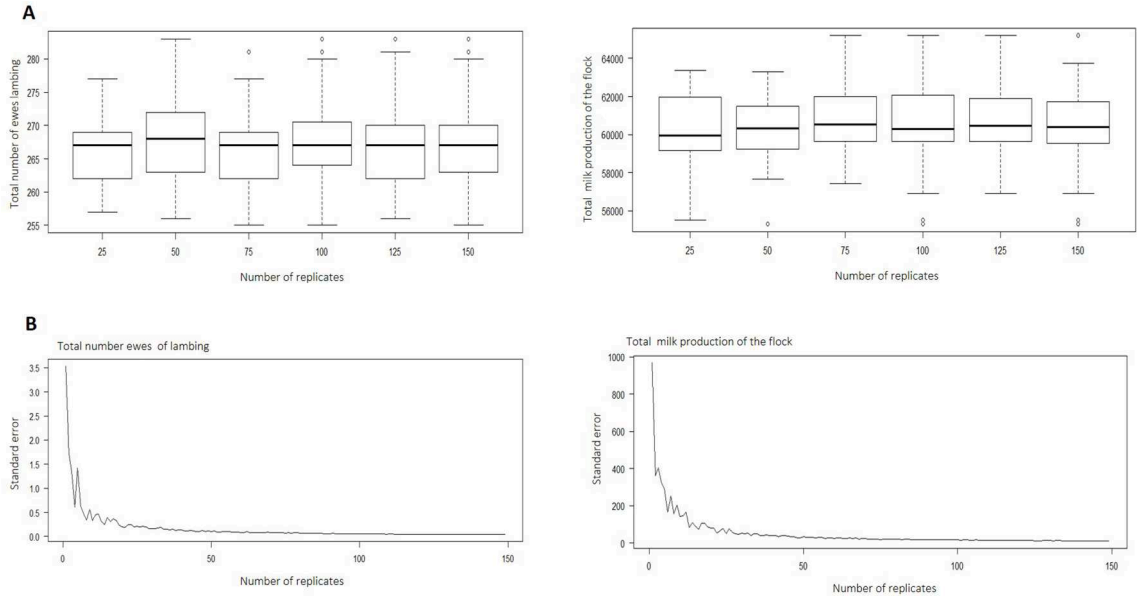

Fig. 5. (A) Box plot of the total number of ewes lambing and the total milk production of the flock per number of repetitions. (B) Standard error of the total number of ewes lambing and the total milk production of the flock per number of repetitions.

the Roquefort area. These data were extracted from the SIOEL database, which is an information system implemented for dairy sheep in France, to manage genetic and techno-economic data (Astruc et al., 2008). Both commercial farms managed reproduction without hormones, with a first mating in April (i.e., off-season). Adjustments to the model parameters were made to match the flock management specificities of each farm. Each simulation was repeated 75 times to take into account the model stochasticity (Section 2.3). The total number of ewes lambing and the total milk yield of the commercial farms were then compared with the simulated ones by calculating prediction errors. The correlations between the mean values of dynamic simulated outputs (weekly number of ewes lambing and monthly milk yield) and the same observed performances in the commercial farms were also calculated.

2.5. Sensitivity analysis

A sensitivity analysis was performed to identify the parameters that most contributed to the variability of the outputs. This analysis, similar to the one performed by Lurette et al. (2009), followed the methodology developed by Lamboni et al. (2009) that allows to analyse time series outputs by combining principal component analysis and analysis of variance. Sensitivity indices were then proposed to synthesise the influence of each parameter on the whole time series output.

All analyses were performed using R 3.6.2 software (R Core Team, 2019). The Multisensi package (Bidot et al., 2018) was used to analyse the dynamic outputs, and ANOVA was performed on the mentioned punctual outputs.

2.5.1. Experimental design for sensitivity analysis

The model presented 12 input parameters and variables that could influence the output results. To study the sensitivity of the simulation outputs to these different parameters and variables, a factorial design, in which each of the input parameters (called factors) had two levels of extreme values, was built (Table 4). For each factor, the range of values chosen was set arbitrarily between a low and a high value, regardless of what can be observed in the field, the aim being to analyse the sensitivity of the simulation tool to its input parameters.

A complete factorial design for 12 factors at 2 levels each corresponds to $2^{12} = 4096$ possible combinations of these factors. To reduce the number of combinations to be studied, a fractional factorial design of resolution IV using the FrFr2 function of R software (Grömping, 2014) was carried out. This IV resolution made it possible to estimate the main effects and the two-by-two interactions of factors, assuming that the higher-order interactions were negligible. Thus, a fractional factorial design composed of 32 combinations of our study factors was established. Seventy-five repetitions of each were needed to take into account the stochasticity of the model. Therefore, our sensitivity analysis was performed on the results of $32 \times 75 = 2400$ simulations.

Table 4
Input parameters and values for the model sensitivity analysis.

Input parameters and variables	Unit	Level	
		Low value	High value
BCS (mean)	–	1.5	3.5
Age (mean)	–	2	4
TDMY (mean)	ml	500	1000
IDMYe (mean)	L	2.3	2.8
IDMYel (mean)	L	1.7	2.2
LTMY (mean)	L	100.0	300.0
LMEI (mean)	days	90	180
Pa	%	1	3
Pel	%	92	100
Pms	%	40	60
Pso	%	70	90
MMYA	L	0.6	1.0

BCS = pre-mating body condition score; IDMYe = Initial daily milk yield (for ewes > 1 year old); IDMYel = Initial daily milk yield (for ewe-lambs < 1 year old); LTMY = Last total milk yield; LMEI = Lambing to male effect interval; MMYA = Minimum milk yield accepted at milking; TDMY = Third daily milk yield; Pel = Probability of an easy lambing; Pso = Probability to be in seasonal oestrus; Pa = Probability of abortion; Pms = Probability for a successful lambing

2.5.2. Analysis of punctual outputs

Two ANOVAs were performed on the results of the 2400 simulations to compare the influence of the 12 factors on each punctual output (total number of ewes lambing and total milk yield of the flock). A factor was considered significant when the p-value <5%. Then the contribution of the factors to the variability of each output was quantified by calculating the ratio between the sum of squares of each significant factor (including interactions) and the total sum of squares for all of the factors studied.

2.5.3. Analysis of dynamic outputs

Following the method proposed by Lamboni et al. (2009), it was first considered that dynamic outputs can be represented as tables built of N rows and p columns, where $N = 2400$ (number of simulations) and $p = 70$ (number of successive time points, i.e., the number of weeks during which the dynamic output was observed). A principal component analysis (PCA) with N individuals and p variables was then performed to provide linear combinations (also called components) of the initial p variables explaining the maximum inertia (i.e., variability) between the simulation outputs. Only the first three principal components (PCs) were retained, as they were sufficient to cover most of the variability observed between simulations. The PCA provided a score on each component for each simulation (i.e., for each row on tables). A final step consisted of an ANOVA, including the main and the two-factor interaction effects on the simulation scores, for each of the components considered. Sensitivity indices (SI), corresponding to the main effect or interactions, were then calculated for each factor and for each component. An effect was considered significant when SI > 5%.

2.6. Virtual experiment: Impact of flock composition

Once the validity and sensitivity of the model were studied, different flock composition scenarios were tested using the simulator. The impact of the flock distribution of ages (Age), pre-mating BCS and total milk yields from previous lactation (LTMY), which are the three main factors that impact the probabilities of being cyclical off-season and responding to the male effect (Debus et al., 2021), was studied. These are also factors that can vary greatly from one farm to another, with potential farmer intervention to modify them. To study the impact of these three parameters and their distribution on model outputs, a virtual experiment including the analysis of five flock management scenarios was carried out. To take into account the stochasticity of the model, each scenario was simulated 75 times. Table 5 presents the tested scenarios. The reference scenario (*Ref*) corresponds to the composition of the flock during one of the years of the Debus et al. (2021) monitoring study. Since BCS is an intrinsic trait of the ewe that the farmer can influence (e.g., by adapting feeding strategy), the effect of a variation in the flock's distribution with regard to the ewes' pre-mating BCS, compared to the reference scenario (i.e., *BCS−* and *BCS+* scenarios), was first studied. Then, two extreme theoretical scenarios, for which the three parameters pre-mating BCS, Age and LTMY evolve in the same way and at the same time (*All−* and *All+* scenarios), were studied. It was decided to test scenarios where the mean values of these parameters distributions only evolve by 0.5 units (for age and BCS) or 50 L (for milk yield); these evolutions being considered as theoretically plausible by the experts of the French dairy sheep production, assuming some efforts on feed management in particular.

Table 5
Description of the flock scenarios.

Scenario	Description	BCS		Age (Years)		LTMY* (L)	
		Mean	sd	Mean	sd	Mean	sd
Ref	*Ref*erence scenario	2.5	0.3	2.5	1.9	195	65.8
BCS−	Mean BCS lower than *Ref* scenario's	2	0.3	2.5	1.9	195	65.8
BCS+	Mean BCS higher than *Ref* scenario's	3	0.3	2.5	1.9	195	65.8
All−	Mean BCS, mean Age and mean LTMY lower than *Ref* scenario's	2	0.3	2	1.9	145	65.8
All+	Mean BCS, mean Age and mean LTMY higher than *Ref* scenario's	3	0.3	3	1.9	245	65.8

BCS = pre-mating body condition score; LTMY = Last total milk yield; sd = standard deviation

* Mean and sd of LTMY values distribution for adult ewes only (i.e., ewes that have already produced milk before).

For each scenario that differs from the reference scenario, the individual values of BCS for all ewes and LTMY of adult ewes (i.e., that have already produced milk before) were obtained by randomly sampling a normal distribution whose mean was set according to the scenario (Table 5) and standard deviation was equal to the reference scenario's. For ewe lambs, LTMY was specifically set to zero. The age of each ewe was obtained by randomly sampling a Poisson distribution whose mean was set according to the scenario (Table 5).

As the focus was only on the impact of individual ewe characteristics on the number of ewes lambing and milk yield of the flock, the management of reproduction by the farmer and the size of the flock were the same for all five scenarios.

2.7. Statistical analyses of scenario results

Scenario results were expressed as the means of simulation repetitions.

2.7.1. Total number of ewes lambing and total milk yield of the flock

Two one-factor ANOVAs were performed to study (i) the scenario effect on the total number of ewes lambing and (ii) on the total milk yield of the flock. The lambing rate (total number of ewes lambing in relation to the number of females put to reproduction) for each scenario was also calculated for the modelled campaign.

2.7.2. Number of ewes lambing per week

The modelled management strategy induced two periods of lambing corresponding to lambing from a spring breeding campaign with synchronisation of oestrus using ME and to lambing from seasonal breeding (including lambing of ewe lambs). To simplify the study of the scenarios, two lambing periods over the entire reproduction campaign were defined, and the weekly number of ewes lambing in each period was added to compare simulation results for each of these two periods. The first lambing period, named P1, corresponding to the days between the 24th and 28th weeks of simulation (i.e., between September 25th and October 23th) of year 'n'. The second lambing period, named P2, corresponding to the days between the 35th and 39th weeks of simulation (i.e., between December 11th of year 'n' and January 8th of year 'n + 1').

A one-factor ANOVA was then carried out for each period to evaluate the scenario effects on the number of ewes lambing over a given period (P1 or P2). The proportion of the total number of ewes lambing (in %) over each period (P1 and P2) was also calculated.

2.7.3. Weekly milk yield of the flock

Individual daily milk yield was modelled by a decreasing exponential function (Lagriffoul et al., 2003), with the highest values obtained at the beginning of lactation. The modelled management strategy therefore assumed two milk yield peaks for the flock: a first one linked to the individual milk yield of ewes that lambed during period P1 and a second one linked to those ewes that lambed during P2. A single-factor ANOVA was thus performed for each flock milk yield peak to evaluate the scenario effects on the flock milk yield at each of these peaks.

3. Results

3.1. Model validation

The model slightly underestimated the total number of ewes lambing as well as the total milk yield, for each of the two farms, with an average prediction error, across the two farms, of −5.5% for each of those two outputs. For the dynamic outputs (weekly number of ewes lambing and monthly milk yield), depending on the farm and on the week observed, the model either overestimated or underestimated the outputs values

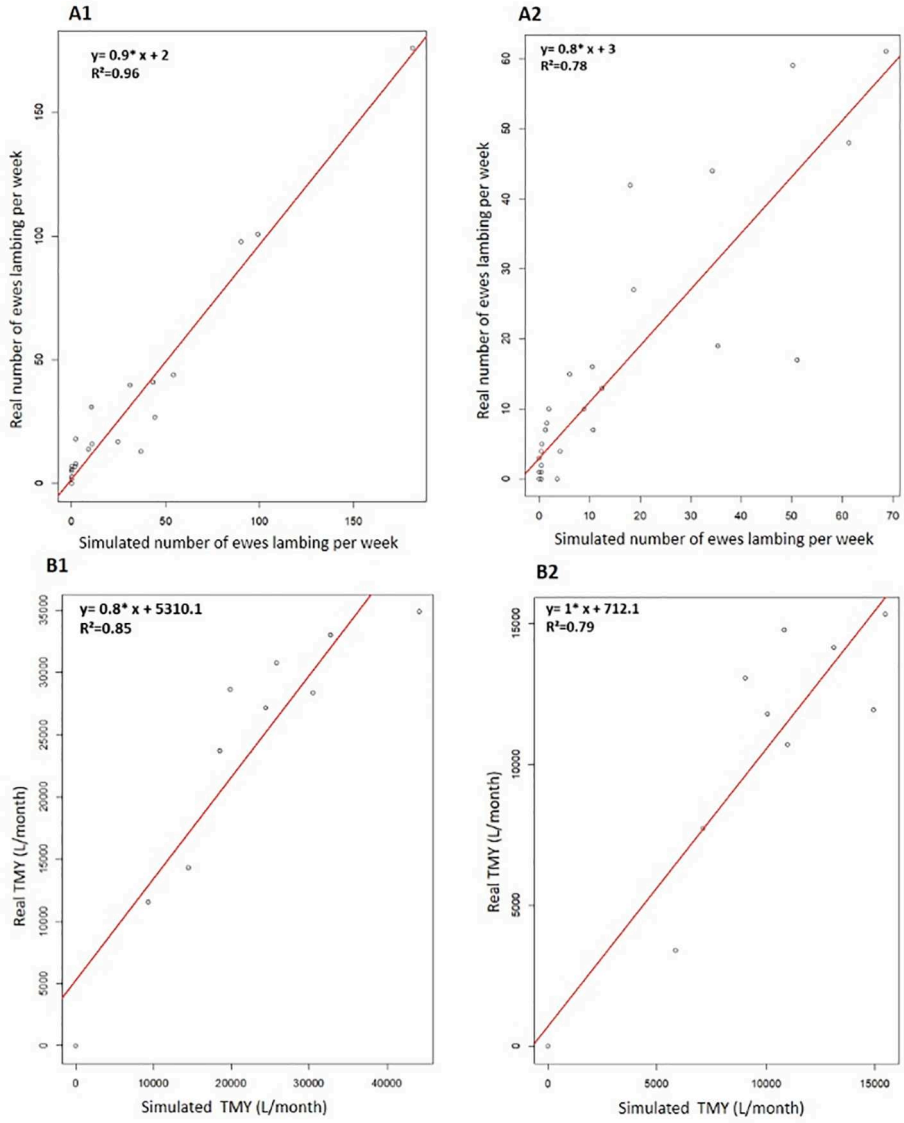

Fig. 6. Means (n = 75) of simulated (A) number of ewes lambing per week and (B) total milk yield (TMY) per month compared to observed values on each farm (1 and 2).

(Fig. 6). However, overall, high correlations, (from 0.78 to 0.96, Fig. 6) between the mean values of each dynamic simulated outputs and their corresponding observed values, were found for each of the two farms of the SIOEL database.

3.2. Sensitivity analyses

3.2.1. Influence of factors on the total number of ewes lambing and on the total milk yield for one production campaign

Table 6 presents the overall contributions of the 12 factors studied to the sensitivity of the outputs "total number of ewes lambing" and "total milk yield of the flock".

The sensitivity of the output "total number of ewes lambing" was related, by more than half, to the Pel. The factors Pso and LTMY also contributed, together, to more than 25% of the overall sensitivity. The age of the ewes and their pre-mating BCS also had a small influence on the "total number of ewes lambing" output, with a contribution of less than 10%. For the output "total milk yield of the flock", MMYA was the factor with the highest contribution, more than twice that of ewes' IDMYe (23%).

3.2.2. Influence of factors on the number of ewes lambing per week

For the number of ewes lambing per week, 80.1% inertia was obtained for the first main component (PC1; Fig. 7A). This means that this component alone explained the most important part of the variability observed between the 2400 simulations for this output. Therefore, only the result of this first component was detailed here.

The factors that contributed most to the variability in the number of ewes lambing events over time (SI > 5%) were, in decreasing order, LTMY, age, pre-mating BCS and TDMY, with total sensitivity indices (TSIs) of 43.3%, 22.3%, 18.7%, and 11.6%, respectively (Fig. 7B). The variability of the output depended almost identically on the main effect of these four factors and on their two-way interactions.

3.2.3. Influence of factors on the weekly milk yield of the flock

For the output "weekly milk yield of the flock", it was found that the first two main components (PC1 and PC2) had inertia values of 52.1% and 41.6%, respectively (Fig. 8A). Together, these two components had an inertia of 93.7% and explained most of the variability observed between the 2400 simulations for this output. Therefore, only the results of these two components was detailed below.

The most influential factors (SI > 5%) on the weekly flock milk yield

Table 6
Factor contributions to the sensitivity of the total number of ewes lambing and milk yield of the flock for one lactation.

Factors	Contribution to sensitivity (%)	
	Total number of ewes lambing	Total milk yield (L per flock)
BCS	5.72	0.97
Age	8.55	1.71
TDMY	2.66	0.79
LTMY	11.90	1.90
LMEI	0.06	0.24
Pel	55.48	8.97
Pso	14.50	2.41
Pa	1.07	0.18
Pms	0.02	ns
MMYA	0.03	60.08
IDMYe	ns	22.72
IDMYel	ns	0.01

ns = non-significant at p-value < 0.05; BCS = pre-mating body condition score; IDMYe = Initial daily milk yield (for ewes > 1 year old); IDMYel = Initial daily milk yield (for ewe-lambs < 1 year old); LTMY = Last total milk yield; LMEI = Lambing to male effect interval; MMYA = Minimum milk yield accepted at milking; TDMY = Third daily milk yield; Pel = Probability of an easy lambing; Pso = Probability to be in seasonal oestrus; Pa = Probability of abortion, Pms = Probability for a successful lambing.

for PC1 were LTMY, MMYA, Age, BCS and TDMY at their last lactation. Their two-way interactions contributed almost identically to the variability of this output.

The second main component (PC2) revealed the factors that reduced the difference between the two peaks of milk yield while at the same time revealing the presence of a small peak at the end of the milking period. PC2 essentially presented the effects of the MMYA (TSI = 52.6%) and IDMYe (TSI = 21.3%) factors (Fig. 8B).

3.3. Virtual experimentation (scenarios)

3.3.1. Total number of ewes lambing and total milk yield of the flock at the end of the production campaign, according to the scenarios

For the total number of ewes lambing as well as for the total milk yield of the flock, a significant effect ($p < 0.05$) of the simulated scenario was observed. Only the *BCS−* scenario did not differ from *Ref*. The number of ewes lambing for *BCS+* (277 ewes i.e., a 90% lambing rate) and *All+* (282 ewes, 92% lambing rate) were significantly higher than the number of ewes lambing obtained in *Ref* (273 ewes, 89% lambing rate) (Fig. 9A). On the other hand, the number of ewes lambing in *All−* (266 ewes, 87% lambing rate) was significantly lower than in *Ref* (Fig. 9A).

Similarly, for the total milk yield of the flock, a significant positive effect of the *BCS+* (+1172 L) and *All+* (+2309 L) scenarios, compared to *Ref,* was observed. In contrast, a significant negative effect of *All−* (−1214 L) was observed for this parameter. No significant effect was found with *BCS−* (Fig. 9B).

3.3.2. Number of ewes lambing per week according to the scenarios

The number of ewes lambing over time differed according to the scenarios (Fig. 10A). A significant effect ($p < 0.05$) of the scenarios on the average number of ewes lambing was observed for the two lambing periods P1 (weeks 24–28) and P2 (weeks 35–39). On both P1 and P2, the average number of ewes lambing in the *BCS+* (P1: 218; P2: 59), *All−* (P1: 162; P2: 103), and *All+* (P1: 243; P2: 39) scenarios were significantly different from *Ref* (P1: 200; P2: 72; Fig. 10B and 10C).

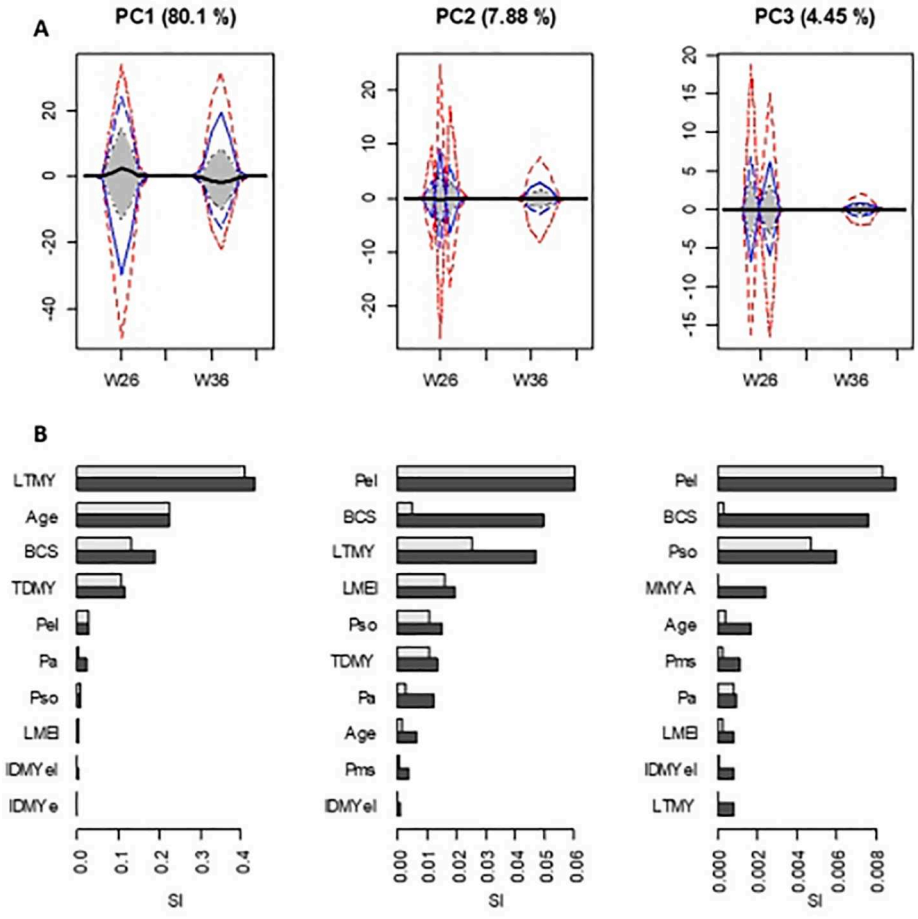

Fig. 7. Sensitivity analysis of the number of ewes lambing over time: results of ANOVA performed for the first three components (inertia: 80.1%, 7.9%, 4.5%). (A) Loadings defining the principal component for each time variable (in abscissa) and (B) total sensitivities for the 10 most influential factors ranked in descending order. Sensitivities are split into main effects (black) and two-way interactions (grey). BCS = pre-mating body condition score; IDMYe = Initial daily milk yield (for ewes >1 year old); IDMYel = Initial daily milk yield (for ewe-lambs <1 year old); LTMY = Last total milk yield; LMEI = Lambing to male effect interval; MMYA = Minimum milk yield accepted at milking; TDMY=Third daily milk yield; Pel = Probability of an easy lambing; Pso = Probability to be in seasonal oestrus; Pa = Probability of abortion; Pms = Probability for a successful lambing

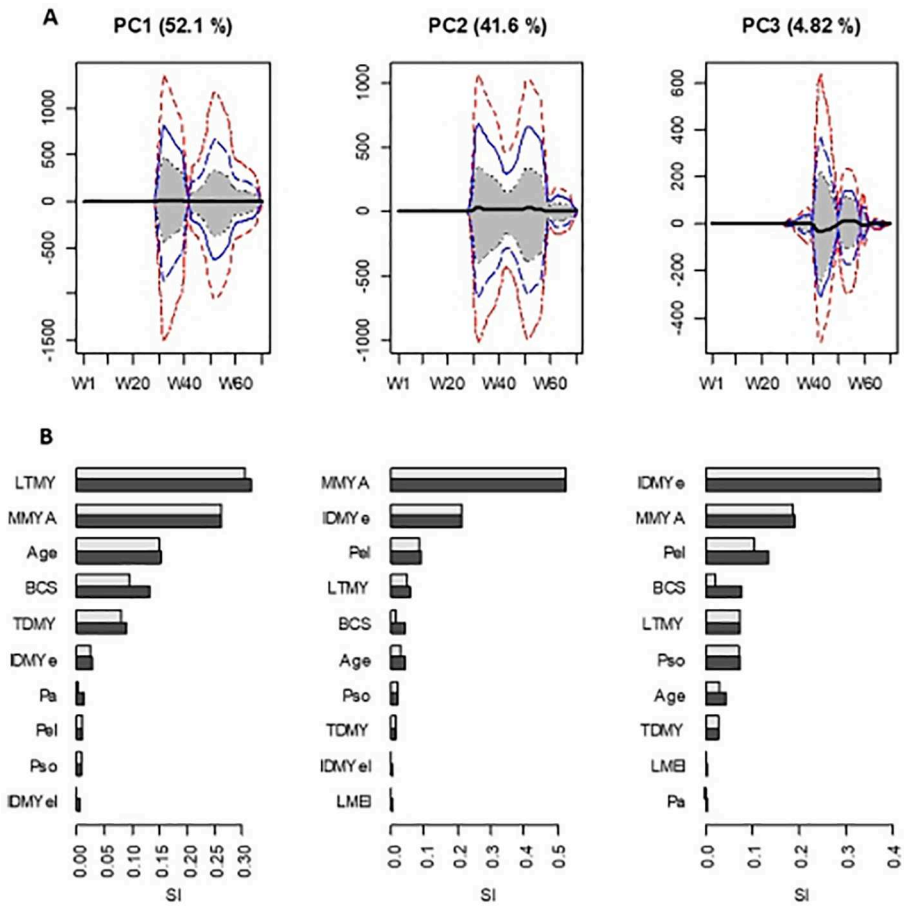

Fig. 8. Sensitivity analysis of flock milk production over time: results of ANOVA performed for the first three principal components (inertia: 52.1%, 41.6% and 4.8%). (A) Loadings defining the principal component for each time variable (in abscissa) and (B) total sensitivities for the 10 most influential factors ranked in descending order. Sensitivities are split into main effects (black) and two-way interactions (grey). BCS = pre-mating body condition score; IDMYe = Initial daily milk yield (for ewes >1 year old); IDMYel = Initial daily milk yield (for ewe-lambs <1 year old); LTMY = Last total milk yield; LMEI = Lambing to male effect interval; MMYA = Minimum milk yield accepted at milking; TDMY = Third daily milk yield; Pel = Probability of an easy lambing; Pso = Probability to be in seasonal oestrus; Pa=Probability of abortion; Pms = Probability for a successful lambing

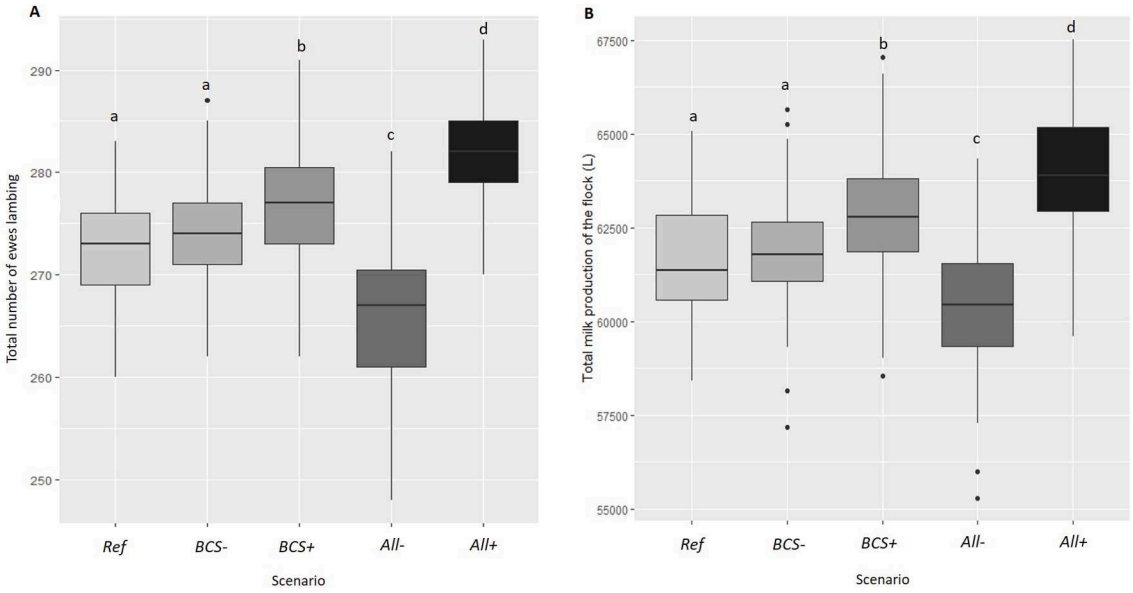

Fig. 9. (A) Boxplot of the number of ewes lambing; (B) Boxplot of the total milk production of the flock for a campaign full lactation period (n = 75 repetitions per scenario). Ref = Reference flock scenario; *BCS−*, *BCS+*, *All−*, *All+* = Alternative scenarios to Ref. a,b,c,d: Values with a separate letter differ at p-value <0.05.

Over the P1 period, a higher number of ewes lambing was observed in *BCS+* and *All+* than in *Ref* (79% and 86% of the total number of ewes lambing achieved, compared to 73% in *Ref*, respectively). As a result, the number of ewes lambing over the P2 period was lower in *BCS+* and *All+* (21% and 14% of the total number of ewes lambing) than in *Ref* (27% of the total number of ewes lambing). The *All−* scenario led to a lower number of ewes lambing compared to *Ref* in P1 (61% of the total number of ewes lambing versus 73%, respectively), which resulted in a higher number of ewes lambing than *Ref* in P2 (39% of the total number of ewes lambing versus 27%, respectively, for *All−* and *Ref*).

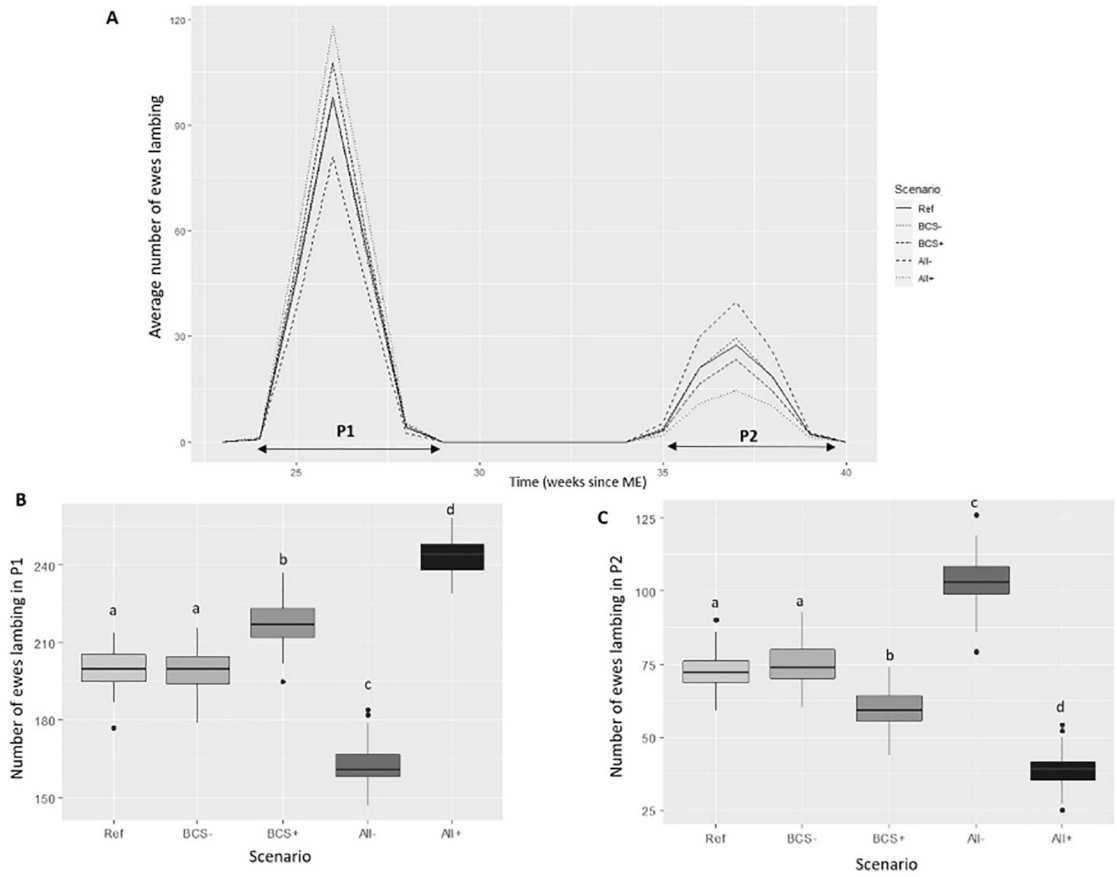

Fig. 10. (A) Average number of ewes lambing per week according to the flock scenarios (n = 75 repetitions per scenario) between the 24th and 39th weeks from the start of the simulation (in our case, the male effect date (ME)); P1 = first lambing period between weeks 24 and 28, P2 = second lambing period *(weeks 35–39). (B)* Boxplot of the number of ewes lambing during P1 for each scenario. (C) Boxplot of the number of ewes lambing during P2 for each scenario. Ref = Reference flock scenario; *BCS*−, *BCS*+, *All*−, *All*+ = Alternative scenarios to Ref. a, b, c, d: For each period, values with a separate letter differ at a p-value <0.05.

3.3.3. Weekly milk production of the flock according to the scenarios

Two peaks of milk production were seen (Fig. 11A): the first one at the 32nd week of simulation and the second at the 42nd week of simulation, i.e., 3 weeks after the end of each lambing period (P1 and P2). A significant effect ($p < 0.05$) of the scenarios on the overall flock milk yield at these 2 peaks was also observed.

For the first peak, the comparison of the scenarios highlighted a significant difference ($p < 0.05$) between *BCS*+, *All*−, *All*+ and *Ref* (Fig. 11B). Indeed, at the first peak of weekly milk yield, the ewe flock produced more in *BCS*+ and *All*+ than in *Ref* (+9% and + 22%, respectively, compared to *Ref* milk yield at peak 1). On the other hand, milk yield was lower in *All*− (−18%) than in *Ref*. At the second peak of weekly milk yield, only *All*− and *All*+ presented milk yields significantly different from *Ref* (Fig. 11C), which resulted in an additional 128 L of milk when adopting the *All*− scenario (i.e., +4% compared to *Ref)* and an average reduction of 84 L with *All*+ (i.e., −3% compared to *Ref)*.

4. Discussion

This dairy sheep flock, was built aiming to simulate the overall productive and reproductive performance of the flock based on the aggregation of individual ewe performance. Thanks to the dynamic modelling of the oestrus occurrence process, the model integrated a representation of the variability of individual responses to hormone-free reproductive management. Sensitivity analyses of the model have shown that age, pre-mating BCS and LTMY are factors that had an important impact on the simulated variability in lambing events number and distribution, as well as on the simulated milk yield of the flock over time (i.e., on the performances of the flock). Results obtained have also shown that the proposed model took into account particular relationships between individual ewe characteristics and their related individual reproductive performance. Indeed, several authors have reported a positive correlation between BCS and reproductive performance (Vatankhah et al., 2012; Kenyon et al., 2014). A positive effect of age on reproductive performance has also been demonstrated (Festa-Bianchet and King, 2007; Maatoug-Ouzini et al., 2013; Meraï et al., 2014). In contrast, the effect of milk yield on the reproductive performance of dairy ewes is still controversial. David et al. (2008) observed a negative genetic correlation between milk yield and fertility to animal insemination in Lacaune ewes, whereas Kassem et al. (1989) and Gootwine and Pollott (2000) found no significant effect of milk yield on the postpartum reproductive performance of ewes. Debus et al. (2021), whose experimental data were used to model the process of oestrus occurrence here, showed that there was a combined effect of age, pre-mating BCS and milk production level on the occurrence of ewe oestrus following ME.

The sensitivity of the outputs to individual input factors has also shown that this model effectively captured the relationship between the diversity of individual ewe features (age, pre-mating BCS and milk yield) and the overall flock performance. This is an original finding considering that it was not possible in previous existing sheep flock models, where reproductive success was previously fixed by deterministic decision rules or randomly chosen within a fixed range of values (Lesnoff, 1999; Gebre et al., 2014). Only a few sheep models integrated some individuality and randomness, mainly through the integration of fertility and fertilisation probabilities that depended, among other things, on indicators specific to each ewe (success or failure in the previous

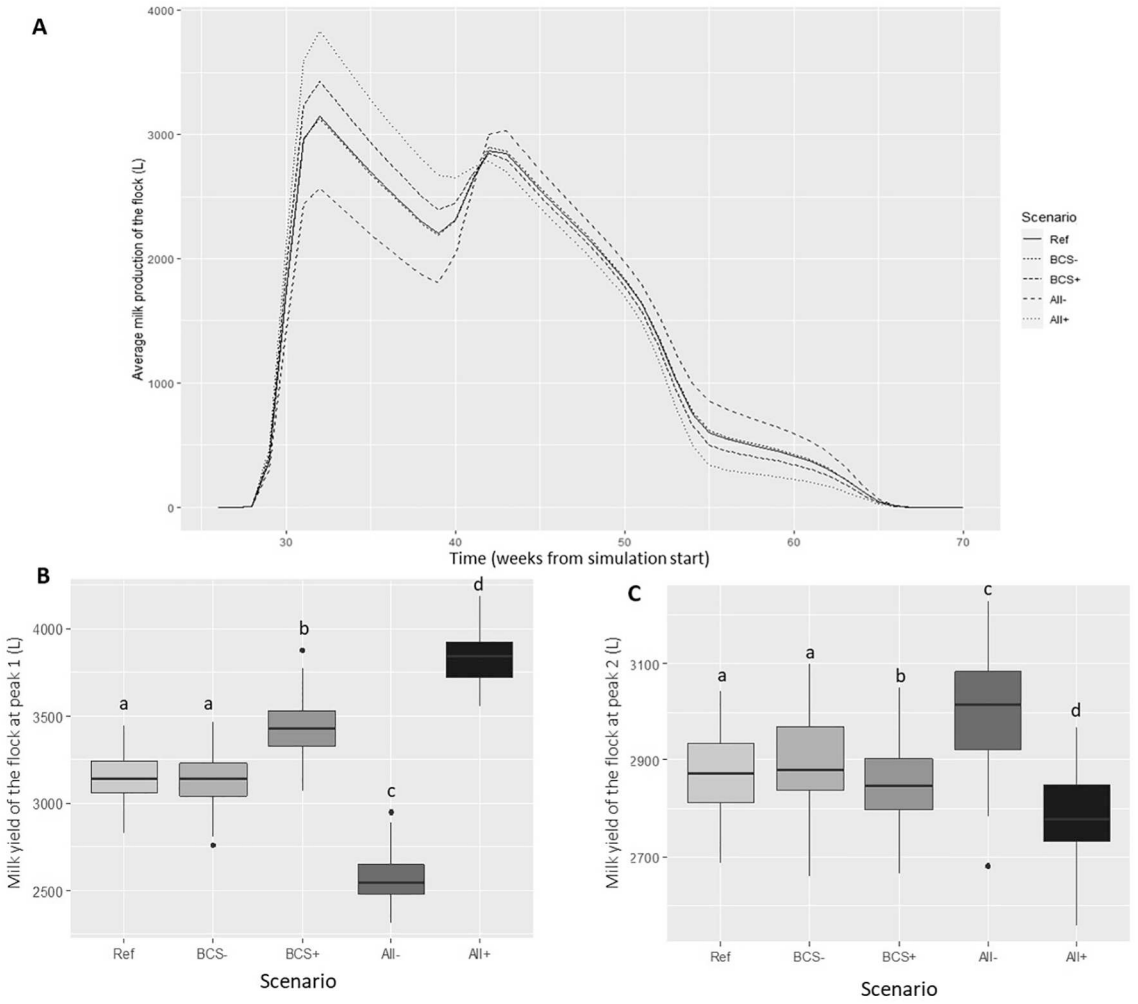

Fig. 11. (A) Flock's average weekly milk production, according to the flock scenarios (n = 75 repetitions per scenario). (B) Boxplot for flock milk production at peak 1 for each scenario. (C) Boxplot for flock milk production at peak 2 for each scenario. Ref = Reference flock scenario; *BCS*−, *BCS*+, *All*−, *All*+ = Alternative scenarios to Ref. a, b, c, d: For each period, values with a separate letter differ at a p-value <0.05.

breeding season; Cournut and Dedieu, 2004), for example.

The model developed here also appears to be a good tool for exploring the link between flock structure, the related management strategies shaping it, and expected flock performance. This study could contribute to optimising the management of reproduction in sheep farming with hormone-free ambitions and goals. Indeed, the productive and reproductive performances of a flock are significantly affected by management practices, as illustrated by the high sensitivity of the flock's milk production to the MMYA set by the farmer in the model (SI < 60%). However, these parameters are also strongly conditioned by the different individual biological mechanisms operating for each individual (Puillet et al., 2010a). Several models aiming to study or optimise herd performances were thus designed to represent the variability of the biological response to various feed and/or reproduction management practices. The integration of this variability is generally made through the modelling of individual biological mechanisms, such as the partitioning of nutrients in the processes of milk production and constitution of body reserves (Puillet et al. (2008) in their dairy goat herd model; Cadéro et al. (2018) in their pig herd model; Villalba et al. (2019) in their dairy ewe model) or the oestrus and heat mechanism in the reproductive process (Oltenacu et al. (1980) and Brun-Lafleur et al. (2013) in their dairy cattle herd model). These different mechanisms are key elements to consider in livestock production and are the result of interactions with farmers' management strategies and decision making. They are driven, however, by specific individual characteristics of the animal, which add complexity to the whole picture (e.g., production potential, Puillet et al., (2008); BCS, Brun-Lafleur et al., (2013)).

The different flock scenarios simulated in this study allowed to explore the extent to which age, pre-mating BCS and milk yield level affect flock performance during a production campaign. Scenarios corresponding to a pre-mating BCS increase alone (*BCS*+) and a combined increase in pre-mating BCS, age and milk yield in the flock (*All*+) led to an improvement in productive and reproductive performance. Indeed, a gain of 1% (*BCS*+) and 3% (*All*+), respectively, on the rate of ewes lambing in the flock was observed, which correspond to 4 and 9 additional ewes lambing, respectively, compared to *Ref*. Similarly, a gain of 2% (*BCS*+) and 4% (*All*+), respectively, was observed on the flock's milk yield compared to *Ref*, which correspond to +1560€ and +3080€ in milk sales, respectively, in the current context where the price of French organic milk is 1334€/1000 L (DRAAF Occitanie, 2021). It would therefore appear that a pre-mating BCS increase, alone or in association with an increase in age and individual milk yield, would lead to an improvement in performance at the flock level. It can therefore be assumed that the demonstrated effects of age, pre-mating BCS and milk yield on individual performance have been reflected in the overall performance of the flock.

Scenarios corresponding to a single pre-mating BCS decrease (*BCS*−) and to a joint decrease in the pre-mating BCS, age and milk yield in the flock (*All*−) led to a decrease in the productive and reproductive performance of the flock. However, only the decrease caused by the *All*−

scenario was significant. The pre-mating BCS decrease alone (*BCS*−), contrary to what might have been expected, did not have a significant impact on flock performance (punctual and dynamic). This may be due to the fact that for the Lacaune breed, as for many other breeds, there is an optimal pre-mating BCS at which a significant effect on ewe performance is observed. Above and below this optimal value, lower reproductive performances are generally observed (Yilmaz et al., 2011, Vatankhah et al., 2012). The optimal value differs according to the breed. For the Manchega ewe, for example, Molina et al. (1994) identified an optimal pre-mating BCS of 3, whereas it appears to be between 2.01 and 3 for Kivircik ewes (Yilmaz et al., 2011). The optimum for the Lacaune ewes is not clearly referenced but the results obtained here imply that the BCS decrease, modelled in *BCS*− (−0.5 points out of the average), was not too drastic, so that in *BCS*− and *Ref*, the number of ewes reaching the optimal pre-mating BCS of the Lacaune breed was equivalent. In contrast, in *BCS*+, a larger number of ewes with optimal pre-mating BCS can be assumed. These results have also shown that two flocks with different individual characteristics appeared to have similar overall performance, suggesting that two management strategies leading to two different sheep flock structures could lead to the same flock performance. This confirms the relevance of the integration of individual characteristics in the REPROsheep model to examine ways of optimising reproduction management practices in dairy sheep flocks. Puillet et al. (2010a) suggested with their dairy goat model that taking individual performance into account in a herd functioning model is relevant and necessary for the evaluation of herd management practices, as the aggregation of individual data at the herd level can sometimes cover differences between management strategies. In this case, the nonsignificant difference at the flock level between the results of the *BCS*− and *Ref* scenarios suggests that the farmer could have a small margin to manoeuvre in the BCS maintenance of his ewes (e.g., through feeding management) without compromising the reproductive performance of his flock.

Overall, it was noted that the changes in performance observed within *BCS*+, *All*+ and *All*−, although significant, remained small, in regard to the total lambing rate of the flock (+1%, +3% and −3% on the total lambing rate for each scenario, respectively). Indeed, plausible flock scenarios for an organic farm of the Roquefort Basin were simulated, leading to fairly modest increases in average age and BCS modelled (0.5 BSC and/or 0.5 years, from a starting point of 2.5), with fairly low standard deviation for the pre-mating BCS (sd = 0.3). Thus, it should be acknowledged that with a more extreme flock population, results could have been different.

On the over hand, the effect observed on the distribution of lambing over time was much more noticeable. Indeed, *BCS*+ and *All*+ led to a better concentration of lambing during the first lambing period (P1) when compared to *Ref* (proportion of the total number of ewes lambing is higher by 6% and 13% for *BCS*+ and All+, respectively), accompanied by a better flock milk yield at the first peak of milking (peak 1) (+9% and +22% of milk produced in *BCS*+ and *All*+, respectively, compared to *Ref*). This suggests a better synchronisation of oestrus following ME. This is consistent with the positive effect of age, BCS and milk yield stated in the literature (Fahmy, 1989; Kassem et al., 1989; Maatoug-Ouzini et al., 2013; Kenyon et al., 2014; Debus et al., 2021). Similarly, the *All*− scenario led to a lower concentration of lambing during P1 and a lower milk yield at peak 1 (proportion of total lambing during P1 lower by 12% and 18% less milk produced at peak 1, compared to *Ref*), suggesting less oestrus synchronisation compared to *Ref*. Therefore, a significant effect of individual characteristics on lambing distribution over time was simulated, which confirms the suitability of the model with important management issues in sheep farming. It is true that lambing distribution over time is a determining factor in sheep farming, as it relates to other important issues such as work organisation, distribution of production and sales (of milk and lambs) or development of grassland and grazing resources (Cournut and Dedieu, 2000). It also accounts for the success or failure of the oestrus synchronisation method implemented by the farmer.

The REPROsheep model therefore seems relevant to predict how a management strategy (determining flock structure in terms of age, body condition or production potential) can impact the performance of a dairy sheep flock, particularly the distribution of lambing over time, in the context of reproduction on natural oestrus or even for the implementation of animal insemination. However, to draw accurate and definitive conclusions, the REPROsheep model would need to be applied to a wider range of different organic dairy sheep flocks. The outputs obtained and the conclusions drawn during the exploration of the REPROsheep model therefore remain theoretical and need to be confirmed by applying it to a larger number of farms managed without hormones as well as simulating several successive breeding campaigns (over several years). Indeed, a model allowing a simulation of successive breeding periods would require additional assumptions that were not included here, such as, for example, taking into account the genetic aspect in renewal choices, which could mean adding conditions in order to adapt the stated relationships to the modelled context. This aspect will have to be taken into account in a future version of the model to test the impact of the implementation of animal insemination in organic dairy sheep farming. It would make it possible, among other things, to precisely link the trends observed with flock management strategies and to assess the long-term impact of changes in practices or of innovative practices introduction in the context of sheep reproduction hormone-free management (Maton et al., 2014).

5. Conclusion

The REPROsheep model was interesting for studying the dynamic effects of implementing a hormone-free reproductive management strategy in a dairy sheep flock. It allowed us to assess flock level performance over time by considering particular individual performances of ewes composing the flock. This model therefore represents a tool to better understand mechanisms and trade-offs occurring in the interplay between the individual and flock levels, exacerbated (or not) by applying sheep reproduction management practices without hormones, for oestrus induction and synchronisation. Nevertheless, the flock management results obtained here, even if exploratory, suggested that management favouring an optimum pre- mating body condition score and age, as well as good milk yield in the individuals of the flock, might be a lever for optimising flock performance, especially the distribution of lambing over time. Further research is warranted to fully validate this hypothesis by applying the model to other hormone-free dairy sheep flocks and to perform simulations with a long-term perspective. It would also be interesting to conceive how the stated findings interact with the management of other components at the whole farming system level (and not just the flock) in the context of the agroecological transition of dairy sheep farming systems.

CRediT authorship contribution statement

E. Laclef: Conceptualization, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft. **N. Debus:** Conceptualization, Investigation, Methodology, Writing – review & editing. **P. Taillandier:** Conceptualization, Methodology, Software, Writing – review & editing. **E. González-García:** Conceptualization, Methodology, Writing – review & editing. **A. Lurette:** Conceptualization, Methodology, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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III-3. Conclusion du chapitre

Le modèle REPROsheep présenté dans l'article précédent est un modèle multi-agent, stochastique et dynamique qui a été développé pour simuler et analyser les effets de caractéristiques individuelles des brebis, sur les performances globales de production et de reproduction du troupeau. Il prend en compte la variabilité individuelle de réponse à l'effet mâle grâce à une représentation détaillée du processus individuel de reproduction et simule des sorties dynamiques (nombre hebdomadaire de brebis qui agnèlent et production laitière hebdomadaire) et des sorties annuelles (nombre total de brebis qui agnèlent et production laitière totale du troupeau). Sa validation à partir de données de la base SIOEL (Astruc et al., 2008) montre qu'il simule efficacement les performances du troupeau dans un contexte d'induction et synchronisation des chaleurs par effet mâle. L'analyse de sensibilité du modèle a montré que ses sorties (c.-à-d. performances simulées du troupeau) étaient principalement affectées par les valeurs moyennes des distributions de trois caractéristiques des brebis dans le troupeau : leur âge, leur NEC avant la lutte et le rendement laitier de leur précédente campagne de production. La comparaison des résultats de simulations de différents scénarios de troupeaux OVL, faisant varier les valeurs moyennes de ces distributions, permet de dire que les stratégies de gestion favorisant un âge et une NEC avant la lutte optimum, ainsi qu'un bon rendement laitier pour les individus du troupeau, peuvent être des leviers pour optimiser les performances du troupeau. Notamment la répartition des agnelages dans le temps dans le cadre d'une reproduction sans TH avec une synchronisation des chaleurs par effet mâle.

En définitive, le modèle REPROsheep présenté dans ce chapitre est un modèle pertinent pour représenter l'impact de la variabilité individuelle de réponse à l'effet mâle sur les performances productives et reproductives d'un troupeau de brebis Lacaune. Il peut ainsi servir de base à des modèles plus complexes s'intéressant à d'autres aspects du fonctionnement de troupeaux, voire d'exploitations OVL gérées sans hormones de synchronisation.

Chapitre IV :

Simulation des conséquences de l'utilisation d'alternatives aux hormones sur la gestion de l'alimentation du troupeau

Chapitre IV- Simulation des conséquences de l'utilisation d'alternatives aux hormones sur la gestion de l'alimentation du troupeau

Ce chapitre présente les résultats de simulations de scénarios d'utilisation d'une méthode de gestion de la reproduction ovine utilisant l'effet mâle comme alternative aux TH de synchronisation, avec une conservation de l'IA sur une partie du troupeau à partir de l'exemple du troupeau OVL conventionnel de la ferme expérimentale de la Fage. Cette simulation a été faite en utilisant le modèle de troupeau REPROsheep2.0 (version étoffée du modèle REPROsheep). L'objectif spécifique de ce travail est présenté dans ***la première partie de ce chapitre****. La description du modèle, des scénarios simulés ainsi que les résultats des simulations sont présentées dans* ***la deuxième partie de ce chapitre*** *sous forme d'un article soumis à la revue Journal of Dairy Science. Une* ***dernière partie*** *résume les conclusions principales du travail présenté dans ce chapitre.*

IV-1. Introduction du chapitre

L'efficacité de l'effet mâle pour induire et synchroniser les chaleurs des brebis d'un troupeau étant variable, son utilisation suppose un étalement des agnelages ainsi qu'une perturbation de la courbe de production de lait du troupeau par rapport à une gestion classique utilisant des TH de synchronisation. Cela entraîne également des impacts collatéraux sur le reste des composantes du système d'exploitation. Il est important de considérer en premier lieu l'impact sur la gestion de l'alimentation. En effet, le système d'alimentation mis en place au sein d'un élevage détermine les performances du troupeau et représente généralement plus de 70 % dans l'économie d'un élevage (Makkar, 2018). Une bonne maîtrise de l'alimentation du troupeau est donc nécessaire pour atteindre les objectifs de production fixés tout en limitant les frais de fonctionnement de l'exploitation. Les stratégies d'alimentation reposent principalement sur la combinaison de la gestion des besoins nutritionnels du troupeau au cours du temps, conséquence de la distribution des stades physiologiques dans le troupeau au cours du temps, et de l'efficacité de l'utilisation des ressources alimentaires (et fourragères) disponibles. Nous faisons l'hypothèse que pour les troupeaux conventionnels utilisant des TH de synchronisation, les conséquences directes de l'introduction d'alternatives aux TH sur les besoins nutritionnels du troupeau, reflèteront une plus grande variabilité dans la distribution des stades physiologiques présents dans le troupeau tout au long de l'année par rapport aux schémas classiques. Ainsi, la gestion de l'alimentation du troupeau devrait être impactée. Par ailleurs, une bonne gestion des surfaces fourragères disponibles est nécessaire puisque les prairies peuvent constituer une ressource alimentaire très intéressante lorsqu'elles sont bien adaptées aux besoins du troupeau car elles ont un faible coût de production unitaire par rapport à d'autres aliments (Wilkinson et Lee, 2018). Dans le cas des systèmes pastoraux des régions méditerranéennes

comme les systèmes d'élevage OVL de l'AOP Roquefort, la bonne maîtrise des ressources est d'autant plus importante car ces systèmes sont historiquement basés sur des systèmes herbagers incluant des règles de gestion des troupeaux avec des séances de pâturage quotidiennes dès que les conditions météorologiques le permettent (INAO, 2017).

L'objectif du travail présenté dans ce chapitre était donc de simuler les conséquences d'une gestion de la reproduction incluant l'utilisation de l'effet mâle comme alternative aux TH de synchronisation des chaleurs sur les performances productives et les besoins nutritionnels (i.e. énergie et protéines) d'un troupeau OVL conventionnel représentatif des troupeaux du BNO. Un modèle dynamique multi-agents REPROsheep2.0 qui s'appuie sur la structure du modèle de troupeau REPROsheep décrit dans le précédent chapitre a ainsi été développé pour simuler l'utilisation d'alternatives aux TH pour gérer la reproduction d'un troupeau OVL conventionnel et étudier les conséquences sur ses performances productives et la gestion de son alimentation en comparaison avec sa gestion actuelle.

IV-2. Article 2: Alternative hormone free reproduction management of a dairy sheep flock disrupts the farm's annual feeding system calendar and its associated strategies

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 address current societal demands, but it suggests to be prepared for collateral impacts in related system components. Efficiency of HF practices [e.g. using male effect (ME) for estrus induction and synchronization] is indeed uncertain compared to hormonal treatment (HT). Direct consequences on feeding regimes, for example, will reflect higher variability in the flock physiological stages patterns throughout the year. The objective of this work was to simulate impacts of HF reproduction management, including artificial insemination (AI), on the

temporary distribution of productive performances and nutritional requirements of a conventional dairy sheep flock. Using the REPROsheep2.0 model, six scenarios were compared over one typical production season for the same flock (n= 597 Lacaune ewes) intensively reared in the Roquefort region of France i.e. 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 number of ewes lambing and, consequently, in the annual milk production of the farm was observed (-1 to -7 %). This affected annual performances 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 days shift in the appearance of milk production peaks and related nutritional requirements compared to HT. Transitioning from conventional to HF reproduction management, while preserving AI, would increase farm workload and lengthen milking period operations, whereas a readjustment of feeding management strategies would be necessary with regard to available feed resources. Depending on the production season, the observed delay in the distribution of nutritional requirements could be either an interesting or unfavorable outcome for farmers. The delay may be concordant e.g. with recent impacts of climate change observed on seasonal forage availability in Mediterranean regions (less spring herbage production and warmer temperatures) thus leading to modulate farmers' decision makings for a most efficient use of forage and feed resources.

Keywords: Dairy sheep, Hormone-free reproduction, Agent-based model, Feeding management

1. Introduction

In the conventional livestock farming industry, breeding strategies including artificial insemination (AI) are often dependent on the use of hormonal treatment (HT) for estrus synchronization. However, this practice is increasingly questioned by society worldwide including higher consumer demands for healthier products that come from farming systems that minimize the use of HT while favoring 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). The male effect (ME), for instance, is a hormone-free (HF) breeding practice that allows to stimulate ewe ovulation and to concentrate the peaks of parturition in the flock (Rosa and Bryant, 2002; Pellicer-Rubio et al., 2019). Indeed, a sexually active male, via sensory signals, is able to induce and synchronize heats and ovulations in a group of anovulatory (i.e., sexually resting or uncycled) females by increasing

the activity of their hypothalamic-pituitary axis, leading to ovulations and the resumption of estrous cycles (Delgadillo et al., 2009; Thimonier et al., 2000). It has been shown that combining this practice with an electronic device solution for helping precise estrus detection makes it possible to do AI without HT (Debus et al., 2019). However, the success of a synchronization with the ME 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., 2021) or the time between drying off and mating (Tournadre et al., 2009). Therefore, AI without HT is still complicated to implement, and the uncertainty on the results to be expected on flock performances but also on the associated management practices, both at flock and farm levels, are limiting factors for the wide adoption of these alternatives in farms.

Among the most sensitive associated farming management practices, the feeding system is the most important. Indeed, performance of the herd depends on the feeding and it 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 is a consequence of the progression through different physiological stages) and the efficiency of using the available feed (and forage) resources. The current global context of climate change affect forage autonomy of livestock farming systems, as farms are more and more subject to fluctuations in the availability and quality of grazing, forages and roughages resources. Therefore, proper management of the available land required as grasslands can be a significant low unit cost feed resource when well matched to the flock requirements (Wilkinson and Lee, 2018). This is the case for pastoral systems in Mediterranean regions e.g. dairy sheep farming systems of the Roquefort region of France which are traditionally based on grazing systems including rules for managing flocks with daily grazing sessions as soon as the meteorological conditions allow it (INAO, 2017).

The aim of this work was thus to simulate the impacts of establishing an alternative HF reproduction management in a flock belonging to a typical, representative conventional semi-intensive dairy sheep farming system. Effects on both annual and dynamic, temporary distributions of the flock's reproduction and milk production performances, as well as the related nutritional requirements repartition over time were simulated and evaluated. The direct consequences on the flock feeding system management were then discussed.

2. Materials and methods

The study was carried out with available information, experiences and historical database from the management of a flock belonging to one representative dairy sheep

farming system located in the Roquefort region of France i.e. the INRAE (French National Research Institute for Agriculture, Food and Environment) experimental unit La Fage, in the region of the Causses du Larzac (43_54'54.5200N; 3_05'38.110 0E; ~800 m above sea level). To carry out such *in silico* experimentation, a dynamic agent-based model was used to evaluate different, alternative scenarios of reproduction management.

2.1. Characteristics of the 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 thus can easily perform AI. Conventional farms are usually characterized by the systematic use of AI (in one portion or the totality of the flock), after synchronizing ovulations using HT. In addition, in the Roquefort area, dairy sheep farms are divided into two 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, whereas in "late" the ewes are mated in mid-summer, close to the natural mating season for sheep (i.e. autumn), which induce lactations between January and October. Indeed, in response to the industry demand in this large dairy sheep production basin, a spreading of 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 periods schedules was considered in the design of the scenarios to be tested in the current study.

2.2. 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) and its source code can be accessed at https://github.com/elaclef/REPROsheep2.0_ABM.git.

2.2.1. 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 a HF regime. Briefly, the model presents two main types of agents (or entities) i) a decision-making or human entity, the farmer; and ii) biotechnical animal entities: (individuals, sheep), which are sub-divided into two agents: ewes and rams. REPROsheep was designed to simulate a reproduction season followed by its milk production period with a time step of 12 hours. It is composed of biotechnical processes 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 ME 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 are carried out during this period, called production season, allowing to model the succession of the physiological stages 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 already present in the previous version (Laclef et al., 2021) to generate the new version of the model used here (REPROsheep2.0). Indeed, relying on daily updates of ewes' physiological stages, a daily calculation of requirements in net energy (using the FUL system i.e. Forage Unit for Lactation) and digestible protein (using the PDI system i.e. Protein Digestible in the Intestine; Jarrige, 1989) of each ewe was integrated, based on the INRAE feeding system and the equations for estimating nutritional requirements (Hassoun and Bocquier, 2010).

2.2.2. Reproduction and lactation submodels

The representation of the reproduction biotechnical process is an adaptation of that developed by Laclef et al. (2021). It could be functional either in HT or HF contexts practicing AI. Concretely, in a HT context a fixed probability of synchronization success is assigned and determines if the ewe is sexually receptive ("in heat" or estrus) (Figure IV.1). On the contrary, in a HF context, the probabilities of being in estrus is determined by the probability for a ewe to be cyclic, PC (i.e. spontaneously ovulating and showing estrus) and, if not cyclic, by the probability of responding to the ME, PREM. In this revised version of the model, the PC differs according to the reproduction season considered. Indeed, when the reproduction takes place during the spring (i.e. out of the natural reproduction season of the ewes), the PC 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 takes place during the full natural reproduction season of ewes (i.e. autumn), or close to it (i.e. summer), the PC for a ewe is high (Chemineau et al., 1992; Chanvallon et al., 2011). Since, to our knowledge, there are very few recent studies on the natural seasonality of the dairy Lacaune breed, the PC was set arbitrarily to 0.8 when reproduction takes place in summer and to 1.0 when it takes place in autumn, leaving less room for the ME to impact the reproductive response of the ewes. It is indeed acknowledged that the ME can only induce the resumption of cyclicity for anovulatory ewes (Delgadillo et al., 2009). Therefore, during the natural season of reproduction where

most ewes are spontaneously cyclic the ME impact is basically null. Based on previous accumulated experience, collected information and available databases, a probability coefficient of AI success ($P_{AI\ SUCCESS}$) was also added to determine if 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 or other environmental factors (Anel et al., 2005). For dairy Lacaune ewes, pregnancy rate usually runs between 65 % and 71 % in adult ewes (David et al., 2008). In the current study, the lactation process was modelled 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 now added, including the probability of decision making to stop the lactation of that given ewe.

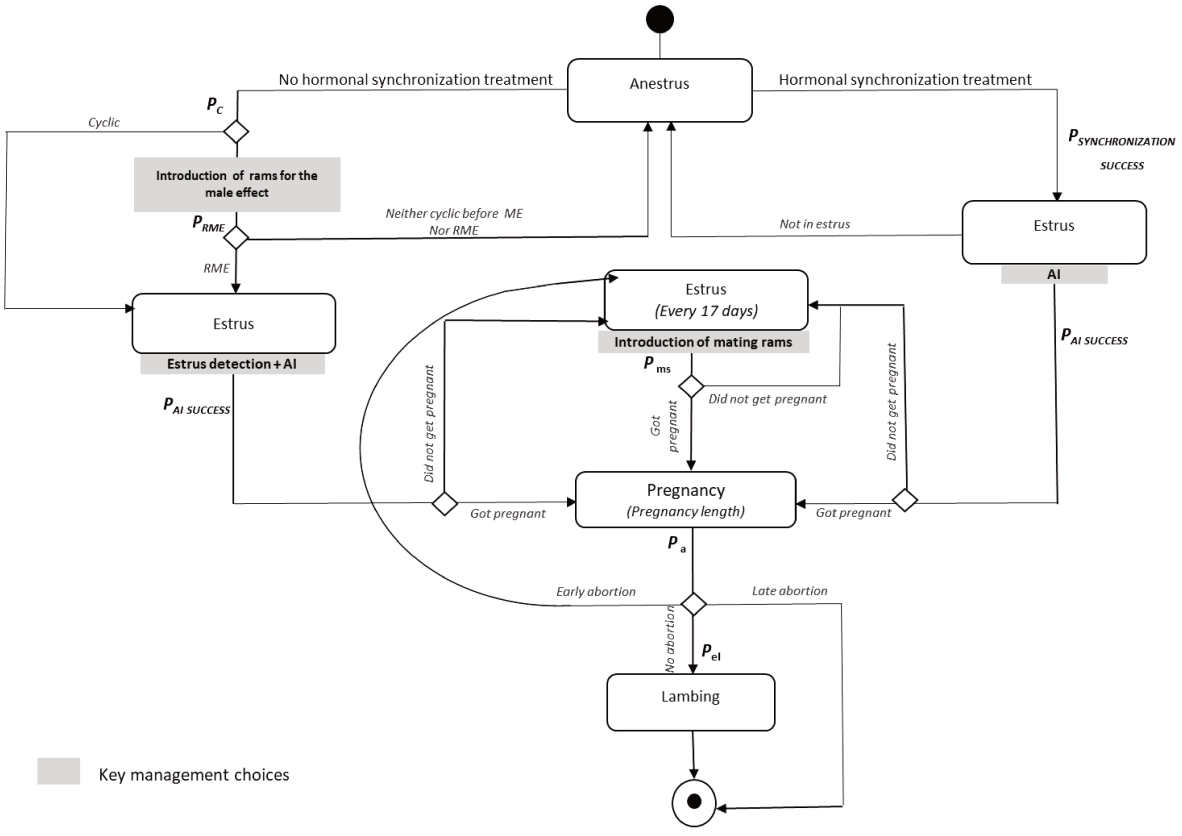

Figure IV. 1. The individual ewe's reproduction phases modelled in REPROSheep 2.0, according to the sequence of physiological and/or biotechnical steps, including farmer decisions' makings in a context of reproduction practicing artificial insemination. Reproduction starts with an ewe in seasonal anestrus and ends at lambing.

AI= Artificial Insemination, 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 complication), P_{ms}= Probability of mating success, P_{RME}= Probability to Respond to Male Effect.

2.2.3. Reproduction management submodel

The reproduction management submodel was also modified from the previous REPROsheep version to include different reproduction management possibilities considering or not the use of HT with adapted AI protocol. With HT there is 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 days of HT. In HF context, we chose to represent a reproduction management protocol including the use of the ME followed by AI, only on adult ewes. Indeed, it has been shown that young ewes usually respond poorly to the ME, mainly due to stress and lack of sexual experience (Chanvallon et al., 2010). In addition, in HF context, the AI protocol differed according to the reproduction season considered. Out of the natural reproduction season, the response to the ME has been found to induce the resumption of cyclicity in ewes, with peaks of estrus activity between 18 and 20 days and between 24 and 26 days after the male introduction for the ME (Thimonier et al., 2000; Rosa and Bryant, 2002). Thus, in this case, 6 days of AI were scheduled around these days. However, during the full natural reproduction 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 days after the ME.

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

2.2.4. 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 modelled flock was initially composed of 11 Lacaune rams, 160 ewe lambs (i.e. young ewes, nulliparous) and 437 adult (i.e., ewes with at least one lambing at the start simulations) Lacaune ewes (i.e., in total 597 ewes in reproduction). For each female represented, information on several individual characteristics were available (Table IV.2a and IV.2b). At this farm, reproduction usually takes place during summer (between July and September) and two groups of females are managed separately until milking starts: adult ewes start the reproduction process 42 days earlier than the young, primiparous ewes. The programmed milking period of this farm (i.e., the period set by the

farmer during which the flock produces milk for sale in agreement with dairy sector in the region) has a total duration of 210 days (between late December and late July) and each lactating ewe enters milking after weaning their lambs, with an average 32-day 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 Table IV.2a and IV.2b.

2.3. Model outputs

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

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

Reproduction management	Reproduction season	Estrus synchronization protocol	Artificial Insemination (AI)	Mating
With hormones	All year	14-day hormonal treatment [vaginal fluoro-gestone acetate (FGA) sponge + pregnant mare serum gonadotropin (PMSG) injection]	55 hours (after sponge removal) AI is performed for all the treated females	15 days after AI rams are introduced for mating during 32 days
Without hormones	Spring (*Early*)	Male effect during 14 days on adult ewes	Each day between 18 and 20 days and between 24 and 26 days after male introduction, AI is performed on ewes detected in heat	6 days after the last AI date rams are introduced for mating of adult ewes during 32 days. Then, 1 month later, mating of ewes lambs batch for 32 days.
Without hormones	Summer and Autumn (*Late*)	Male effect during 14 days on adult ewes	Each day between 17 and 22 days after male introduction, AI is performed on ewes detected in heat	6 days after the last AI date rams are introduced for mating of adult ewes during 32 days. Then, 1 month later, mating of ewes lambs batch for 32 days.

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

Attributes and state variables	Definition	Notation	Type	Units	Initial value/range of values	Source
Age of the ewes	-	Age	Integer[2]	years	0-7	Data from La Fage experimental farm
Age of the rams	-	Age	Integer	years	2-4	
Ewe's body condition score	See (Laclef et al., 2021)	BCS	Float	-	1-5	
Initial daily milk yield (for ewes > 1 year old)[1]		$IDMY_e$	Float[3]	L	1-4.5	
Initial daily milk yield (for ewe-lambs <1 year old)[1]		$IDMY_{el}$	Float	L	1-4.5	
Last daily milk yield monitoring (of previous lactation)		LDMY	Float	mL	0-993	
Last total milk yield[1]		LTMY	Float	L	0-450	
Lactation number		$Lact_{num}$	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	kg	75	
Mean live weight of ewe lambs	Mean live weight of ewe lambs at starting date(i.e. first day of reproduction process)	-	Float	kg	47	
Lambing to reproduction interval[1]	Days between last lambing date and the hormonal treatment or the date of rams introduction for male effect	LMEI	Integer	days	0-235	
Pregnancy length[1]	-	PL	Integer	days	145-157	Expert
Hormonal treatment	If reproduction strategy of the farmer includes hormonal treatment	-	Boolean[4]	-	True	-
Anestrus	See (Laclef et al., 2021)	-	Boolean	-	True	
Cyclic before male effect		CBME	Boolean	-	False	
Responding to male effect		RME	Boolean	-	False	
Show first estrus		-	Boolean	-	False	
In estrus	Ewe in estrus	-	Boolean	-	False	
Pregnant	Ewe pregnant	-	Boolean	-	False	
Abortion	Ewe aborts	-	Boolean	-	False	1
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: Set randomly by a normal distribution whose mean and standard deviation are taken from the corresponding source.
2: Integer= whole numbers.
3: Float = values that have potential decimal places.
4: Boolean = Statement that can only be equal to yes or no.

Table IV.2b. Main global parameters of the model.

Parameters	Definition	Notation	Type	Units	Initial value/range of values	Source
Starting date of the simulation	-	-	Date	-	June 19th, n	Data from La Fage experimental farm
Ending date of the simulation	-	-	Date	-	July 29th, n+1	
Starting date of hormonal treatment for adult ewes	-	-	Date	-	June 19th, n	
Starting date of hormonal treatment for ewe lambs	-	-	Date	-	July 31st, n	
Ram introduction date for male effect	See (Laclef et al., 2021)	-	Date	-	-	
Rams 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	-	July 20th, n	
Rams introduction date for the mating of ewe lambs and adult latecomers	Date on which the farmer introduces rams to mate young ewes (<1 year old) and the adult ewes that did not get pregnant during the previous mating periods	-	Date	-	August, 8th, n	
Dry-off date	See (Laclef et al., 2021)	-	Date	-	July 28th, n+1	
Minimum milk yield accepted at milking		MMYA	Float[2]	L/day	0.45	
Probability of abortion		Pa	Float	-	0.003	
Milk fat content at milking start	Mean fat content of the flock's milk at the start of milking	-	Float	g/L	60.7	
Milk protein content at milking start	Mean protein content of the flock's milk at the start of milking	-	Float	g/L	45.9	
Probability of an easy lambing	See (Laclef et al., 2021)	Pel	Float	-	0.94	
Probability of synchronization rate	Probability for a ewe (or a ewe lamb) to start ovulating following hormonal treatment	$P_{SYNCHRONIZATION\ SUCCESS}$	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	$P_{AI\ SUCCESS}$	Float	-	0.67	
Probability of AI success for ewe lambs	Probability for a ewe lamb to be pregnant following AI	$P_{AI\ SUCCESS}$	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	-	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	
Selected culling age	See (Laclef et al., 2021)	-	Integer[3]	years	6	
Selected free mating duration		-	Integer	days	32	
Mean suckling length		SL	Integer	days	32	
Selected turnover rate		-	Float	%	25	
Probability to be in estrus during season[1]		Pso	Float	-	0.8	Adapted from Chanvallon et al. (2011)
Probability for a successful mating		Pms	Float	-	0.5	Expert

1: 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). 2: Float = values that have potential decimal places. 3: Integer= whole numbers.

2.4. Description of the studied scenarios

From the reference management of the La Fage farm, six different reproduction management scenarios of the same flock (i.e. with the same individuals, n= 597) were built (Figure IV.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*); as well as the HF version of these three scenarios (*HF-Early*; *HF-Summer Late* and *HF-Autumn Late*, respectively). They differed i) in the use (or not) of HT to synchronize ovulation before AI and ii) in their mating dates and thus, the consequent reproduction periods. The use of the ME, to try to synchronize estrus events in the flock, is common nowadays 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 ME in all the HF scenarios. Then, the AI of adult ewes only was implemented in these HF scenarios following the protocol described in Section 2.2.3. 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*) and/or alternative reproduction strategies (*HF-Autumn Late*, *HF-Early* and *HF-Summer Late*, respectively). In HF scenarios, the number of rams was set to 24 so that the number of rams was enough to perform an effective ME on adult ewes and mating of all ewes. To complete a full production season, each simulation started arbitrarily on the first day of the reproduction process (date of the ME 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 days 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 days.

2.5. Statistical and descriptive analysis of simulation outputs

Scenario results are expressed as means of 75 simulation repetitions (threshold value allowing to manage 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).

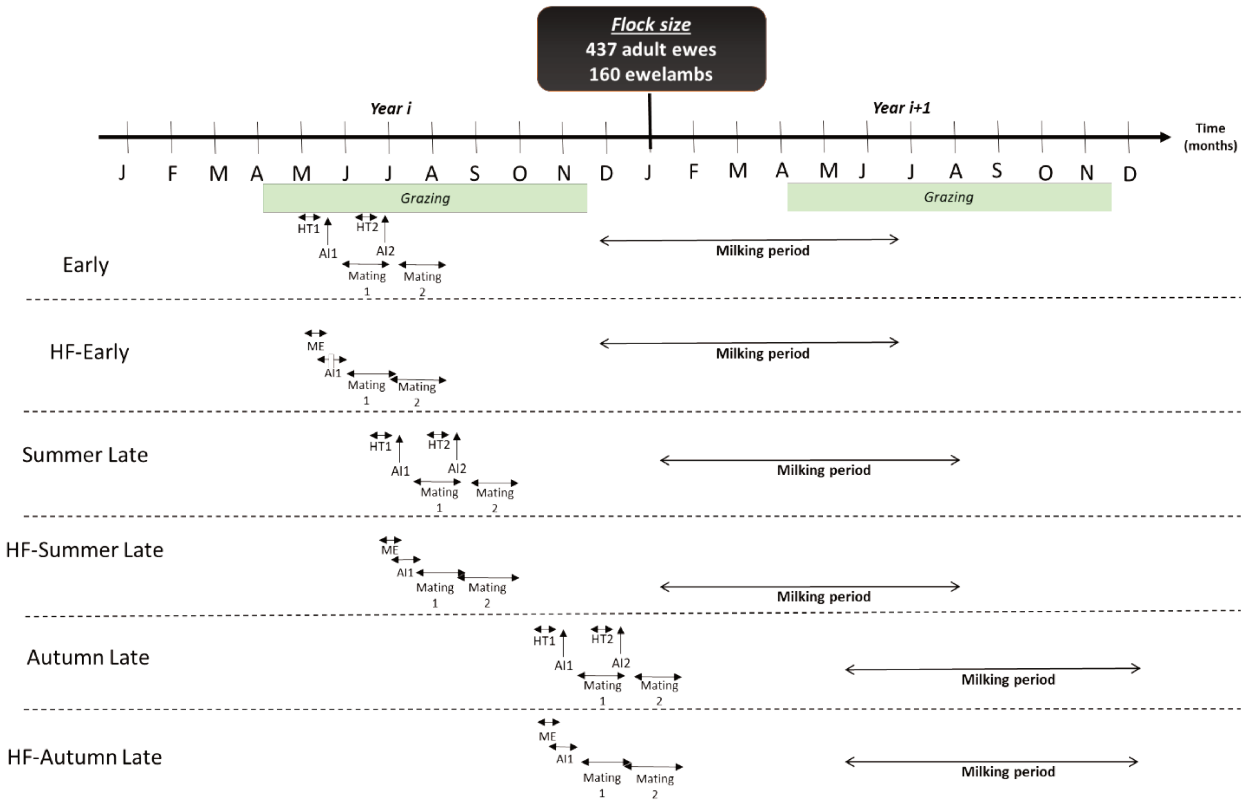

Figure IV. 2. Main steps of the reproduction and lactation management scheduled followed over the simulated production season.

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.

2.5.1. Total number of ewes lambing and milking, total milk production of the flock and total nutritional requirements for the ewes

One-factor ANOVAs were performed to study the scenarios effects on the total number of ewes lambing, the total milk production of the flock and the total nutritional requirements of the flock.

2.5.2. Progression of number of ewes lambing and milking, 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 in order to perform a descriptive analysis of these dynamic simulation outputs.

3. Results and discussion

3.1.1. 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 when comparing the HT scenarios and their HF equivalents (Table IV.3). Indeed, in the HF scenarios, significantly lower annual number of ewes lambing and milking were observed. These lower values are the consequence of the adoption of a HF reproduction strategy while maintaining the same mating and milking time schedules, resulting in a lower number of ewes lambing per year. It could be explained by the fact that, when the ME is applied to trigger and synchronize ewes' ovulations out of their natural reproduction season, like in the *HF-Early* scenario, the result is more variable than when using HT (Martin and Kadokawa, 2006). In fact, success in applying ME on anestrus ewes will depend on several parameters from different natures 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., 2022). Moreover, it has been admitted that the use of the ME is only effective on ewes in anestrus (Delgadillo et al., 2009). Thus, when reproduction takes place 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 cyclic will be high, the ovulations are not as synchronized around farmer's reproduction dates as they would be if receiving HT. Therefore, in all HF scenarios the number of ewes in estrus on AI days, and then during the mating period, is more variable than in HT scenarios. In addition, the simulated scenarios were designed 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 ME 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 ME have a chance to come into heat spontaneously and be covered later. This could also be associated with a longer milking period, since a longer reproduction period could lead to some ewes entering in the milking parlor later on.

Furthermore, when looking at the ewe's average annual individual milk production (in L/ewe/year; Table IV.3), it was rather similar to that of HT reproduction management, suggesting that introducing a HF reproduction management doesn't 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/year; Table IV.3) and *HF-Summer Late* (+2 L/ewe/year; Table IV.3) which could be explained by the fact that ewes that better respond to the ME corresponded to ewes with good annual milk production level (Debus et al., 2022;

Laclef et al., 2021). 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 to that of their HT equivalents (P<0.05; Table IV.3), but the differences between the performances of each HF scenario and its HT equivalent remained relatively small (between -1 % and -7 %; Table IV.3).

As a consequence of these lower performances, the annual nutritional requirements of the flock were also negatively affected, as they are strongly correlated to the production level of the flock. This suggest that potential farm reduced incomes due to reduced annual milk but also lamb production (and thus sales) in HF context could be decreased or even compensated by the reduced nutritional requirements of the flock (i.e., saving money for feeding).

There was also a significant difference between the simulated performances and nutritional requirements of the various HF scenarios (P<0.05; Table IV.3). Indeed, they were higher as the reproduction was closer to the natural reproduction season of the ewes (i.e. autumn). This is a consequence of the fact that spontaneous cyclicity and therefore spontaneous ovulatory activity for ewes increases as we get closer to the natural reproduction season of the ewes (Chanvallon et al., 2011). Thus, use of ME to induce and synchronize ovulations in the *HF-Early* scenario doesn't seem to compensate for the lower spontaneous ovulatory activity at this time, affecting the flock performances.

3.1.2. Number of ewes lambing per day

Throughout the year, lambing events were more spread out in the HF scenarios, then distributed differently compared to the HT equivalents (Figure IV.3). Consequently, the peaks of daily lambing events were less pronounced and staggered in time in ewes submitted to HF regime. Indeed, in the HT scenarios, the maximum number of ewes lambing/day occurred on the first day of the lambing period with between 114 and 115 ewes lambing in one day, depending on the scenario. In contrast, in the HF scenarios, the maximum number of ewes lambing/day was not observed until 12 to 24 days 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 ME with HF reproduction management. For instance, fertility after AI for adult ewes (% of ewes lambing following AI) ranged from 13-20 % versus 63 % (in HF with ME and HT scenarios, respectively).

Table IV. 3. Milking performances and nutritional requirements (annual accumulated values) of a Lacaune dairy sheep flock (n= 597 ewes), under six contrasting reproductive management scenarios.

	Scenario[1,2]					
	Early	***HF-Early***	***Summer Late* (Ref)**	***HF-Summer Late***	***Autumn Late***	***HF-Autumn Late***
Simulations *per* scenario	75					
Reproduction period[3]	May 1rst, i – August 12th, i		June 19th, i – September 30th, i		October 15th, i – December 26th ,i	
Milking period (number of days)	November 11th, i – June 9th, i+1 (210)		December 30th, i – July 28th, i+1 (210)		April 27th, i+1 – November 23th, i+1 (210)	
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]
Total 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 (±2510)[d]	140 495 (±2911)[a]	150 716 (±2352)[d]	143 773 (±2619)[b]	151 079 (±2698)[d]	149 183 (±2971)[c]
Diff (%)[4]	7		5		1	
Average annual individual milk production (L/ewe/year)	287	291	287	289	287	287
Total energy requirement[5] (Mean ± SD)	383 943 (±2664)[d]	363 077 (±3456)[a]	384 005 (±2454)[d]	368 961 (±3084)[b]	384 023 (±3145)[d]	377 213 (±2928)[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, b, c, d: Values in the same row with different superscripts differ at p-value<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 hormone-free equivalent.

[5]Total milk production of the flock (in 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 g of PDI (Protein undegraded in the rumen which is Digestible in the Intestine).

At the farm level, it would imply significant changes in terms of work organization and management of batches in the flock. Indeed, it implies a staggering of lambing events that will lead to a larger diversity of the concomitant 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. in function of the conventional reproduction management scheme), instead of having a large batch of ewes starting milking at the same time, the farmer will have to manage staggered milking starts with ewes arriving progressively and indistinctly, in a less programmed manner. This would imply the farmer adopting a more operational day-to-day decision making routine, to manage for example the feeding of ewes with 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 et al., 1993). Therefore, since the evolution of milk production follows an exponential path with a maximum production at the beginning of lactation (Lagriffoul et al., 2003), it's well known that ewe's nutritional requirements to cover milk production are higher at the beginning of lactation and decrease as the lactation progresses. A staggering in milking starts will thus force the farmer to manage different feed requirements at the same time for the several different stages of lactation (*Early*, mid, late) of also different 'sub-batches' of ewes present in the flock during milking, after having arrived at different times to the milking parlour.

Nowadays, in the farms of the Roquefort region, the feeding system of dairy ewes is managed according to the largest and most homogeneous batches of animals (in terms of physiological stage) present in the flock. The strategy looks for adjusting the individual daily dry matter intake in 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, usually during milking, around 17 % of the ewes of the flock (the most productive) run the risk of being underfed whereas more than 50 % of the flock (the least productive) would probably be overfed. Therefore, in the case of HF reproduction management, if the farmer decides to keep a small number of batches, there is a risk of a greater disparity 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.

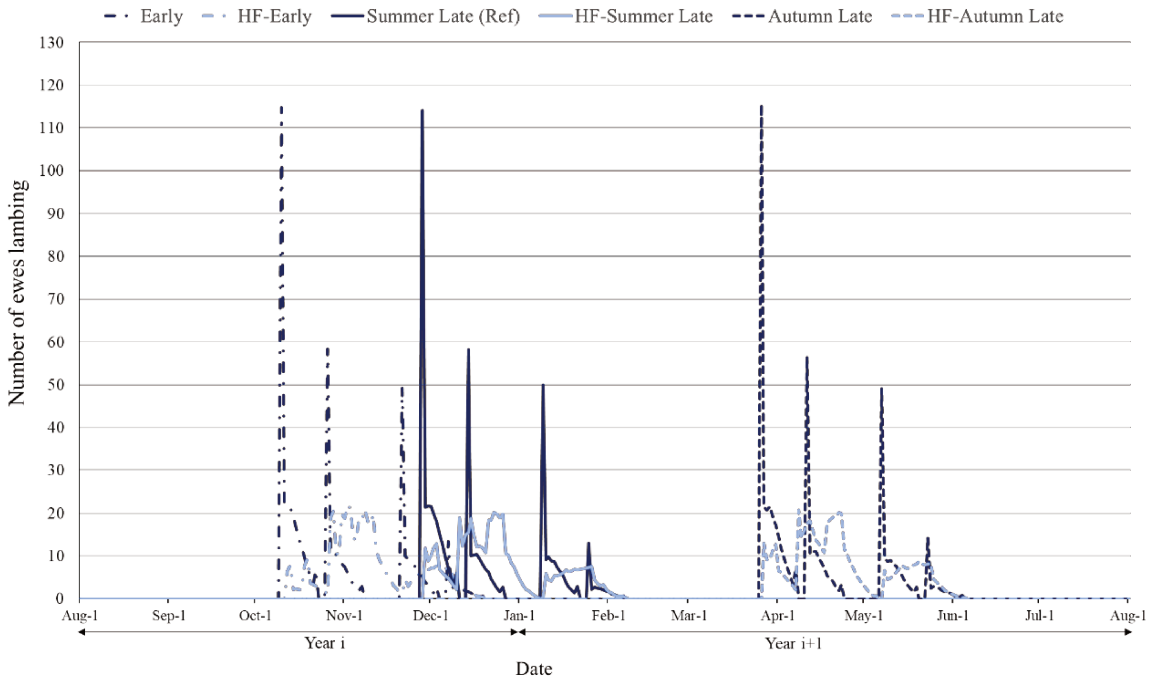

Figure IV. 3. Daily number of ewes lambing for each scenario over the simulated production season.
Ref= Current management context in the intensive dairy sheep reference farming system.
Early= *Early* reproduction scenario; *Late*= *Late* reproduction scenarios; HF= Hormone-free.

For example, ewes in mid- or late lactation will be fed with the same regime as ewes at the very beginning of lactation and will therefore potentially be overfed. One solution might be to constitute more batches of animals as much as it would be possible in practice. This may be planned 'physically' by separating the ewes in different places in the shed facility, in function of their category, which may be complicated as the number of batches are multiplied. But it may also be planned 'virtually' e.g. using precision feeding equipment like an automatic dispenser for concentrates (i.e. the most expensive feed component of the diet) to fix its daily distribution in function of specific individual requirements (with the help of individual electronic identification), which may contribute to better meet ewes' individual nutritional requirements (Hassoun et al., 2018). However, saving concentrate, when planning more than three batches in a flock such as that of La Fage farm, has been found to be irrelevant, while representing a practical constraint due to considerable increase in the workload and thus labour demand (Bocquier et al., 1995). Nevertheless, improving batches conformation (specially to take into account the specific requirements e.g. in function of parity), still a necessary practice not to ignore in order to maintain a good trade-off between performances at the flock level, 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 levels and therefore higher nutritional requirements than

primiparous ewes, even belonging to the same batch. On the other hand, primiparous ewes have specific nutritional requirements due to the fact that they are still growing while starting their productive life. These two categories of ewes should thus not be fed in the same way, whatever the reproduction scenario to be adopted.

In addition, it should be noted that in the HF scenarios the level of estrus detection was considered to be at 100 %, as it could be 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 where 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 the one simulated here.

3.1.3. Milk production and nutritional requirements 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 when comparing HT and HF scenarios.

Impacts on milk production dynamics

As shown by the flock's daily milk production evolution curves plotted in Figure IV.4.A, the HF scenarios resulted in a 10 to 14 days shift in the occurrence of the production peaks, whatever the reproduction season. This is a direct consequence of the staggering of lambing events in these scenarios, which led to change 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 2nd month of the milking period (i.e. according with the conventional milking period of 210 days traditionally programmed in the La Fage farm due to practical and local market reason), 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/day on average for the *HF-Early*, *HF-Summer Late* and *HF-Autumn Late*, respectively). Indeed, with HT the synchronization of milking entries dates was better as expected. Therefore, in the last month of this programmed milking period, the batches of ewes at milking are homogeneous in terms of physiological stages and the ewes that lambed during the first lambing phase (i.e. the largest proportion of the flock) are 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 are more heterogeneous due to the staggering of milking starts. The number of ewes already dried is therefore lower and more ewes are still being milked at the end of the programmed milking period, with still a high daily production for

some of them. This would imply a prolongation of the milking activities in the farm, allowing to continue milking those ewes which arrived later on to the milking parlour with a progressive decrease in the rhythm of drying-off planning. The question of labour demand and workload is once again on the table with this discussion. Moreover, in farms that sell their milk exclusively to dairies, the re-planning of the milking schedule could be a challenge, as the milking period is usually set by the dairy according to its demand and the farmer has less flexibility in the choice of dates for milking period during the year. Therefore, this complex issue would imply the necessity of organizing collective brainstorming at the territorial scale to reach common agreements and decision makings considering the different interests and objectives of each stakeholder involved in the value chain of the dairy sheep sector.

In addition, it has been shown that ewes with high milk production levels, close to the programmed date of introduction of rams for inducing ME, tend to have fewer spontaneous ovarian cycles with a concomitant lower response to the ME (Debus et al., 2021). Therefore, if keeping the same reproduction schedule, the higher number of ewes still being milked at the end of the programmed milking period in the HF scenarios could have negative impact 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 ME.

Impacts 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, impacts 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 IV.4.B) and protein (Figure IV.4.C) requirements of La Fage farm's flock showed delays of 7 to 10, and 10 to 13 days, in the peaks of daily energy and protein requirements, respectively, in the HF scenarios compared to their equivalent HT. Indeed, the largest part of the total nutritional requirements is known to be associated with the milk production trait. Thus, accordingly, a shift in the peak of daily milk production 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 IV.4.C), 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 like in the *Early* scenario, most of the milking phase takes place under 100

% confinement with a "passive" feeding regime (i.e. 100 % of the diet distributed). Therefore, the feeding management becomes somehow easier for making the required adjustments in function of the physiological stages progression. On the contrary, in *Late* scenario, it may be necessary to redefine and revisit other direct or indirect components of the farming system e.g. the use of arable land destined to grazing in order to better use grass and forage resources matching the biomass availability and quality with the flock requirements in a more complex and operational manner. It includes the management of the peaks of milk production, especially for the farms that have their peak in summer (June and July) like it is the case in the *Autumn Late* scenario. In addition, in a 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 parlour. If the last months of milking are during the grazing period, this would imply that they have been sent to graze on areas close to the farm. On the contrary, in HT scenarios, at the same period of the year the ewes would have been dried-off for the most part and could have sent to graze, independently of the proximity of the milking parlour or facility from the grazing paddock.

Depending on the production season chosen, the changes in the nutritional requirements evolution curves simulated here could be either an interesting or unfavourable outcome. Indeed, in the current context of climate change, it seems that relying on grazing to feed local dairy sheep flocks is increasing, as is also the delay in the biomass availability, compared to historical patterns in the Mediterranean regions such as Roquefort. This provokes farmers to also delay the start of grazing periods, during the spring, for their flocks (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 interesting adaptation response to climatic changes challenges affecting the availability of pasture. However, in the *HF-Autumn Late* scenario the daily requirements of the flock are higher compared to 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, where the biggest part of the milking period takes place during summer, the number of ewes milked is almost the same as in the *Autumn Late* scenario and consequently, the peak of production and therefore of nutritional requirements is equivalent, but delayed. It leads to higher daily nutritional requirements in summer in comparison with the equivalent HT scenario. This could thus be a challenge as it has been shown that summers are getting warmer, leading to less grazing land 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 provoked 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 lead to other impacts with complex "domino effects" that could lead to change management practices affecting more or less other aspects of the flock and overall farm performances. It should also be noticed that only one production season was simulated here. Therefore, further efforts simulating several successive production seasons seems necessary following the introduction of HF reproduction with AI in dairy sheep farms to make solid and holistic interpretations in time. This would contribute to corroborate the tendencies observed in the current work in a more complex and long-term dynamic perspective. It would also allow to observe other important differences linked to those changes in the reproduction strategies, especially the impacts on flock breeding policies and thus performances throughout several, successive production seasons.

4. Conclusion

Transitioning from conventional to HF reproduction in a dairy sheep flock represents a disruption of the annual lambing events repartition over time, followed by a shift in milk production peaks and related nutritional requirements of the flock through the year. A reduction of the annual milk performances of the flock was observed, especially in farms for which mating was performed in spring (i.e. out of natural breeding season for ewes). It thus suggests necessary readjustments of the overall management of the farm, starting with that of the feeding system which include revisiting allocation policies of available feed resources and decision makings for the efficient use of farm land particularly for grazing, and forage production. We may conclude that changing the reproduction management towards hormone-free, and therefore more fluctuant strategies, implies sub-sequent and significant changes in the feed resources planning and management at the farm and local levels, which may be taken into consideration. Further simulations on several production cycles are warranted to confirm tendencies observed here, verify if changes in nutritional requirements vary over time and other impacts such as readjustments in the overall farming system and beyond (e.g. industry).

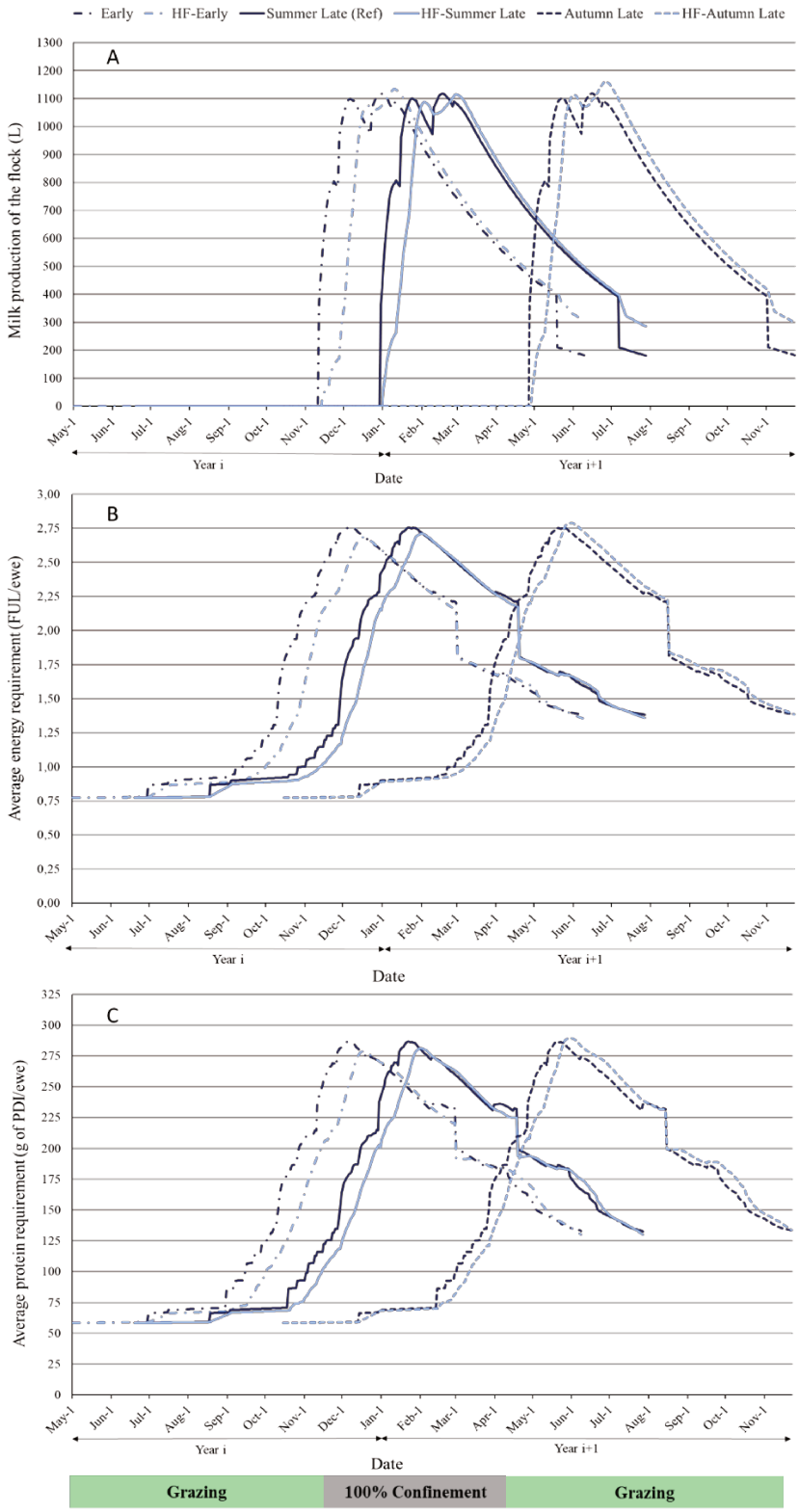

Figure IV. 4. A: Daily milk production (in L/day), B: Daily average energy requirements (in FUL/ewe/day), and C: Daily average protein requirement (in g of PDI/ewe/day) of the flock throughout one full production season, for each simulated scenario.

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.

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IV-3. Conclusion du chapitre

La simulation de différents scénarios de gestion de la reproduction du troupeau OVL conventionnel de la ferme expérimentale de la Fage (n= 597 brebis Lacaune), en utilisant le modèle REPROsheep 2.0 (décrit dans ce chapitre), a permis de dresser des premières conclusions concernant l'impact d'un passage à une gestion sans hormones dans un troupeau OVL conventionnel typique du BNO pour une campagne de production. En effet, les résultats de comparaison de scénarios qui différaient selon le type de gestion de la reproduction (avec TH + IA ou sans TH + IA) et selon la période de reproduction (« Hâtif », « Tardif » d'Été, « Tardif » d'Automne) pour un même troupeau, permettent d'appréhender quelques impacts majeurs de la mise en place d'une gestion alternative de la reproduction sur les performances et les besoins nutritionnels d'un troupeau OVL conventionnel typique du BNO. Le passage d'une gestion conventionnelle de la reproduction à une gestion sans hormones, tout en conservant la pratique de l'IA, entraînerait notamment une réduction du nombre de brebis qui agnèlent et, par conséquent, de la production laitière annuelle de l'exploitation. Ces réductions des performances annuelles s'accompagneraient d'une diminution subséquente des besoins nutritionnels annuels du troupeau. Les scénarios sans hormones ont également conduit à un décalage des agnelages, ce qui a entraîné un décalage de plus d'une semaine dans l'apparition des pics de production laitière et des besoins nutritionnels par rapport aux scénarios équivalents avec TH. L'introduction d'alternatives aux TH impliquerait donc une augmentation de la charge de travail et un allongement de la période de traite programmée, ainsi qu'un réajustement de la gestion de l'alimentation du troupeau en fonction des ressources alimentaires disponibles pour conserver les performances actuelles du troupeau. Selon la saison de production, le décalage observé dans la distribution des besoins nutritionnels peut être un résultat intéressant ou défavorable pour les éleveurs compte tenu des récents impacts du changement climatique sur la disponibilité saisonnière des fourrages dans la région méditerranéenne (pousse de l'herbe précoce au printemps, disponibilité du fourrage affectée par des températures plus chaudes en été) qui conduisent à moduler les décisions des éleveurs pour une utilisation efficace des ressources fourragères et alimentaires.

Les résultats de ce chapitre mettent ainsi en exergue des premiers impacts associés à l'introduction de pratique alternative aux TH dans la gestion de la reproduction de troupeau conventionnels à l'échelle du troupeau et sur une courte période (une campagne de production). Ces premiers éléments laissent entrevoir d'autres conséquences à l'échelle plus large de l'exploitation et pose la question de l'évolution de ces impacts sur le moyen et long terme.

Chapitre V :

Modélisation des conséquences à long terme de la mise en œuvre d'une gestion de la reproduction sans hormones sur la durabilité d'une exploitation ovine laitière

Chapitre V- Modélisation des conséquences à long terme de la mise en œuvre d'une gestion de la reproduction sans hormones sur la durabilité d'une exploitation ovine laitière

Ce chapitre présente le développement du modèle REPRIN'OV, un modèle d'exploitation OVL destiné à simuler le fonctionnement d'une exploitation OVL au cours du temps. Ce modèle, développé sur la base des travaux présentés aux chapitres III et IV, simule notamment plusieurs indicateurs de la durabilité du fonctionnement d'une exploitation OVL. L'objectif du développement du modèle REPRIN'OV est présenté dans ***la première partie de ce chapitre****. Sa description ainsi qu'un exemple d'utilisation sont présentés dans* ***la deuxième partie de ce chapitre*** *sous forme d'un article soumis dans la revue Computers and Electronics in Agriculture. Une* ***dernière partie*** *résume les conclusions principales du travail présenté dans ce chapitre.*

V-1. Introduction du chapitre

L'introduction de pratiques de gestion de la reproduction impliquant l'usage de l'effet mâle comme alternative aux TH laisse envisager des impacts collatéraux sur le fonctionnement global des systèmes de production classiques (cf. Chapitre IV) et pourrait affecter leur durabilité à long terme. Afin de proposer des solutions alternatives pérennes, il est particulièrement important de réfléchir aux répercussions qu'il pourrait y avoir sur l'ensemble des aspects de la durabilité (économique, sociétaux et environnementaux) du système de production, et ce, sur le long terme. L'objectif du travail présenté dans ce chapitre était donc de concevoir un modèle multi-agent d'exploitation OVL permettant de simuler et d'étudier les conséquences à long-terme de l'introduction de méthodes alternatives aux TH, incluant l'utilisation de l'effet mâle, sur une série d'indicateurs de performances biotechniques, économiques et environnementales de l'exploitation, ainsi que sur la charge de travail de l'éleveur. Il s'agissait de développer un modèle d'exploitation dynamique sur la base du modèle de troupeau OVL présenté dans les chapitres précédents et de l'utiliser pour explorer les conséquences d'un changement de la seule gestion de la reproduction (c.-à-d. sans adaptation d'autres pratiques associées) sur les performances globales d'un élevage conventionnel OVL à partir d'un exemple d'élevage typique du BNO. Des scénarios alternatifs incluant l'utilisation (ou pas) de l'IA ont été simulés pour un cas-type d'exploitation OVL conventionnelle du BNO afin d'explorer la diversité de conduites alternatives possibles pour les élevages conventionnels dans l'hypothèse d'un arrêt de l'utilisation de TH (cf. Chapitre II).

V-2. Article 3: Modelling the long-term consequences of implementing hormone-free reproductive management on the sustainability of a dairy sheep farm

Modelling the long-term consequences of implementing hormone-free reproductive management on the sustainability of a dairy sheep farm

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Abstract

Livestock production systems are strongly influenced by societal constraints that induce changes in their overall chain value organization and functioning. In dairy sheep farming, to stop the use of hormonal treatments (HT) for heat induction and synchronization, alternatives such as the use of the male effect (ME) supported by precision tools (heat detector) are developed. However, the effectiveness of these hormone-free (HF) alternatives for managing ewes' reproduction remains more uncertain than that of conventional HT. Thus, HF implementation implies collateral impacts on the overall functioning of the production system and could affect its long-term sustainability. In the current work, a new multi-agent model (called REPRIN'OV) was designed to simulate consequences of introducing alternative methods to HT (including ME) on a series of biotechnical, economic and environmental farm performance indicators, including farmer workload. Three reproduction management scenarios were simulated over five consecutive years for a case study of a conventional dairy sheep farm. They were defined as: use of HTs and insemination (HAI); no use of HTs while preserving insemination practice (HFAI); no use of HTs and direct mating only (i.e., no insemination; HFM). Results confirm that implementing HF reproductive management without accompanying it with further changes in farm management, could negatively impact several indicators of the farm sustainability in the medium and long-term. Indeed, the HF scenarios resulted in overall lower farm biotechnical and economic performances (e.g., -4% for the fertility rate; -5% for the total milk production; -3% for the total gross margin compared to HAI; $P< 0.05$). An increase in farmer's workload during the lambing period was also observed (i.e., +33% and +32% of working time in HFAI and HFM, respectively; $P< 0.05$) and in the simulated environmental indicators (e.g., +6% and +5% of farm CH4 emissions for HFAI and HFM, respectively; $P< 0.05$). Nevertheless,

positive outcomes were also simulated in the HF scenarios as ewes lambing peaks were lower than in HAI suggesting e.g., a possibility to improve ewes and lamb surveillance during lambing. HF scenarios also led to higher gross margin per litre of milk produced for the studied farm because no HT was used reducing the production costs compare to HAI. In addition, implementing insemination in HF context (HFAI) improved farm milk production and quality (i.e., fat and protein content), which resulted in improved gross margin compared to HFM. Overall, simulation results showed that to warrant sustainable introduction of HF strategies (including ME), new frameworks in the organization of key operations at the farm level should be explored (e.g., extending reproduction or milking periods length) and trade-offs should be discussed, considering all involved stakeholders of the dairy sheep industry and the chain's value requirements. The REPRIN'OV model, may provide an effective tool to simulate the collateral impacts of establishing HF reproductive management practices and could be used as a decision support system to accompany the ambitious transition towards a HF dairy sheep industry in Europe and beyond.

Keywords: Small dairy ruminants; Reproduction; Milk production; Multi-agent model; Farm sustainability

1. Introduction

In the major European dairy sheep production areas, conventional farms often rely on the use of hormone treatments (**HT**) to synchronize the ewes' estrus (or heat) and lambing peaks in the flock. Such HT are a way of securing good reproduction performances while making easier the planning of farmer's work (i.e. with concentration of the main activities in specific periods across the year). HTs allow the ewes to come into estrus at any time of the year, despite their reproduction seasonal nature. Their use thus makes it possible to better respond to milk and lambs market demands after effective ad hoc harmonization of the reproduction and production cycles in the flock (Martin et al., 2004). As ovine AI is limited to the use of fresh semen with a short service life (Anel et al., 2006), the use of HTs to effectively anticipate and synchronize the moment when ewes come into estrus is also considered as an essential step for the good implementation of artificial inseminations (AI). Therefore, the HT are firmly established in the flock management schemes of most of the worldwide intensive and semi-intensive dairy sheep farming systems, including the European and French sectors.

Nevertheless, HT is increasingly questioned by society worldwide. Consumers are the more and more requesting for products that come from farming systems with a minimum (or not at all) use of HT while favouring practices that do not compromise animal welfare (Martin et al., 2004). For these reasons, some alternatives to HT such as the use of photoperiodic protocols (Pellicer-Rubio et al., 2019), the "female-female" effect (i.e. stimulation of the ewes

ovarian activity, provided by social cues emanating from other females of the flock ; Rosa and Bryant, 2002), the male effect (i.e. stimulation of the ewes ovarian activity via hormonal signals following contact with rams; Martin et al., 1986, 2004) or even synthetic pheromones to mimic the rams olfactive stimuli (Cohen-Tannoudji et al., 1994), have been studied in the last years to stimulate ewes ovulation and to concentrate the peaks of lambing events in sheep farming. The male effect (**ME**), in particular, is a well-known hormone-free (**HF**) practice that relies on the fact that a sexually active male, via sensory signals, is able to induce and synchronize estrus and ovulation in anovulatory females (i.e. sexually resting or non-cycling; Thimonier et al., 2000; Delgadillo et al., 2009). However, with the use of this HF practice, collateral impacts must be expected in the rest of the farming system components as the efficiency of the ME for estrus induction and synchronization is more uncertain compared to conventional HT. The reproductive performance of the flock in a HF context including the use of ME is indeed subject to variability in estrus onset due to the diversity of individual characteristics of the ewes present in the flock such as their age, body condition or milk production level but also due to management decisions issues like the time left between drying off and mating (Tournadre et al., 2002; Debus et al., 2022). Such variability in estrus onset is expected to induce a staggering of lambing events and thus a disruption of their repartition over time, followed by a shift in milk production peaks, the whole suggesting necessary readjustments on the overall management of the farm, including feeding for example (Laclef et al., 2022).

To date, the consequences on the other aspects of the farming routines, as well as the medium- and long-term effects at the farm level are still unknown, as most of the research on alternatives to hormonal induction and synchronization treatments in sheep farming has focused on technical solutions without taking into account a systemic approach and the side effects on key issues like impacts on farmer workload or on the economic and environmental performances of the farm. Nevertheless, knowing how a technical innovation affects a farm global dynamic over time is an essential to consider its further implementation in the farming systems (Ingrand et al., 2014). In addition, livestock farming activities are often criticized for their environmental impacts e.g. as a major source of greenhouse gases (GHG; Bochu et al., 2013) or as a significant consumer of energy and water resources. Therefore, a multicriteria approach must be adopted when proposing innovations, in order to evaluate impacts in economic, environmental and societal indicators. In this context, a question then arises about how implementing HF reproduction management in a conventional dairy sheep farm affects its short-, medium- and long-term sustainability.

The aim of this study was to conceive a model allowing to perform a series of simulations for assessing the impacts to be expected when implementing HF reproduction management in dairy sheep farming. Key biotechnical, economic and environmental performance indicators reflecting the functioning of a dairy sheep farm as well as those related to the farmer's workload during milking and lambing periods were then considered.

2. Material and Methods

A multi-agent model was designed to simulate performances in both annual and dynamic (daily or weekly) indicators of dairy sheep farms under different reproduction management scenarios, using the available information, experiences and databases on representative dairy sheep farming systems for the Roquefort basin (South of France). The simulated farm performance indicators were compared over five consecutive production cycles in order to assess the long term impacts of a HF reproduction management. The model was implemented using the GAMA software (Taillandier et al., 2019), designed for the development of multi-agent simulations. Its source code can be accessed on https://github.com/elaclef/REPRINOV-model.git

2.1. Characteristics of the modelled dairy sheep farming system

The Roquefort basin (South of France) is the first region of sheep milk production in France (74% of the national production; Chambre d'agriculture Occitanie, 2021), which is related to the fact that a large part of its territory belongs to the appellation area of the Roquefort PDO cheese. In this region, dairies traditionally collect milk from December to August, resulting in a homogeneous model of livestock management, with a short mating period and a milking period for the whole flock that begins between November and February for most of the farms (Lurette et al., 2018). The dairy sheep farming systems in this area are strongly influenced by the production constraints and rules of the dairies and for many farms by the specifications of the Roquefort PDO (79% of the milk collected in the region in 2019 was delivered to Roquefort PDO; Chambre d'agriculture Occitanie, 2021). Therefore, the Lacaune is the main breed used in the Roquefort basin and grazing represents one of the most significant components of the feeding systems. The Inosys Network is a monitoring program (IDELE, 2014) comprising a database conceived to represent the functioning of the most representative French farming systems in several specific production areas of the country. For this study, the characteristics of the modelled farm were mainly based on the information provided by this database. The latest database of one of the representative dairy sheep farming systems of the Roquefort basin (De Boissieu and Morin, 2022) was then arbitrarily chosen, in order to simulate and evaluate how the changes in the reproduction

management can affect dairy sheep farms functioning and sustainability based on a case study.

2.2. Model description

The following description is given according to the rules of the O.D.D. protocol (Overview, Design concepts, Details), specifically created for the description of multi-agent models (Grimm et al., 2020).

2.2.1. Overview of the model

The REPRIN'OV (REPRoductive INnovation in OVine farming) model represents the dynamic functioning of a dairy sheep farm and has been designed to simulate and compare different scenarios of flock reproduction management practices, with or without using hormones. It consists in the integration into a farm model of a modified version of the stochastic dairy flock model (REPROSheep) previously developed by our team (Laclef et al., 2021), which aimed to model the functioning of a dairy sheep flock under a HF reproduction management using ME. The main addition, modifications and progresses in REPRIN'OV include inputs in the farm functioning and yearly evolution rules allowing to simulate the dynamic long-term functioning of a dairy sheep farm under several reproduction management scenarios. It looks to simulate and evaluate the "ex-ante" impacts on the main biotechnical, economic, and environmental performances of the farm, as well as the farmer's workload. The final goal is to identify sustainable ways to introduce HF insemination in dairy sheep farming, considering all three main dimensions (economic, environmental, and societal) of the sustainability.

2.2.2. Entities, state variables and scales

Entities

The economic and environmental indicators of the farm are driven by the biotechnical performances of the flock (i.e. namely reproduction and milk production outcomes). Therefore, the central entities of this model are the *Sheep* agents, representing the biotechnical animal entities of the farm. Two types of sheep agents are distinguished: *Ewe* (female sheep) and *Ram* (male sheep) agents, which are defined by several individual characteristics i.e. age, body condition score (**BCS**), milk production level, or physiological and nutritional status over time (Appendix A/Table A2.1). They carry out their daily life activities (reproducing, producing milk, eating and resting) during a production cycle according to the management rules of a *Farmer* agent (i.e. the human entity in charge of decision making). The *Farmer* agent is characterized by its flock management choices and decision makings (reproduction, milking and grazing dates, use of HT or ME, insemination or mating, culling and replacement criteria). *Feed* and *Land* agents have also been defined

as they play a major role in the functioning of a dairy sheep farm. The *Feed* agent represents the different diets and feeds supplied to the ewes over time, and their related features (name and type of feed, batch of animals to which it is offered, distribution period…). The total amount of feed distributed to the flock over a production cycle has an impact on the nutritional intake of the animals present in the flock, but also on the economy of the farm, hence the importance of representing in detail the distribution of the different feeds to the flock over time. With the *Land* agent, the management of the different agricultural lands available in the farm was taken into account, which is important since part of the feed comes from it. Their use is closely related to the progressive feed requirements of the flock, which may of course significantly affect the economy but also the environmental performance of the farm. Each *Land* agent was therefore defined by its type (grassland, rangeland or cropping – cereal- land), its finality (mowed, grazed and/or cultivated), its size, the yield obtained at each harvest (if mowed), the inputs used for its maintenance (fertilizer, seeds and other treatments) as well as the price of these inputs.

State variables and attributes

Appendix A/Table A2.1 describes the main state variables and attributes of this model (both at the global and the agent levels).

Temporal scale

The time step used is 12 hours i.e. half a day. The REPRIN'OV model simulates five successive production cycles, which represents a time period of approximately five years (a production cycle covering from the beginning of reproduction to the end of milking period). It typically takes four cycles for a dairy sheep flock to be completely replaced in the Roquefort region, given the average 28 % renewal or culling rate practiced in the region (De Boissieu and Morin, 2022). Five is thus a good number of production cycles allowing to assess the long-term impacts of changes in reproductive management on farm performance.

2.2.3. Processes overview and scheduling

Initialization

A simulation is initialized by creating a flock (Ewes and Ram agents) and setting a management strategy for the modelled farm (i.e. flock's reproduction, feeding and lands management) based on criteria emerging from the literature, expert knowledge and the available database from the French Livestock Institute (IDELE), as previously cited. All the details on initial values of the main attributes and state variables of the agents as well as those from the parameters used in the model are specified in Appendix A. Each simulation starts on the first day of reproduction (i.e. date of the ram introduction for the ME or on the first day of HT) and last until the end of the fifth year (i.e. the day after the end of milking

in the fifth simulated production cycle). Such starting and management dates are set according to the modelled farm functioning (through an external CSV file).

Description of the main modelled processes

The main processes represented in the model follow each other over the simulated production cycles and the different agents represented intervene in one or more of these processes (Table V. 1).

Table V. 1. Main processes and/or farming activities considered in the REPRIN'OV model *(in bold the additional processes modelled in comparison to the REPROsheep flock model; Chapitre III).*

Process	Agents implicated	Submodels
Reproduction	Ewes and Rams	SM1
Lactation	Ewes	SM2
Feeding the flock	**Feed, Farmer, Ewes and Rams**	**SM3**
Reproduction management	Farmer	SM4
Milking management	Farmer	SM5
Flock replacement policy (culling)	Farmer	SM6
Agricultural lands management	**Farmer and Lands**	**SM7**
Updating values for economic, environmental and farm workload indicators	**Global**	**SM8**

2.2.4. Design concepts

The model built is considered as dynamic, as it is modelling the functioning of a dairy sheep farm over time. It is also classified as stochastic, as several processes responding to probability laws ruled the modelled reproduction mechanism i.e. cyclicity and response to the ME of the ewes (Section 2.2.5.SM1). As reproduction processes underlie the observed flock and farm performances, this leads to stochasticity in the overall outputs. In addition, mating, abortion, easy of lambing, mortality, the litter size and being in seasonal anoestrus at time *t* are events that are also estimated using probabilities set at the beginning of the simulation Appendix A/Table A2.2.

2.2.5. Submodels

Reproduction: SM1

The ewes individual biological process of reproduction corresponds to a succession of transitions from one physiological state to another over time. The representation of this

process in the current REPRIN'OV model is an evolution of the one made by Laclef et al. (2021). It represents the reproduction process according to different management decisions and could be functional either in HT or HF contexts, especially as it allows considering the variability of ewe response to ME in the HF context. In a HT context a fixed probability of synchronization success is assigned and determines if the ewe is sexually receptive ("in heat" or estrus; Figure 1). On the contrary, in a HF context, the probability of being in estrus is determined by the probability for an ewe to be cyclic, PC (i.e. spontaneously ovulating and showing estrus) and, if not cyclic, by the probability of responding to the ME, PRME. The PC differs according to the reproduction season considered. When the reproduction takes place during the full natural reproduction season of ewes (i.e. autumn), or close to it (i.e. summer), the PC is fixed at a high level (between 0.8 and 1; Appendix A/Table A.2) since European sheep breeds have been shown to express a high probability of being in estrus during this time of year (Chanvallon et al., 2011). However, when it takes place during the spring (i.e. out of the natural reproduction season of the ewes), the PC is a function of the Age, BCS, last lambing to ME interval and milk production level of each ewe, as defined by Laclef et al. (2021) for Lacaune ewes. The PRME at every time of the year is also a function of ewe's Age, BCS and milk production level, as defined by Laclef et al. (2021). The variables in ewe's PC and PRME equations are therefore individual characteristics of the ewes and evolve over time. As reproduction usually takes place before the end of milking, some ewes are still lactating at that time. Therefore, in the REPRIN'OV model, once past the first year of simulation, in order to calculate the PC and PRME probabilities, an estimate of the total milk yield of producing ewes is made using the total milk yield estimation equation developed by Pollott and Gootwine (2000). For BCS progression over time, as far as we know, there is no available information to represent individual evolution profiles for the ewes of the Lacaune breed. Therefore, a theoretical representation of BCS progression over the years was made for the finality of this study, taking into account the expertise of our team in the body reserves subject for the Lacaune breed in the Roquefort area (González-García et al., 2015). Thus, each year, independently from the feeding management strategy and genetic evolution of the flock, multiparous ewes (i.e. since the beginning of the second production cycle, once finished more than 90% of their growth) lose 0.1 BCS points per year, while young primiparous ewes gain 0.2 BCS points during the first production cycle. Some ram's individual characteristics such as their age, BCS or libido level are also known to influence the ME efficiency (Rosa and Bryant, 2002). However, in this model rams are always considered to be in optimal conditions. Ewes pregnancy or a non-pregnancy state following AI or mating are defined according to a probability of AI success (PAISuccess) or a probability of mating success (Pms).

Then, the other steps of the reproduction process (potential abortion, lambing; Figure 1) are reached as designed in Laclef et al. (2021).

Lactation: SM2

In agreement with Laclef et al. (2021), the lambing event triggers the start of an ewe lactation process. Ewes individual milk production during lactation are calculated using the equation developed by Lagriffoul et al. (2003). This equation takes into account the milk yield on the first day of milking (Initial Daily Milk Yield; IDMY) as well as the duration of milking. At birth, ewe lambs are assigned an IDMY value as well as an initial milk fat and protein content value (IMFC and IMPC, respectively) depending on whether they are born from AI or direct mating. If the ewe lamb is born from AI, then its IDMY, IMFC and IMPC values are those of its mother to which is added a gain value linked to the genetic input of the AI. This gain value was estimated based on expert knowledge and on the evolution of milk production potential in the Roquefort area during the last decade, as recorded in the SIOEL database (an information system implemented for dairy sheep in France to manage genetic and techno-economic data; Astruc et al., 2008). Thus a genetic gap of 5 years (i.e. 20 L/year for the total individual milk production) between farms using or not AI was estimated, and therefore a phenotypic gain of 4 L/year, 0.17 g/L/year of fat content and 0.14 g/L/year of protein content was modelled. However, if the ewe lamb considered is born from direct mating, then its IDMY, IMFC and IMPC values are the same as those of its mother.

Feeding of the flock: SM3

A feeding program is defined by the farmer in order to design the relative and specific amounts per ingredient or component of the feeding system (including the role of pasturelands) to be daily allocated to each animal category present in the flock (i.e. ewes and rams), according to their physiological stages (i.e. gestating, suckling, lactating and maintaining) and the period of the year. Each individual is then expected to receive a daily diet in accordance with such a program, decided by the farmer. Rams are set to receive the same feeding regime of adult dry ewes (in maintenance). It should be noted that, due to simplification reasons, the feeding program is the same (i.e. same type and amount of feed distributed) throughout the production cycles, although in reality, some adaptation should be expected giving the nutritional resources availability and daily individual (or flock) milk production yield and nutritional requirements progression in the flock over time. In addition, no relations between the individual ingestion and the milk yield or body condition of the ewes were represented considering that in the Roquefort basin ewes are fed largely over their needs. Thus, we considered that even though the feeding program wasn't adjusted

throughout the years, it was always sufficient to keep achieving a similar level of performances in the simulated flock for the duration of the simulation.

Managing the reproduction: SM4

Based on the classical organization of a dairy sheep flock in the Roquefort basin, the modelled reproduction management is focused in two batches managed separately until the start of milking operations. The first batch being the adult ewes and the second the ewe lambs (mated at least 15 days after the adult batch depending on the farm reproduction strategy). The main actions or reproduction management decisions executed by the farmer are the following:

- *Choosing ewes to inseminate:*
  - ***With HT:*** Every year, on the first day of reproduction, the ewes to be inseminated are chosen according to the AI rate defined by the farmer for each batch of females. They are selected among the ewes (adult and young) present at breeding and not chosen for culling.
  - ***Without HT:*** Since there is no way of knowing in advance which ewes will be in estrus, each ewe, if not chosen for culling, is designated as to be inseminated.
- *Choosing AI days:*
  - ***With HT:*** (see. Table IV.4; Chapitre IV).
  - ***Without HT:*** The AI protocol differs according to the reproduction season considered (see. Table IV.5; Chapitre IV).
- *Inseminate ewes:*
  - ***With HT:*** On the day of AI corresponding to the reproduction management strategy modelled, all ewes chosen for insemination are inseminated.
  - ***Without HT:*** On each AI day, ewes in estrus (and detected as so by the farmer) are inseminated. The level of detection by the farmer is represented via a detection rate. In this study, it was fixed to be at 100 % (i.e. every ewe in estrus on AI days is detected).
- *Managing free mating periods:* During free mating periods, the rams are active for mating and once ended, they are considered no longer active (without the possibility to mate with females). The duration of free mating is set by the farmer according to the reproduction management strategy.
- *Mating of the adult ewes:* The mating rams are introduced twice into the batch of adult ewes:

- ***With HT:*** The mating rams are introduced with the ewes 14 days after the AI day until the end of the first mating period defined by the farmer. Then the rams are introduced a second time when the mating period of ewe lambs starts.
- ***Without HT + AI:*** The ram is introduced 2 days after the last AI day until the end of the first mating period defined by the farmer. Then the rams are introduced a second time at the end of this first mating period until the ram's final withdrawal date defined by the farmer.
- ***Without HT, Without AI:*** The ram is introduced directly after the last day of ME until the end of the first mating period defined by the farmer. Then the rams are introduced a second time at the end of this first mating period until the ram's final withdrawal date defined by the farmer.

- *Mating of the ewe lambs:*

- ***With HT*:** The mating rams are introduced with the ewe lambs 14 days after their AI day until the ram's final withdrawal date set arbitrarily by the farmer.
- ***Without HT:*** As ewe lambs are not inseminated, the ram introduction date for mating is set arbitrarily by the farmer depending on the management context. The date chosen in this work is the one corresponding to the ewe lambs AI date in a HT context. This choice was made to keep an equivalent time lapse between the young and the adult batches reproduction onset in every scenario.

Figure V.1 summarizes the principal steps of the modelled reproduction management strategy from the start of the synchronisation protocol until the end of the mating period in both hormonal and non-hormonal contexts (including AI or not).

Managing the milking: SM5

The milking management sub-model was designed in the same manner as proposed by Laclef et al. (2021), with the difference that ewes only start milking if the milking production period, as defined by the farmer, has already started. Therefore, all ewes that finish their imposed suckling period before the milking start date remain in suckling until milking starts.

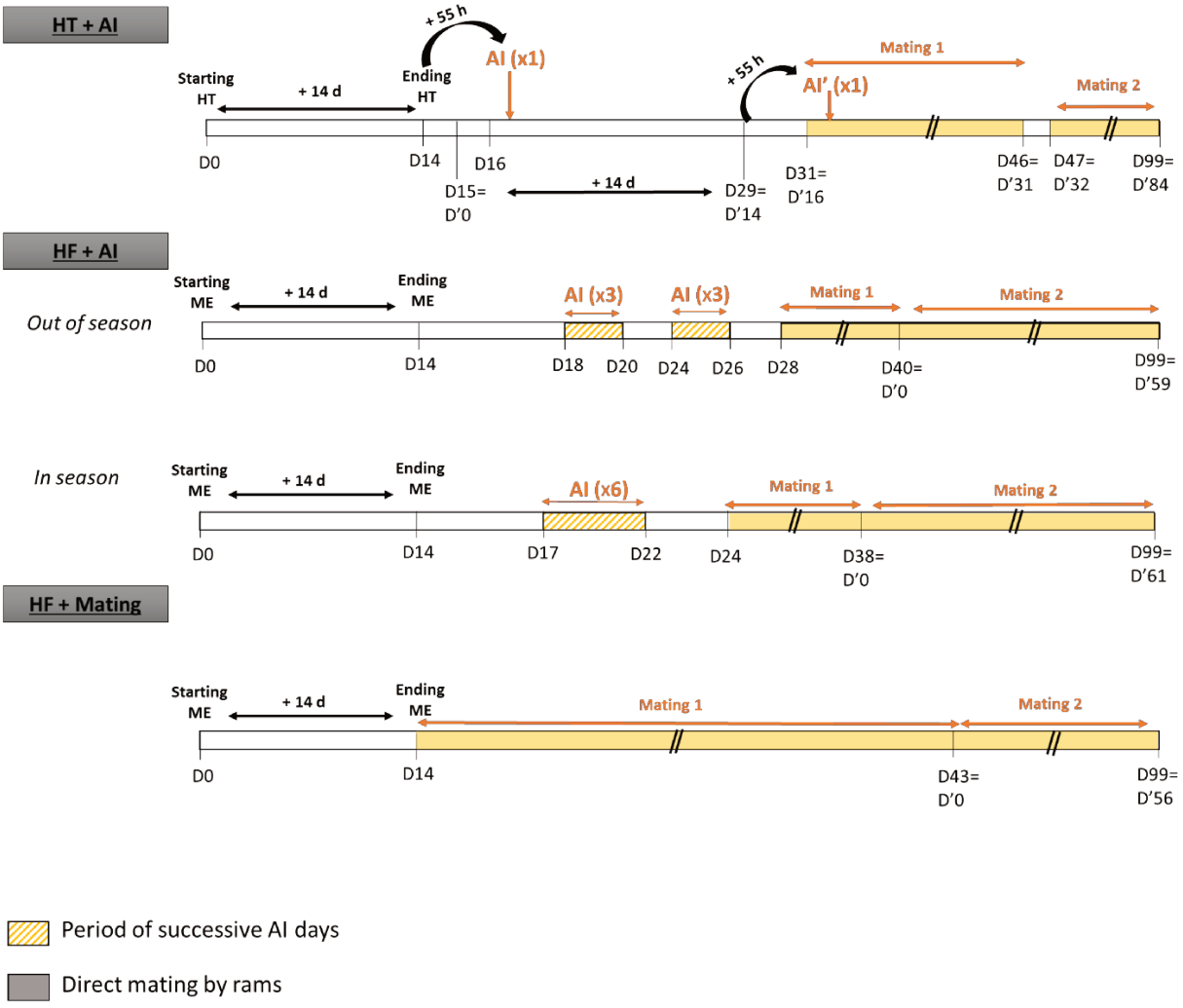

Figure V. 1. Principal steps of the modelled reproduction management strategy from the start of the synchronization protocol until the start of mating for the adult batch in both hormonal and non-hormonal contexts (including AI or not).
In season=From June to December; Out of season= From January to May. D0= Day of reproduction start for the adult batch; Di= i days after the start of reproduction for the adult batch; D'0= Day of reproduction start for the young batch; D'i= i days after the start of reproduction for the adult batch.
AI= Artificial insemination; HF= Hormone-Free; HT= Hormonal Treatment; ME= Male effect. AI (x1)= One AI day for the adult batch; AI' (x1)= One AI day for the young batch;AI(x3)=Three successives AI days for the flock; AI(x6)= Six successives AI days for the flock. In the HF+AI scenario only ewes detected in estrus are inseminated. Mating 1= Mating of the adult batch only; Mating 2= Mating of the young batch and of the adult ewes in heat. The direct mating periods illustrated here are specific to the farm modelled.

Managing the flock renewal: SM6

The retained flock renewal actions are:

- *Culling ewes:* Every year, 2 months from the start of reproduction, a replacement rate and the number of ewes to be culled are set by the farmer agent, looking for a balance between the number of new-borns and departures (so that the size of the flock remain more or less constant). Thus, the number of ewes to be culled will be equal to *the number of ewes present at lambing* × *yearly replacement rate*. This number of ewes to be culled is then adjusted by deducting the number of ewes to be culled due to lambing problems. The ewes to

be culled are chosen based on usual culling criteria in the dairy sheep farms of the Roquefort region (Fréret et al., 2018). Thus, they are chosen firstly among multiparous ewes based on their milk production from the previous production cycle (the ewes with lower production yields are culled in priority). Then, if there is a lack of ewes to cull, a selection is made according to the ewes age (the oldest ewes are chosen as a complement). The culling takes place the day after the last day of milking of the flock.

- *Culling rams:* On the starting date, the number of rams to be culled is calculated so that one third of the total number of mature rams (i.e. ≥ 2 years old) is culled. Then, each year, 10 months after breeding, the farmer selects this number of rams from the mature rams to be culled. Rams designated to be culled are set to die on the day after the last designated day for milking.
- *Choosing or buying ewe and ram lambs for replacement:* If the farm's renewal strategy of the ewes is an auto renewal one (i.e. 100 % of replacement taken from the new-borns of the farm), at the end of their suckling period, new-born weaned females (i.e. that didn't die before weaning) are selected by the farmer to replace the culled ewes, starting with the first born. This choice of selection was made so that by the time of their first mating, in the next production cycle, all ewe lambs selected for replacement could be at least 7 months old (the age at which ewes typically begin puberty and reproduction becomes possible ; Corner et al., 2013). The number of ewe lambs chosen for replacement is equal to the number of culled ewes. Selection ends when the number of ewes necessary for replacement is reached. Renewal rams are selected in the same way in case of auto-renewal. However, if the farm strategy is not an auto renewal one, on the start of milking date, a number of ewe (and/or ram) lambs equal to the number of culled ewes (and/or rams) is bought to replace the culled ones. Therefore, new lambs are created with a birth date arbitrarily set to 1 month before the start of milking date.
- *Selling lambs:* Once the number of renewal lambs is reached, the remaining weaned lambs are sold.

Managing agricultural lands: SM7

The same dates for harvesting forages and crops surfaces are set by the farmer each year, in order to keep the forage and grain stocks (*land size*yield*). To simplify the model, the yield of each crop and forage doesn't change over the years.

Updating the values of economic, environmental and workload indicators: SM8

The model simulates several annual indicators of the farm economic and environmental performances as well as annual and dynamic indicators of the workload on the farm. Economic and environmental indicators are calculated once every simulated year, on the day

before the first day of the classical suckling period of the farm, while workload indicators are calculated daily during specific periods (lambing and milking) as well as once a year, on the last day of the production cycle. The outputs of the flock functioning sub-model (e.g. physiological states, number of ewes lambing or milk production) are used as inputs for the calculation of these indicators.

- *Calculation of economic indicators:* The gross margin of the farm (without taking into account the potential subsidies) is the main economic indicator simulated, which is a result of subtracting operation costs (expenses) to the farm's gross income. The total gross income is simulated by the addition of the gross incomes resulting from yearly animal (milk, lambs and culled ewes and rams sold, renewal ewes and rams bought) and crop (forage, straw and grain sold) productions. The operation costs are simulated by adding those coming from animal production (reproduction, feeding and other eventual costs) and the ones resulting from crop production (cropping land management activities). All these economic indicators are calculated by multiplying the reference prices corresponding to the simulated production systems by the corresponding output simulated by the flock model.

- *Calculation of environmental indicators:* The model simulates two types of environmental indicators of the farm functioning i.e. GHG emissions (CH_4 and CO_2) and water consumption.

• *CH_4 and CO_2 emissions:* Every year, the CH_4 emissions from enteric fermentation and manure management, the CO_2 emissions linked to the feed input distributed to the flock and that due to the use of electricity during milking in the farm are simulated. The model uses a combination Tier1 and Tier2 methods of the IPCC (2019) guidelines for inventories of GHG to simulate the CH_4 and CO_2 emissions.

• *Water consumption:* Water consumption in a dairy sheep farm includes watering of the different categories of animals present in the flock (lactating and pregnant ewes, ewe lambs, rams), water spent during the milking process in the milking parlour. Therefore, for every year, the model makes the simulation of this indicator by taking into account the volumes of water consumed for all these tasks.

- *Calculation of workload indicators:* Every day, during the lambing and milking periods of the simulated farm, the working times related to lambing and milking activities are calculated based on reference values used for dairy sheep farming (IDELE, 2021). The maximum duration being 24h of work per day (as theoretical maximum of hours that could be spent on a task by one or more people in a day).

The detailed calculation used to estimate all these indicators are presented in Appendix B.

2.3. Model outputs

The REPRIN'OV model simulates annual and dynamic reproduction and milk production performance of the flock as well as economic, environmental and workload indicators of the farm functioning. It also simulates several intermediate outputs such as the evolution of physiological states into the flock over time. The outputs evaluated in this study are specified in Table V.2.

Table V. 2. Flock and farm performance outputs, and sustainability indicator outcomes, evaluated with the REPRIN'OV model.

Annual outputs	Dynamic outputs
Biotechnical indicators	
Fertility rate	Number of ewes lambing /day
% of ewes inseminated	Number of ewes lambing from AI/day
% ewes lambing from AI	Milk production (L/day)
% of renewal batch born from AI	
Number of ewes milked	
Total milk production (Tons)	
Average milk production (L/ewe)	
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 (1000 €)	
Gross Margin (€/L of milk)	
Environmental indicators	
CH_4 emissions (kg CO_2eq/L of milk)	
CO_2electricity emissions (kg CO_2eq/L of milk)	
CO_2feed emissions (kg CO_2eq/L of milk)	
Water consumption (L/L of milk)	

2.4. Validation

The REPROsheep flock model underlying the REPRIN'OV model was validated by Laclef et al. (2021), using data from two commercial farms of the Roquefort area. Therefore, the simulated reproductive and dairy performance of the flock (hence the farm) were considered as accurate. The accuracy of the other outputs at farm level was validated using the "face validity" procedure (Sargent, 2015), meaning that they were validated based on expert knowledge or by comparison with the actual values or ranges of values usually observed in the literature.

2.5. Simulated scenarios: virtual experiment

In order to illustrate the use of the REPRIN'OV model, alternative reproduction management scenarios were simulated for a dairy sheep farm. The farm modelled is a conventional dairy sheep farm described as a specialised high altitude grassland system favouring the use of grass for animal feed (De Boissieu and Morin, 2022). The reproduction

strategy of this farm is based on the use of HTs followed by AI on almost the entire flock. The reproduction starts there in mid-June until mid-September and the milk production of the flock lasts 217 days (from December 15th of year *n* to July 20th of year *n+1*). Table V.3 describes the main characteristics of the modelled farm for each scenario. All initial characteristics of the simulated farm are given in the Appendix A. All the reference prices used for economic output calculation were taken from the Inosys Network database (IDELE, 2014) and are specific to the farm functioning simulated. Three different reproduction management scenarios were simulated for this same farm. A first scenario (HAI) representing a reproduction management including the use of HT and AI practice on the whole flock was simulated. This scenario corresponds to the current reproduction management in this farm and served as a reference for the comparisons between scenarios. Then a second scenario (HFAI) representing a HF reproduction management associated with AI practice on adult ewes, and a third scenario (HFM) representing a HF reproduction management followed by mating only, were simulated. In the HF scenarios, the ME was used as an alternative to HT and the ram:ewe ratio was set to 1 ram per 30 ewes so that the number of rams was sufficient to perform an effective ME. Mating strategies were modelled as described in the Section 2.1.5. Each scenario was simulated over five consecutive production cycles. For all three scenarios, the reproduction period was the same (starts on June 9th of year *n* and ends on September 25th of the same year *n*). Only the organization of reproduction differed between the scenarios. The goal being to observe the only effect of a change in reproduction organization in the current farm organization context. Thus, the feeding program as well as milking period of the flock remained identical in all scenarios.

2.6. Statistical and descriptive analysis of simulation outputs

Two-factor ANOVAs were performed to study the combined fixed effects of the scenario and production cycle on the annual outputs. Mixed model ANOVAs were also performed to study the effect of the scenario on the mean values of the annual outputs over the five simulated production cycles. The dynamic outputs were plotted in order to perform a descriptive analysis of the dynamic progression for each parameter. Scenario results per production cycle are expressed as the means of 75 simulation repetitions (threshold value allowing to manage the stochasticity of the flock performances simulated by this model based on Laclef et al., 2021) and therefore, the average scenario results for the 5 production cycles are expressed as mean of (5*75) simulations. All statistical analyses were carried out using the R 3.6.2 software (R. Core Team, 2019).

Table V. 3. Main features of the simulated dairy sheep farming system for each scenario under assessment.

Scenario	HAI (Baseline)	HFAI	HFM
Flock size	405 (295 adults and 110 ewe lambs)		
N° of ewes present at lambing			
N° of rams present at lambing	8 (6 adults and 2 young)	19 (14 adults and 5 young)	
Main breed	Lacaune		
Ewes average live weight (kg)	75		
Renewal rate (%)	27		
Suckling period length (days)	28		
Usable agricultural lands (ha)	70		
Forage and pasture lands (ha)	58		
Cropping (cereal) lands (ha)	12		
Forage annual stock (T of dry matter)	240		
Cereal annual stock (T)	66		
Reproduction period	June 9th, n – September 25th , n		
Delay between the start of reproduction of the adult and young batches (in days)	15	15	18
Milk sales price (€/1000L)	918		
Milk production period	December 15th, n – July 20th, n+1		
Grazing period	Mars 1th, n – November 15th, n		
Hormonal treatment	Yes	No	No
Use of male effect practice	No	Yes	Yes
Number of rams	6	14	14
Artificial insemination	Yes	Yes	No

n=Year; HAI= Hormones + Artificial Insemination; HFAI= Hormone-free + Artificial Insemination on adult ewes; HFM= Hormone-free+ Mating only.

3. Results and discussion

3.1. Biotechnical results

Over the five simulated production cycles the flock size remained stable in all scenarios (405 ewes; Table V.4).

- **Fertility and distribution over time of lambing events**

For all three scenarios, the fertility rate was stable over the production cycles (Table V.4), and was significantly lower in HF scenarios, compared to HAI (-4 % for both HFAI and HFM, respectively; $P< 0.05$; Table V.5). These lower fertility rates are a consequence of adopting a

HF reproduction strategy while keeping the same mating schedule. Indeed, the HF scenarios included the use of ME, whose results in terms of estrus induction and synchronization are much more variable than HT, as they depend on several individual characteristics of the ewes such as their BCS or age (Rosa and Bryant, 2002; Laclef et al., 2021). BCS particularly affects response to ME, as low pre-breeding BCS values results in a lower probability of responding to ME for a ewe, while higher pre-breeding BCS values lead to a good response rate (Debus et al., 2022). It supposes that maintaining a good BCS before reproduction using nutritional strategies such as the flushing strategy (i.e. additional nutritional supplementation a few weeks before reproduction) would be the more important in HF contexts. Furthermore, in this study the reproduction period of the modelled farm is during the summer (i.e. at a time when the ewes start to spontaneously show estrus and ovulation cycles). It has been shown that the use of ME is only effective on ewes in anestrus (Delgadillo et al., 2009). Thus, due to the high number of spontaneously cycling ewes, the ME had little impact and ovulations were not as synchronized around the farmer's reproduction dates as they were with HT leading to a lower fertility rate. This was confirmed when looking at the distribution of ewes lambing events over the production cycles as the peaks of daily lambing events in the HF scenarios were less pronounced and more staggered over time, especially in HFAI (Figure V.2). In HAI, the maximum daily number of ewes lambing was observed on the first day of the lambing period with 75 ewes lambing on average whereas in HF, it was observed 5 and 9 days after the start of the lambing period with an average maximum daily number of lambing events of 17 and 16 in HFM and HFAI respectively. In addition, the staggering of lambing events observed in the HF scenarios was more important in the HFAI scenario suggesting that the introduction of the AI protocol led to a lesser synchronization of lambing events. This might be due to the fact that the simulated AI protocol targeted six specific days where only the ewes in estrus could be effectively inseminated and pregnant. Indeed, ewes in estrus a few days before or after these AI days were not inseminated and had to wait the next cycle to be potentially mated by the rams whereas in the HFM scenario, the rams were free to mate any ewes in estrus from the end of the ME period. It should also be noted that the modelled detection rate of ewes in estrus was set to 100 %, assuming that precision devices like the automated estrus detector are used (Alhamada et al., 2016). If the estrus detection rate is lower (e.g. like it is the case through only visual observation by the farmer), the staggering of lambing events observed in HFAI, as well as the associated impacts, could be even more important.

To increase the fertility rate, while limiting the staggering of lambing events in HF scenarios, a solution could be to work on the composition of the flock to optimize individual

features like the BCS looking to improve the response to ME and thus the synchronization of estrus occurrences during reproduction (Laclef et al., 2021). In the HFAI scenario, another way to reduce the observed staggering of the lambing events could be to increase the number of days of AI following the ME. However, this would increase the operating costs due to AI activity. In addition, in the Roquefort basin, AI is carried out by off-farm operators who have to come to the farm to inseminate the ewes, which imply risks concerning their possible or not availability for a larger number of successive days of AI in the farm, and the related cost. Furthermore, HF insemination requires an accurate detection of estrus in the flock, which would increase farmer workload during the reproduction period for each additional day of AI.

- **AI rate and evolution of AI proportion in the renewal batch**

Only the HAI and HFAI scenarios retained the use of AI on the totality or part of the flock. Over the production cycles, the AI rate and thus the percentage of renewal ewe lambs born from AI remained stable in all scenarios (Table V.4). As expected, the flock's AI rate was significantly lower in the HFAI scenario [-58 % on average (-44 % considering the adult batch only); $P< 0.05$; Table V.5]. Indeed, as stated before, estrus onset around AI days were more variable than in the HAI baseline scenario. In addition, only the adult ewes batch were considered which reduced the potential number of ewes to be inseminated. This led to a significantly lower percentage of lambing events coming from AI (- 41 % on average; $P< 0.05$; Table V.5) and thus a significantly lower percentage of renewal ewe lambs born from AI in the HFAI scenario (-54 % on average; $P< 0.05$; Table V.5). To increase the percentage of the replacement flock born from AI in the HFAI scenario, the number of days of AI on adult ewes could be increased and AI of the ewe lambs batch could be introduced. However, this raises again the questions of increased operational costs, availability of inseminators, and the increased workload for estrus detection.

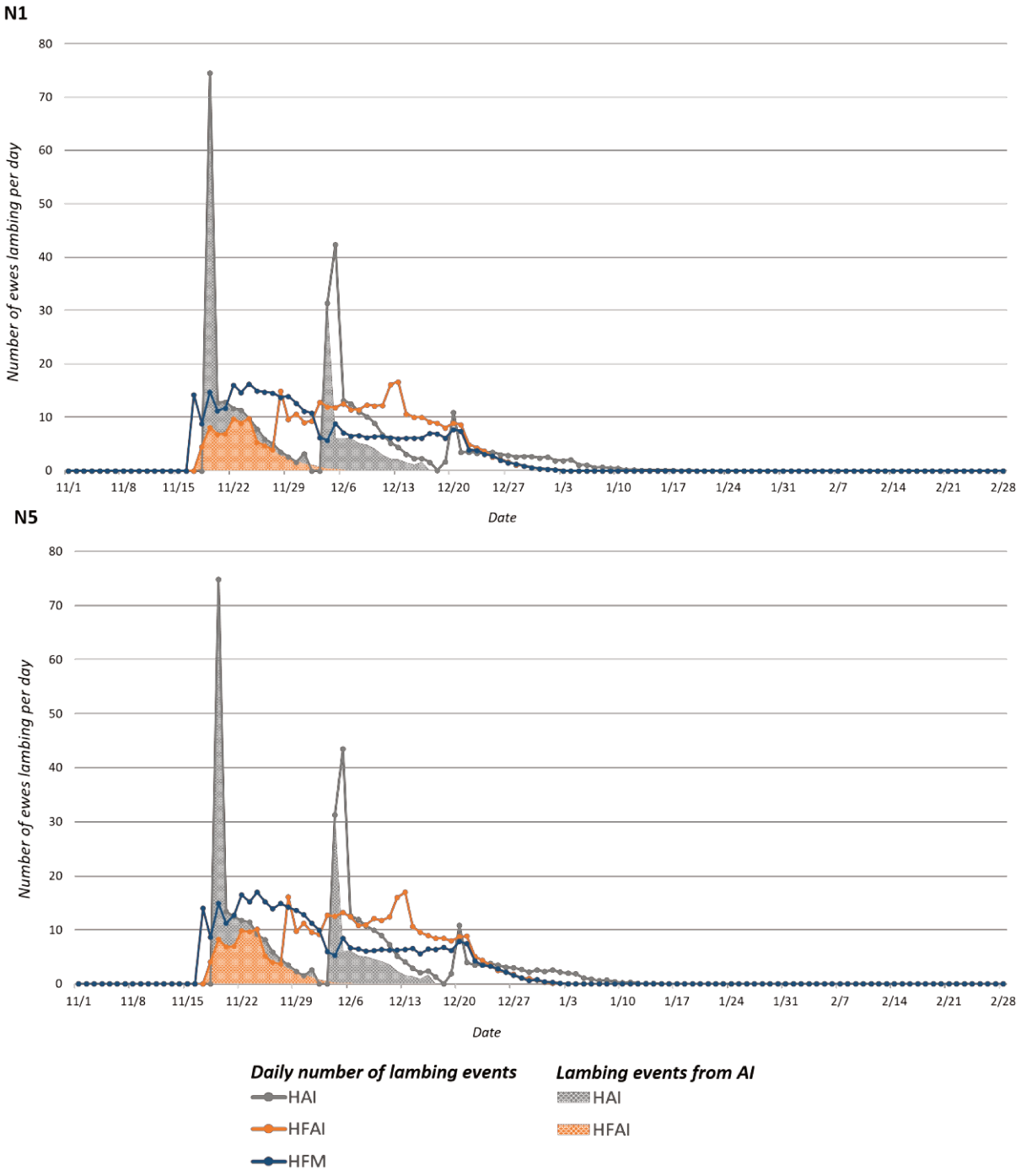

Figure V. 2. Distribution of the average daily number of ewes lambing in each scenario (n= 75 repetition of simulations *per* scenario) during the first (N1) and the fifth (N5) production cycles, including the number of ewes lambing from AI in (HAI and HFAI scenarios).
HAI= Hormones + Artificial Insemination; HFAI= Hormone-free + Artificial Insemination on adult ewes; HFM= Hormone-free+ Mating only.

Nevertheless, comparing the HFAI and the HFM scenario, the introduction of AI in a HF reproduction management context seems like a good way to keep a genetic background coming from AI in a significant proportion of the flock. Based on the average percentage of ewes of the renewal batch born from AI simulated in this study (45 %; Table V.4), Figure V.3 shows that after five production cycles, 45 % of the flock comes from AI against 0 % in HFM.

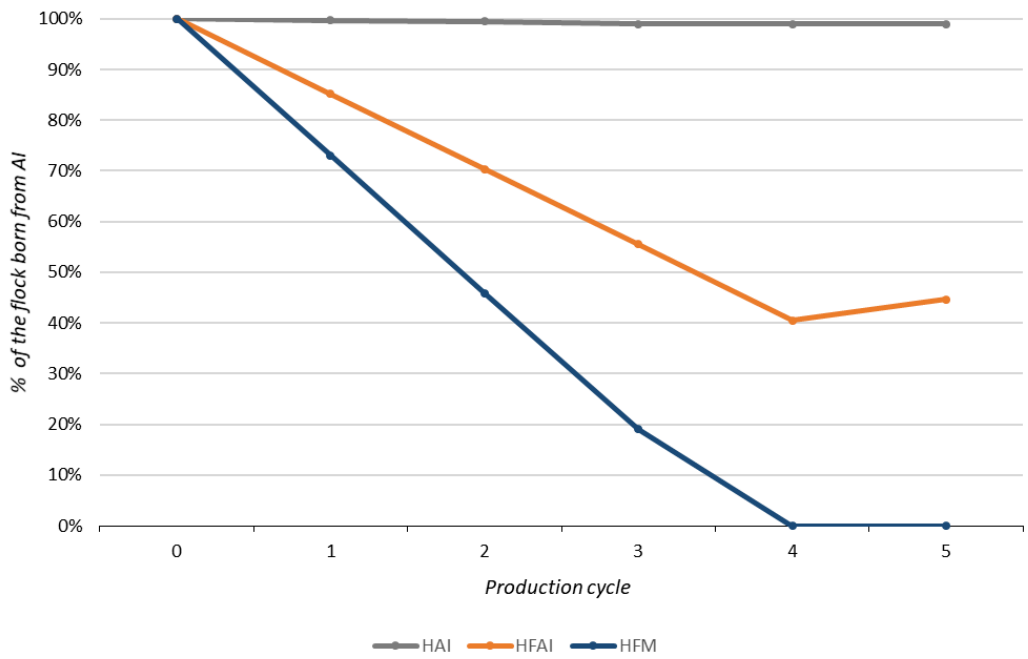

Figure V. 3. Theoretical progression of the percentage of the flock born from AI for the simulated conventional flock (i.e. initially composed of 405 ewes all born from AI) with a 27 % renewal rate. This evolution was plotted over five consecutive production cycles and for each scenario based on the average percentage of ewes of the renewal batch born from AI simulated in this study, assuming that all culled ewes were from the initial flock (i.e. from AI).
HAI= Hormones + Artificial Insemination; HFAI= Hormone-free + Artificial Insemination on adult ewes; HFM= Hormone-free+ Mating only.

- **Milk production**

The number of ewes milked remained stable in all scenarios over the five production cycles (Table V.4). As a consequence of the lower fertility obtained, the number of ewes milked was significantly lower in the HF scenarios (-15 and -16 ewes on average for HFAI and HFM, respectively; $P< 0.05$; Table V.5). Alongside this, the average milk production of the flock (in L/ewe) increased over the production cycles for all scenarios (Figure V.4) as a result of the genetic evolution over time allowed by AI and the renewal strategy that favour keeping the ewes that produce the more milk. It was significantly higher ($P< 0.05$) in HAI than in HF (HFAI, HFM) at each production cycle because more ewes were inseminated hence a higher phenotypic gain for the average milk yield of the flock. Comparing the two HF scenarios, the average milk production of the flock was higher in HFM than in HFAI during the first three production cycles. Since the milking period remained the same in every scenario and the average number of ewes being milked in HFM and HFAI was equivalent, this was mainly a consequence of the higher staggering of lambing events in HFAI that led to staggered entries to the milking parlour and a reduced lactation length for some ewes. Then, from the fourth simulated production cycle onwards, the average milk production of HFM and HFAI were

similar (Figure V.4), suggesting that keeping AI in HFAI compensated for the higher staggering of milking entries in HFAI after three production cycles. In parallel, the total milk production of the flock also increased over the production cycles and was significantly higher in HAI (+5.6 and +5.2 tons on average compared to HFAI and HFM, respectively; $P< 0.05$; Table V.5). However, it was similar in HFM and HFAI over the production cycles (Table V.4). Indeed, when looking at the progression of the cumulative milk production of the flock throughout the production cycles (Figure V.5.B), it was systematically higher in HAI. However, at the fifth production cycle, although the cumulative milk production of the flock was lower in HFAI compared to HFM during the first four months of milking, no differences were observed for these two scenarios during the rest of the milking period. Thus, in spite of more staggered milking entries to the milking parlour in HFAI, the milk production of the simulated flock was similar to that of HFM. This is also the consequence of keeping AI in HFAI (Figure V.3), which allowed to maintain a significant proportion of improved genetic traits in the flock and compensated for the bigger staggering of milking entries. However, 45 % of the flock being born from AI does not seem to be sufficient to reach a level of production equivalent to that of the HAI scenario, where almost 100 % of the flock is born from AI.

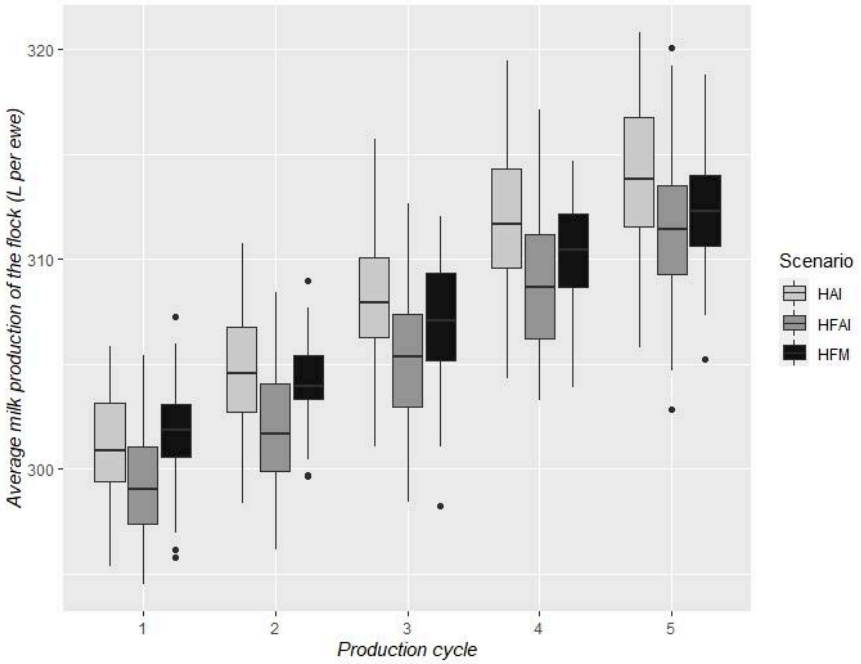

Figure V. 4. Average milk production of the flock (L/ewe) for each scenario (n= 75 repetitions of simulations *per* scenario) over the successive simulated production cycles.
HAI= Hormones + Artificial Insemination; HFAI= Hormone-free + Artificial Insemination on adult ewes; HFM= Hormone-free+ Mating only.

In addition, the progression of the flock's milk production (Figure V.5.A) differed between the evaluated reproduction strategies. The milk production peak occurrence was especially

delayed in HF (11 days' delay on average). This is a consequence of the staggered lambing in HF scenarios which consequently led to staggered entries to the milking parlour.
Furthermore, in HAI, two production peaks were observed. The first one corresponding to the start of milking of the adult batch, observed shortly after the start of milking, and the last one corresponding to the start of milking of the young batch, which was observed about one and a half months after the start of milking. In contrast, in HF (HFAI and HFM), a single peak in milk production was observed about one and a half months after the start of milking. Laclef et al. (2022), argued that staggered milking starts means that instead of having large batches of ewes starting milking at the same time, the farmer will have to manage staggered milking starts and thus a greater diversity of lactation stages in the flock at the same time with ewes gradually coming (and leaving) to the milking parlour. However, it appears that in HFAI, the greater staggering of lambing led to closing the milking entry delay between the adult ewe and the ewe lamb batches. Thus, most ewes in the flock were in the same lactation stage at the same time, leading to a single peak of milk production. Once again, this shows the importance of the reproduction management strategy on the overall flock performance, considering that in this work the programmed delay between the reproduction start of the adult and young batch was 27 days shorter than the one simulated in Laclef et al. (2022).

In addition, the staggering of milking entries observed in the HF scenarios, while keeping the same milking dates as in HAI, also implies that milking stopped while some ewes could still be milked with some of them still having a high production level. This contributed to a decrease in the total milk production of the flock in the HF scenarios. In reality, this would be rather unlikely as farmers would never dry out ewes while still in early or medium stages of lactation. A logical solution to attenuate the collateral effect of applying HF strategies on flock milk production would therefore be to extend the total milking time of the flock. Given the 11 days' delay simulated here for the occurrence of the peak of milk production in HF, extending milking time by the same number of days should not be extremely challenging to implement at the farm level. However, it could be a challenge in the current organization of the dairy sheep farming system of the Roquefort Basin. Indeed, in this large dairy area the milking period is set by the dairies according to their production demands (Lagriffoul et al., 2016). Therefore, the farmers do not have much flexibility in their choice of milking periods during the year and price penalties may be applied to farm milk sales if the milk quality and delivery dates fixed with the dairies are not met. Such changes in the farm's routines should therefore be considered when analyzing the whole value chain, especially if a wide adoption of alternative methods to HT is foreseen.

It was also found that the shift observed in the appearance of milk production peaks for the HF scenarios remained similar along the simulated production cycles. However, in this study we simulated a farm that performs reproduction in summer (close to the ewes' natural breeding season) with little impact of ME on estrus induction and synchronization of estrus in the flock. The conclusion would not necessarily be the same on farms where reproduction takes place out of season. Studies on the response to ME have shown that ewes with high levels of milk production close to the reproduction period tend to have fewer spontaneous ovarian cycles with a concomitant lower response to ME (Debus et al., 2022). Therefore, if keeping the same reproduction schedule, the higher number of ewes still being milked at the end of the milking period in the HF scenarios could have negative impact on the reproductive performances of the following production cycle, which would also accentuate the staggering of lambing events in HF contexts over time.

3.2. Feed consumption

The farm's consumption of forages and concentrates (in kg/L of milk) decreased over the production cycles due to the increase in the amount of milk produced, while the total amount of forages and concentrates consumed remained stable as the feeding plan remained the same over the production cycles (Table V.4). Overall, the amount of forages and concentrates consumed per litre of milk produced was higher in the HF scenarios (+0.14 and +0.04 kg/L on average for forages and concentrates, respectively in both HFAI and HFM; $P< 0.05$; Table V.5). Several factors may explain this higher consumption. First, additional rams were fed in these scenarios because the number of rams in the flock was increased for the ME. Furthermore, the feeding program was the same between the scenarios and was not revised during the production cycles in accordance with the flock performance under HF strategy. Thus, the amount of feed distributed in HFAI and HFM was not adapted to the lower milk production observed in comparison with the HAI baseline and led to a higher feed consumption per L of milk produced, probably with an increased waste of nutrients (e.g. excretion) due to unjustified luxury intake levels without productive responses.

The feeding program, a key component of the farming system management, should thus be revisited in the HF scenarios to better meet the flock's production requirements and optimise the available feedstuffs. This is consistent with the idea that the introduction of the ME as an alternative to hormonal synchronisation should be associated with a redesign of other aspects of the flock management. Recently developed tools such as automatic concentrate dispensers (Fança et al., 2018) which enable individual management of ewe feeding (Hassoun et al., 2018) could also be useful to facilitate flock feeding management in such HF context presenting heterogeneous lactation stages during the milking period.

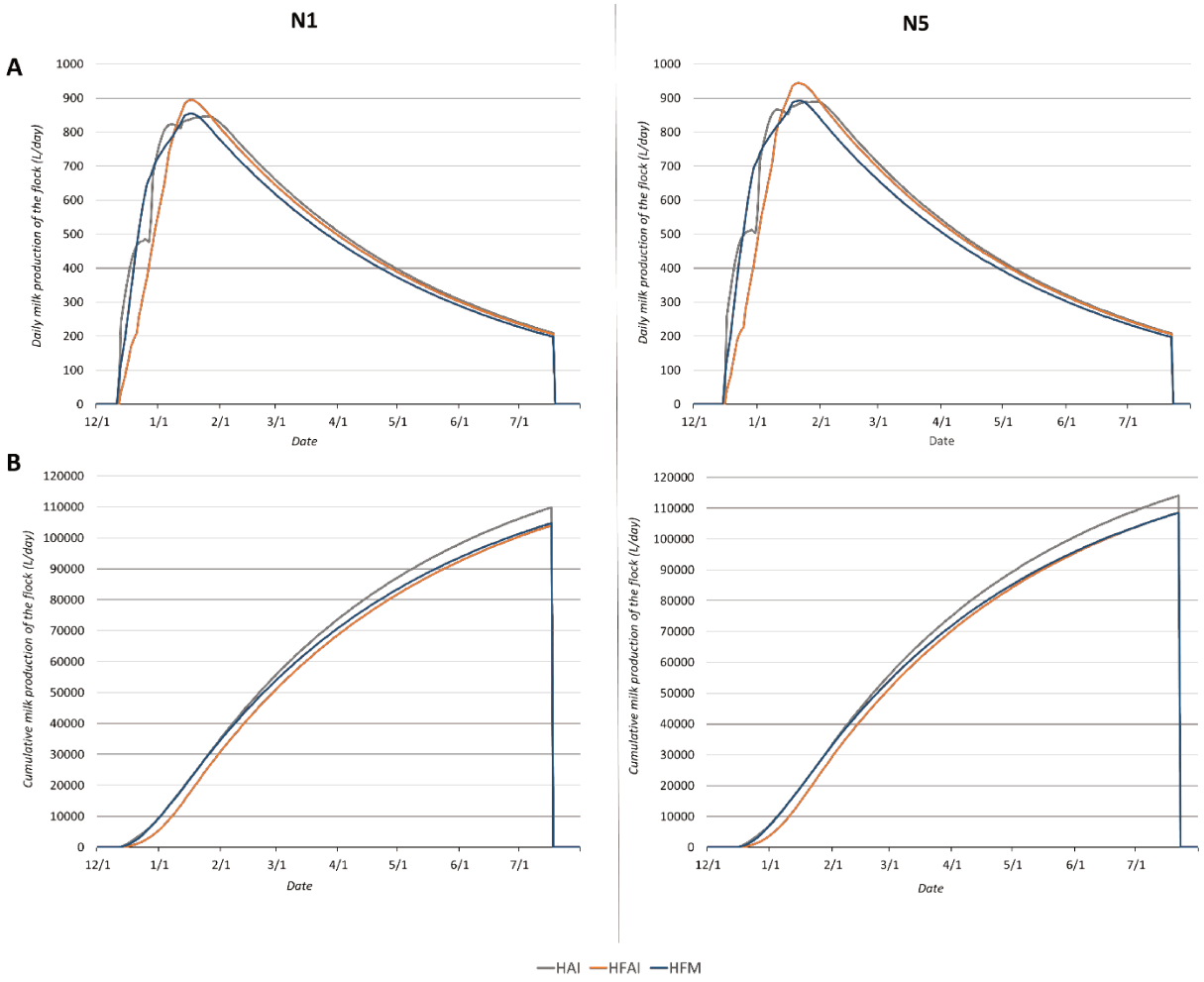

Figure V. 5. Progression of (A) the daily milk production and (B) the cumulative milk production of the flock in each scenario, during the first (N1) and the fifth (N5) simulated production cycle.
HAI= Hormones + Artificial Insemination; HFAI= Hormone-free + Artificial Insemination on adult ewes; HFM= Hormone-free+ Mating only.

3.3. Economic indicators

The gross margin of the farm (in €/L of milk produced) remained stable over the production cycles in every scenario (Table V.4) as the total gross margin (€) increased at the same time as total milk production of the flock. The gross margin per litre was significantly higher in the HF scenarios than in the HAI baseline (+0.01€/L of milk on average in both HFAI and HFM; $P< 0.05$; Table V.5). This was mainly the consequence of lower operational costs than HAI due to stopping HTs use. However, looking at the total gross margin of the simulated farm (in €), it was significantly lower ($P< 0.05$) in HF (HFAI and HFM) compared to the HAI baseline (-2909€ and -3037€, on average, for HFAI and HFM, respectively; $P< 0.05$; Table V.5). This suggests that, even though the gross margin per L of milk was higher in HF scenarios, the higher amounts of milk produced led to a higher total gross margin in HAI. Once again, this difference could be reduced by extending the milking time of the flock

in the HF scenarios. Another solution could be to enhance the value of stopping the use of HT by increasing the price of milk in farms that use alternative methods to HT in order to manage their production. Moreover, adjustments of the feeding program weren't considered over time, whereas in a real life situation the farmer would most likely have adjusted the flock's feeding regimes to its production level as it is recommended to achieve higher feed efficiency (Hassoun and Bocquier, 2010). The amount of feed to be distributed per day in HF scenarios would thus have been limited, leading to savings on feed purchases. It should be noted that the differences found between the gross margin of the HF scenarios was not significant. This suggests that even though the milk quantity produced in HFAI was lower than in HFM (on average), keeping AI practice in HFAI allowed to have a better milk quality leading to a higher price for the milk sold over the years (Table V.5) and thus a gross margin equivalent to that of HFM. It should be noted that the price of AI is based on the current conventional context where inseminators travel to farms once (per batch) in a production cycle. However, one can expect that this price would be increased to include additional travel and transportation costs if inseminators need to be on a farm several days in a row to inseminate ewes.

3.4. Workload indicators

In every scenario, the farm workload during both lambing and milking periods (in s/L of milk produced) decreased over the production cycles (Table V.4), due to the fact that the accumulated number of working hours remained stable in each cycle while milk production increased over time.

- **Workload during lambing**

As expected, the farm workload during lambing was significantly higher ($P< 0.05$) in HF scenarios than in HAI, especially in HFAI (+6.7 and +6.4 s/ L of milk on average for the HFAI and the HFM scenario, respectively; $P< 0.05$; Table V.5). This is a direct consequence of the staggering of lambing events in HF context. The difference of workload between HFAI and HFM (Table V.5) was also significant suggesting that the increased staggering of lambing events due to the HF insemination protocol negatively affects the farm workload during lambing. Such impact at this point could be a serious obstacle for the diffusion and further adoption of alternative practices to HT in conventional dairy sheep farms, despite some positive results in the simulated biotechnical and economic parameters. Indeed, if the economic benefit linked to the implementation of an innovation is often put forward in the adoption decision, it is not the only element to take into account (Barrientos-Fuentes and Berg, 2013). However, when looking at the lambing events distribution in HF, since it is more staggered than in HAI, the peaks of daily lambing events are also lower. This could therefore

conversely be seen by some as a positive aspect of converting to HF reproduction management as it could spread the workload over time, limit the need for extra labour to manage extremely high numbers of ewes lambing per day, and improve the quality of the daily surveillance of ewes and lambs during the lambing period.

- **Farm workload during milking**

The workload during milking was also significantly higher in HF compared to HAI (+0.5 and +0.7 s/L of milk on average in HFAI and HFM, respectively; $P< 0.05$; Table V.5) due to the staggering of the milking entries observed in HF. Considering the total milk produced in each scenario, the total of work hours during milking was found to be slightly lower in the HF compared with the HAI (-14 h and -5 h in the HFAI and HFM, respectively). This could compensate for a small part of the extra work time simulated during lambing. However, it should be noted that this lower total of work hours during milking is due to fewer ewes milked in HF, which also negatively affected the total gross margin of the farm (see Section 3.3). Moreover, as the entries to the milking parlour were more staggered in HFAI while keeping the same milking dates as in the other scenarios, there was less workload during the milking activity for the farmer compared to HFM at the beginning of the scheduled milking period. Thus, the average workload was also significantly lower in HFAI than in HFM.

3.5. Environmental indicators

- **GHG: implications of reproduction management on CH_4 emissions and CO_2 emissions affected by electricity use and feed purchases**

The simulated CH_4 emission potential of the farm, the CO_2 emission potential from electricity use as well as the CO_2 emission potential from feed purchases, to produce a litre of milk (in kg CO_2eq/L of milk) decreased over the production cycles (Table V.4), mainly due to stable accumulated emission values while milk production increased over the production cycles. The CH_4 emissions potential of the farm to produce a litre of milk was also significantly lower in HAI than in the other scenarios (-0.11 and -0.12 kg CO_2eq/L of milk on average than in HFM and HFAI, respectively; $P< 0.05$; Table V.5) whereas it was similar in HFM and HFAI over the production cycles. This is due to the fact that there were more animals in the HF scenarios as the number of rams in the flock was increased for the ME. Consequently, both the enteric CH_4 and manure production were increased in HF leading to more global CH_4 emissions while the milk production of the flock was lower than in HAI. This is consistent with recent studies showing that GHG emissions are lower in contexts enhancing animal productivity (Vigan et al., 2017). However, the CH_4 emissions simulated in HF remained within the typical range observed in dairy sheep farms (Escribano et al., 2020). The CH_4 emissions of HF could be reduced by adjusting the feeding program to that

part of the flock with lower milk production level in HF scenarios, mainly if the amount of forages and concentrates to be distributed is decreased in coherence with the milk yield. The CH_4 emissions of ruminants have been demonstrated to be related to the amount of feed consumed and the diet composition (Van Gastelen et al., 2019); thus feeding programs allowing efficient feed intake according to ewes specific metabolic profiles should contribute to attenuate CH_4 production and emissions (Muro-Reyes et al., 2011).

The CO_2 emissions of the farm, as a consequence of electricity use, was significantly higher in HFM over the production cycles (+0.0002 and 0.0004 kg CO_2eq/L milk on average compared to HFAI and HAI, respectively; $P< 0.05$; Table V.5). For practical reasons readers must be aware that CO_2 emissions estimated here are only those due to the electricity consumption in the milking parlour. Thus, the higher emission in HFM may be explained by the fact that milk production was less synchronized, thus increasing the time of use of the milking parlour, to produce less milk than HAI. Furthermore, as milking entries were more staggered in HFAI than HFM, the milking parlour operating time was slightly reduced in HFAI, resulting in lower CO_2 emissions from electricity consumption than in HFM.
Concerning CO_2 emissions from feed purchases, a significant difference was also found between the evaluated scenarios. Values were higher in the HF scenarios compared to HAI (+0.005 and +0.006 kg CO_2eq/L milk on average in HFAI and HFM, respectively; $P< 0.05$; Table V.5). The volume of CO_2 emissions per L of milk due to feed purchases is directly related to the amount of concentrate fed during milking. Since the quantity of concentrates distributed to produce 1 litre of milk was lower in HAI, it led to lower amounts of CO_2 emissions in this scenario.

Overall, the simulated CO2 emissions in the HF scenarios were higher than in the HAI scenario. It should be noted, however, that given the amount of milk produced in each scenario, the difference in total kg of CO2 (from electricity consumption and feed purchases) between the HFM scenario and the other scenarios remained moderate (+446 and +267 kg of CO2 per year on average, respectively). Considering that in the HAI scenario, inseminators have to travel to the farm several times a year to perform HT and inseminate ewes, it is conceivable that the higher amount of CO2 from electricity consumption and feed purchase simulated in the HF scenarios could be partially compensated in the HFM scenario by the fact that there will be no HT nor AI and thus less car travel to the farm for inseminators. For the HFAI scenario, however, the compensation may not be as significant, as there would more AI days and thus more inseminators travel in this scenario.

- **Water consumption of the farm**

As the GHG emission indicators, the volumes of water consumed in the farm to produce a litre of milk (in L of water/L of milk produced) decreased over the production cycles (Table V.4) in every scenario due to the increase of milk production while the accumulated water consumption was stable. In addition, the water consumption to produce a litre of milk was significantly higher in both HF scenarios than in the HAI baseline (+0.4 and +0.5 L/L of milk on average for HFAI and HFM respectively; $P < 0.05$; Table V.5). This was also a consequence of the increased number of animals present in the farm in HF which wasn't compensated by the reduced use of the milking parlour due to the reduced number of ewes milked in these scenarios.

Overall, the impact of HF reproduction management on the simulated environmental indicators was negative, as the simulated GHG emissions and water consumption were increased in comparison with HAI. However, many other indicators of the environmental impact of the operation were not considered in this work. For example, that related to the traceability of hormonal residues in the final animal products or in human health; the reduction of HT residue flows into the environment (González-Bulnes et al., 2020), linked to stopping the use of HTs, wasn't considered in the current study. Also, HTs are products coming from the pharmaceutical industry and their manufacture generates additional GHG emissions in the chain value. Thus, a reduction in the use of HT in livestock production should represent a globally positive impact on the environment and human health.

3.6. General impact on farm sustainability

One must be aware that the REPRIN'OV model proposed here focused on some of the major indicators of a dairy sheep farm sustainability, the goal being to take into account key major sustainability aspects rather than being fully exhaustive. In addition, for simplification reasons and in order to minimize additional sources of variation beyond reproductive management changes for the simulated farm performances, the model simulates the farm functioning under a stable environment (i.e. uniform climatic conditions and resources availability). It doesn't take into account how climate changes affect the farm performances. However, there are several and relevant negative impacts of climate changes on livestock farming systems (Nardone et al., 2010). For instance, it affects the availability of resources but also the health as well as the productive and reproductive performances of the animals (e.g. hot summers reduce biomass production then both quality and quantity of the farm's forage resources; moreover hot temperatures and water stress may significantly affect animals health and productivity; Aguilera et al., 2020). Consequently, farm resources and performances are more subject to fluctuations from one production cycle to the next one. This fact was not taken into account in this study; therefore, in the simulation results

obtained with our model, the lambing events distribution and milk production of the flock kept the same shape throughout the production cycles. To add sensitivity to climate changes in the model, a sub-model of crop and grass resources progression and performance through analysing the impacts of some climatic challenges or representing the link between episodes of climatic stress and the flock's reproductive and productive performances may add even further realism to the results obtained here. In addition, this model would benefit from incorporating a representation of the ewe's individual variability of response to their feeding system in terms of nutrient acquisition and allocation potentials under several genetic and environmental constraints. Indeed, it influences the variability in the administration of body reserves into a flock over time (Friggens and Waaij, 2008; Puillet et al., 2016), suggesting potential consequences on reproductive performances depending on the context of feeding resources availability. Moreover, in the REPRIN'OV model, the genetic evolution of the yield and the composition of the milk (fat and protein content) were represented based on the average value observed at the scale of the sheep population of the Roquefort basin. This does not allow to consider the specificity of the flock of a given farm nor its impact on its genetic evolution. It would therefore be interesting to develop this aspect of the model to better include the specificity of the farm in the genetic evolution for each breeding management scenario.

Still, the REPRIN'OV model provides some first insights into the complex relationships involved in the construction of the global farm performances in a HF reproduction management context. The simulation results obtained here, for a representative dairy sheep farm of the Roquefort area in France, showed that implementing HF reproduction management without changing anything else in the overall management had mostly neutral or negative long term consequences on the farm sustainability (Figure V.6). Mostly, the biotechnical performances were decreased and the methane (CH_4) emission potential, the CO_2 emissions due to electricity use and feed purchases, as well as the water consumption of the farm were increased. Only the gross margin per L of milk was increased. Overall these differences with the HAI baseline scenario were significant but remained small. However, beyond the consequent (and expected) difference in the proportion of AI in the flock, a large difference with the baseline reproduction scenario (HAI) was observed for the farm workload indicator during lambing. This should be a very sensitive point to take into account as reluctance from farm workload intensification has already been mentioned as a major point against the adoption of HF alternatives for managing dairy sheep flock reproduction (Lurette et al., 2016).

Table V. 4. Mean values (± SD) of the evaluated farm sustainability indicators at each simulated production cycle (mean of 75 repetitions of simulations *per* scenario).

	HAI (Baseline)	HFAI	HFM	HAI (Baseline)	HFAI	HFM	HAI (Baseline)	HFAI	HFM	HAI (Baseline)	HFAI	HFM	HAI (Baseline)	HFAI	HFM
Production cycle	**N1**			**N2**			**N3**			**N4**			**N5**		
Biotechnical indicators															
Flock size	405^{a} (±0)	405^{a} (±0)	405^{a} (±0)	405^{a} (±0)	405^{a} (±0)	405^{a} (±0)	405^{a} (±0)	405^{a} (±0)	405^{a} (±0)	405^{a} (±0)	405^{a} (±0)	405^{a} (±0)	405^{a} (±0)	405^{a} (±0)	405^{a} (±0)
Fertility rate	93^{b} (±1)	89^{a} (±2)	89^{a} (±1)	93^{b} (±1)	89^{a} (±2)	89^{a} (±2)	93^{b} (±1)	89^{a} (±2)	89^{a} (±1)	93^{b} (±1)	89^{a} (±2)	89^{a} (±1)	93^{b} (±1)	89^{a} (±2)	89^{a} (±2)
% of ewes inseminated	88^{c} (±2)	30^{b} (±2)	0^{a} (±0)	88^{c} (±2)	30^{b} (±2)	0^{a} (±0)	88^{c} (±2)	30^{b} (±2)	0^{a} (±0)	88^{c} (±2)	30^{b} (±2)	0^{a} (±0)	88^{c} (±2)	30^{b} (±2)	0^{a} (±0)
% ewes lambing from AI	63^{c} (±2)	22^{b} (±2)	0^{a} (±0)	63^{c} (±2)	22^{b} (±2)	0^{a} (±0)	63^{c} (±2)	22^{b} (±2)	0^{a} (±0)	63^{c} (±3)	22^{b} (±3)	0^{a} (±0)	63^{c} (±2)	22^{b} (±2)	0^{a} (±0)
% of renewal from AI	99^{c} (±3)	45^{b} (±7)	0^{a} (±0)	99^{c} (±3)	45^{b} (±7)	0^{a} (±0)	98^{c} (±4)	46^{b} (±8)	0^{a} (±0)	98^{c} (±4)	45^{b} (±9)	0^{a} (±0)	99^{c} (±3)	43^{b} (±8)	0^{a} (±0)
Number of ewes milked	361^{b} (±6)	344^{a} (±7)	345^{a} (±7)	361^{b} (±6)	345^{a} (±8)	345^{a} (±7)	360^{b} (±6)	347^{a} (±7)	345^{a} (±7)	361^{b} (±6)	347^{a} (±8)	346^{a} (±7)	362^{b} (±6)	346^{a} (±7)	344^{a} (±7)
Total milk production (Tons)	108.7^{f} (±2.0)	103.0^{a} (±2.1)	104.0^{ab} (±2.3)	110.1^{g} (±2.1)	104.2^{ab} (±2.5)	105.0^{bc} (±2.3)	110.9^{g} (±2.4)	106.0^{cd} (±2.3)	105.9^{c} (±2.1)	112.7^{h} (±2.1)	107.2^{de} (±2.9)	107.2^{de} (±2.3)	113.6^{h} (±2.3)	107.6^{ef} (±2.4)	107.6^{ef} (±2.4)
Average milk production (L/ewe)	301^{b} (±3)	299^{a} (±3)	302^{b} (±2)	305^{c} (±3)	302^{b} (±2)	304^{c} (±2)	308de (±3)	305^{c} (±3)	307^{d} (±3)	312^{h} (±3)	309^{ef} (±3)	310^{fg} (±3)	314^{i} (±3)	311^{gh} (±4)	312^{h} (±3)
Forage distributed (kg/L of milk)	2.08^{d} (±0.03)	2.22^{k} (±0.04)	2.21^{jk} (±0.04)	2.05^{c} (±0.04)	2.19^{j} (±0.04)	2.19^{ij} (±0.04)	2.03^{bc} (±0.03)	2.16^{gh} (±0.05)	2.17^{hi} (±0.04)	2.01^{b} (±0.04)	2.14^{efg} (±0.04)	2.15^{fgh} (±0.04)	1.99^{a} (±0.03)	2.13^{e} (±0.05)	2.13^{ef} (±0.04)
Concentrates distributed (kg/ L of milk)	0.85^{e} (±0.01)	0.89^{l} (±0.01)	0.88^{kl} (±0.01)	0.84^{d} (±0.01)	0.88^{jk} (±0.01)	0.88^{j} (±0.01)	0.83^{c} (±0.01)	0.87^{hi} (±0.01)	0.87^{i} (±0.01)	0.82^{b} (±0.01)	0.86^{fg} (±0.01)	0.86^{gh} (±0.01)	0.82^{a} (±0.01)	0.85^{e} (±0.02)	0.85^{ef} (±0.01)
Farm workload indicators															
Workload during lambing (s/L of milk)	20.8^{d} (±0.8)	27.6^{i} (±0.8)	27.1^{hi} (±0.8)	20.6^{cd} (±0.9)	27.4^{hi} (±1.0)	27.0^{gh} (±0.7)	20.3^{bc} (±0.8)	27.0^{gh} (±0.9)	26.6^{fg} (±0.7)	19.9^{ab} (±0.9)	26.6^{fg} (±0.9)	26.4^{ef} (±0.8)	19.7^{a} (±0.9)	26.5^{ef} (±0.7)	26.1^{e} (±0.8)
Workload during milking (s/L of milk)	18.6^{fg} (±0.3)	19.1^{jk} (±0.4)	19.2^{k} (±0.4)	18.4^{cd} (±0.3)	18.8^{hi} (±0.5)	19.1^{jk} (±0.4)	18.2^{bc} (±0.4)	18.7^{fgh} (±0.4)	18.9^{ij} (±0.4)	18.0^{b} (±0.3)	18.5^{def} (±0.4)	18.8^{ghi} (±0.4)	17.8^{a} (±0.3)	18.4^{cde} (±0.4)	18.6^{ef} (±0.4)
Economic indicators															
Gross Margin (1000 €)	85.7^{efg} (±1.9)	82.9^{a} (±2.1)	83.4^{ab} (±2.1)	87.1^{hi} (±1.9)	83.8^{abc} (±2.0)	84.3^{bcd} (±2.0)	87.9^{i} (±2.0)	85.4^{def} (±2.2)	85.0^{cde} (±2.1)	89.4^{j} (±2.4)	86.8^{ghi} (±2.3)	86.1^{efgh} (±1.9)	90.3^{j} (±2.0)	87.0^{hi} (±2.6)	86.4^{fgh} (±2.2)
Gross Margin (€/L of milk)	0.79^{a} (±0.01)	0.80^{cd} (±0.01)	0.80^{d} (±0.01)	0.79^{ab} (±0.01)	0.80^{cd} (±0.01)	0.80^{c} (±0.01)	0.79^{ab} (±0.01)	0.81^{de} (±0.01)	0.80^{cd} (±0.01)	0.79^{b} (±0.01)	0.81^{e} (±0.01)	0.80^{cd} (±0.01)	0.79^{b} (±0.01)	0.81^{e} (±0.01)	0.80^{cd} (±0.01)
Environmental indicators															
CH_4 emissions (kg CO_2eq/L of milk)	1.93^{c} (±0.04)	2.05^{h} (±0.04)	2.03^{gh} (±0.04)	1.90^{b} (±0.04)	2.03^{g} (±0.04)	2.01^{fg} (±0.05)	1.89^{b} (±0.04)	1.99^{ef} (±0.05)	1.99^{f} (±0.04)	1.86^{a} (±0.04)	1.97^{de} (±0.04)	1.97^{de} (±0.04)	1.84^{a} (±0.03)	1.96^{d} (±0.05)	1.96^{d} (±0.04)
CO_2 electricity emissions (kg CO_2eq/L of milk)	0.0134^{efg} (±0.0002)	0.0136^{hi} (±0.0002)	0.0137^{i} (±0.0003)	0.0133^{cde} (±0.0002)	0.0135^{fg} (±0.0003)	0.0136^{hi} (±0.0003)	0.0132^{bc} (±0.0002)	0.0134^{defg} (±0.0003)	0.0136^{h} (±0.0002)	0.0132^{ab} (±0.0002)	0.0133^{cd} (±0.0002)	0.0135^{gh} (±0.0002)	0.0130^{a} (±0.0002)	0.0133^{bcd} (±0.0002)	0.0134^{def} (±0.0002)
CO_2 feed emissions (kg CO_2eq/L of milk)	0.163^{ef} (±0.003)	0.168^{jk} (±0.002)	0.168^{k} (±0.002)	0.161^{cd} (±0.002)	0.166^{hi} (±0.003)	0.167^{ij} (±0.003)	0.160^{b} (±0.002)	0.164^{efg} (±0.003)	0.165^{gh} (±0.002)	0.158^{a} (±0.002)	0.163^{ef} (±0.002)	0.164^{fg} (±0.002)	0.157^{a} (±0.002)	0.161^{c} (±0.003)	0.163^{de} (±0.002)
Water consumption (L/L of milk)	8.8^{d} (±0.1)	9.3^{l} (±0.2)	9.3^{l} (±0.1)	8.7^{c} (±0.1)	9.2^{jk} (±0.1)	9.2^{k} (±0.2)	8.6^{c} (±0.1)	9.0^{hi} (±0.2)	9.1^{ij} (±0.2)	8.5^{b} (±0.1)	8.9^{ef} (±0.2)	9.0^{gh} (±0.1)	8.4^{a} (±0.1)	8.8^{de} (±0.2)	8.9^{ef} (±0.2)

AI: Artificial insemination; a, b, c: For each simulated indicator, values with a separate letter differ at p-value<0.05. The value with the letter a being the significantly lowest one.

Table V. 5. Mean values (± SD) of the sustainability indicators of the farm functioning over the five production cycles (i.e. mean and SD of the 5 × 75 repetitions of simulations *per* scenario).

	HAI (Baseline)	**HFAI**	**HFM**
Production cycle	**All cycles (mean ± SD)**		
Biotechnical indicators			
Flock size	405[a] (±0)	405[a] (± 0)	405[a] (±0)
Fertility rate	93[b] (±1)	89[a] (±2)	89[a] (±2)
% of ewes inseminated	88[c] (±2)	30[b] (±2)	0[a] (±0)
% ewes lambing from AI	63[c] (±2)	22[b] (±2)	0[a] (±0)
% of renewal from AI	99[c] (±3)	45[b] (±8)	0[a] (±0)
Number of ewes milked	361 [b] (±6)	346[a] (±7)	345[a] (±7)
Total milk production (Tons)	111.2[b] (±2.8)	105.6[a] (±3.0)	105.9[a](±2.6)
Average milk production (L/ewe)	308[c] (±6)	305[a] (±5)	307[b] (±5)
Forage consumed (kg/L of milk)	2.03[a] (±0.05)	2.17[b] (±0.05)	2.17[b] (±0.05)
Concentrates consumed (kg/L of milk)	0.83[a] (±0.02)	0.88[b] (±0.02)	0.88[b] (±0.02)
Workload indicators			
Workload during lambing (s/L of milk)	20.3[a] (±0.9)	27.0[c] (±0.9)	26.7[b] (±0.7)
Workload during milking (s/L of milk)	18.2[a] (±0.3)	18.7[b] (±0.4)	18.9[c] (±0.3)
Economic indicators			
Gross Margin (1000 €)	88.1[b] (±2.6)	85.2[a] (±2.8)	85.0[a] (±2.4)
Gross Margin (€/L of milk)	0.79[a] (±0.01)	0.80[b] (±0.01)	0.81[c] (±.0.01)
Environmental indicators			
CH_4 emissions (kg CO_2eq/L of milk)	1.88[a] (±0.05)	2.00[b] (±0.06)	1.99[b] (±0.05)
CO_2electricity emissions (kg CO_2eq/L of milk)	0.0132[a] (±0.0002)	0.0134[b](±0.0003)	0.0136[c] (±0.0003)
CO_2feed emissions (kg CO_2eq/L of milk)	0.160[a] (±0.003)	0.165[b] (±0.004)	0.165[c] (±0.003)
Water consumption (L/L of milk)	8.6[a] (±0.2)	9.0[b] (±0.2)	9.1[c] (±0.2)

AI: Artificial insemination; a, b, c: For each simulated indicator, values with a separate letter differ at p-value<0.05. The value with the letter a being the significantly lowest one.

The results obtained in this study thus suggests that a general reorganization of the management strategy, while taking into account the different constraints of the stakeholders of the dairy sheep industry as well as the socio-environmental context, will be necessary to maintain the farm sustainability in the long-term if HF reproduction becomes a real priority to put in place by the dairy sheep industry.

4. Conclusion

The REPRIN'OV model resulted in an efficient tool to better understand the complexity of the functioning of a dairy sheep farm under a potential transition towards HF reproductive management strategies. The model allowed to highlight the different causal links due to the functioning and the intercommunication of the different entities composing a dairy sheep farm. Also, through the simulation of practical, potential scenarios, it was able to explore how the introduction of alternative HF reproductive management strategies, without changing any other aspect of the flock management, disrupts (or not) the current organization and performances of a dairy sheep farm. The results obtained for the specific case study of a

conventional farm representative from the Roquefort basin, suggest that a general reorganization of the farm's management strategy according to the current constraints of the territory and the dairy sheep industry is necessary to maintain the biotechnical and economic performances of the farm in the long-term perspective. However, limiting negative environmental impacts and meeting farmer workload expectations linked to the implementation of the male effect (e.g., the increase of the workload during lambing or the increase of methane emissions due to the increased number of rams) seems more complicated to manage, suggesting that trade-offs should be made. The results obtained also highlight positive aspects of HF management (e.g., lower daily work peaks during lambing, or higher gross margin per litre of milk due to no HT being used) that should be taken into account when discussing trade-offs. Overall, the REPRIN'OV model could be used as a decision support tool to accompany stakeholders in the evaluation of potential solutions for the future, aiming to discuss the best ways for introducing alternatives to HT in the management of reproduction in dairy sheep farms. To do so, following the example of other dairy sheep farming models that include both simulation and optimization, often from an economic and/or environmental perspective, it would be interesting to add an optimization program to this simulation tool, so that optimal trade-offs between the three dimensions (economic, environmental, and societal) of sustainability can be foreseen. This, could help find the best ways to implement HF reproductive management in a variety of dairy sheep farms, depending on the needs and preferences of the different stakeholders involved along the dairy sheep industry value chain.

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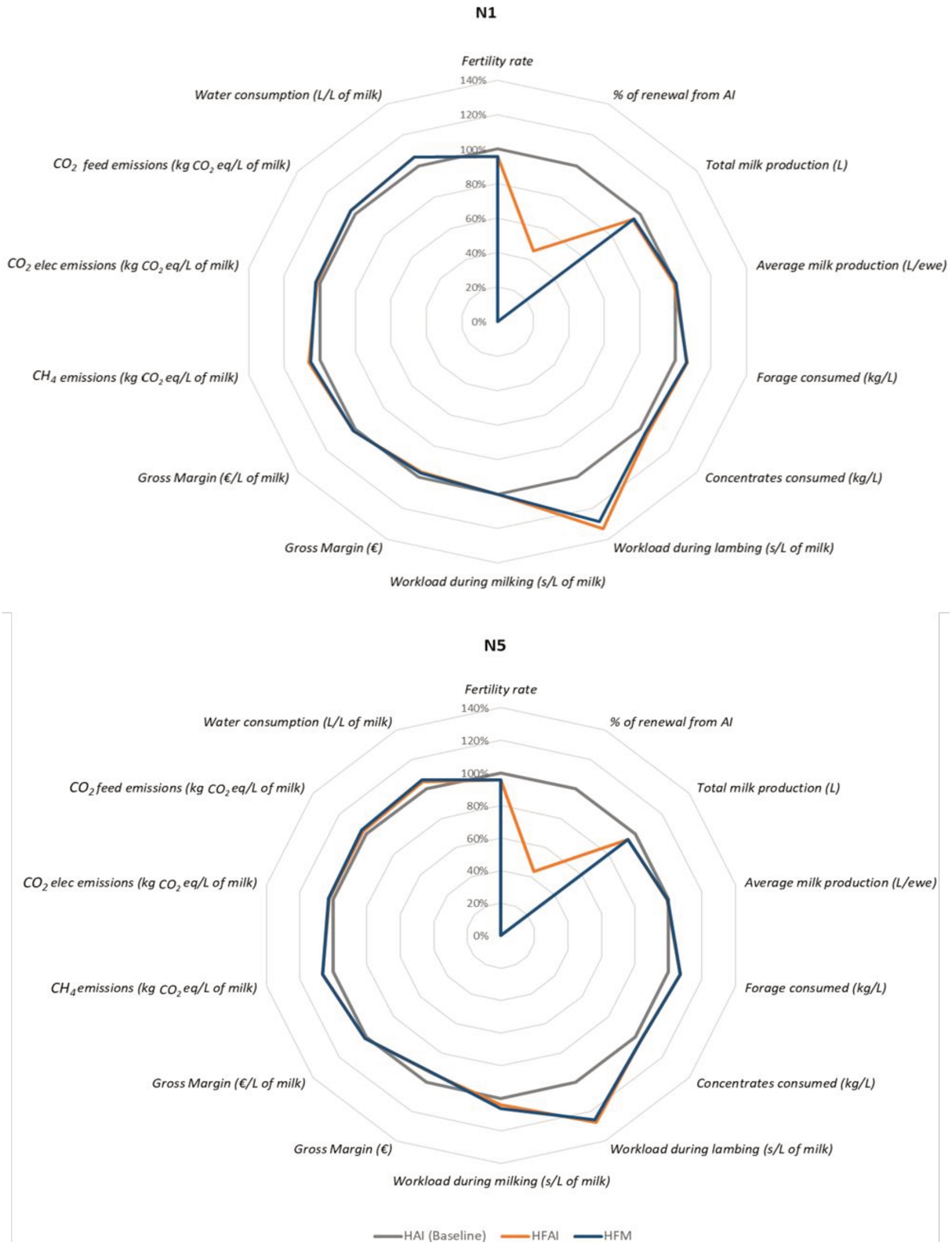

Figure V. 6. Comparison of the radar diagrams of the main sustainability indicators of the farm functioning, according to each scenario; in the first (N1) and fifth production cycles (N5). Each indicator value of the HAI baseline scenario corresponds to 100 % on the radar scale.

HAI= Hormones + Artificial Insemination; HFAI= Hormone-free + Artificial Insemination on adult ewes; HFM= Hormone-free+ Mating only.

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Appendix A. Annexe 2

Appendix B. Annexe 3

V-3. Conclusion du chapitre

Le modèle REPRIN'OV décrit dans ce chapitre est un outil efficace pour mieux comprendre la complexité du fonctionnement d'une exploitation OVL et appréhender les effets potentiels de l'introduction de stratégies de gestion de la reproduction sans hormones. En effet, la comparaison des résultats de simulations de trois scénarios distincts de gestion de la reproduction (avec TH+ IA, sans hormones + IA, sans hormones, sans IA) pour une exploitation OVL conventionnelle typique du BNO, sur cinq campagnes de production successives, a montré que les réductions de performances et les perturbations des courbes de production observées à l'échelle du troupeau ont conduit à des répercussions majoritairement négatives sur les autres indicateurs simulés de la durabilité de l'exploitation. Il a notamment été constaté une baisse de la marge brute totale de l'exploitation, une augmentation des émissions des principaux postes d'émission de gaz à effet de serre (**GES**) au sein de l'exploitation et une augmentation de la charge de travail de l'éleveur (notamment pendant les agnelages). De plus, la charge de travail s'est accrue avec la mise en place d'un protocole d'IA sans hormones. En revanche, les différences entre scénarios avec et sans TH sont restées stables au fil des campagnes de production successives. Ces résultats de simulations permettent supposer que pour introduire de nouvelles stratégies de gestion de la reproduction incluant l'utilisation de l'effet mâle comme alternative aux TH tout en garantissant des performances technico-économiques au moins équivalentes à celles observées actuellement, il faudrait envisager d'accompagner ces nouvelles pratiques d'une réorganisation d'autres opérations associées de la gestion de l'exploitation. Deux adaptations de pratiques seraient notamment envisageables pour atténuer les effets négatifs du passage à une gestion non hormonale de la reproduction, tout en conservant les mêmes périodes de reproduction (et donc en perturbant le moins possible le calendrier de production), dans les exploitations conventionnelles typiques du BNO :

- Rallonger la durée de traite du troupeau pour pallier l'étalement des entrées en traite lié à la variabilité de réponse à l'effet mâle dans le troupeau. Les durées de rallongement de traite estimées (entre 7 et 15 jours) restent faibles et sont donc facilement envisageables à l'échelle de l'exploitation. Cependant, cette solution ne peut être mise en place que si elle est validée collectivement à l'échelle de la filière. Les dates de traite des élevages étant fixées par leur contrat avec les industries laitières qui se basent eux même sur la disponibilité en lait au cours de l'année sur l'ensemble du territoire.
- Adapter le plan d'alimentation du troupeau à la nouvelle dynamique de distribution des états physiologiques dans le troupeau au cours du temps (notamment pendant la traite), afin d'éviter un déséquilibre entre besoins nutritionnels des animaux (réduits dans un scénario de gestion sans hormones) et apports de la ration alimentaire. Cela permettrait également d'éviter un gaspillage alimentaire et donc un surcoût économique mais aussi environnemental pour l'exploitation.

En outre, au vu des retombées négatives également simulés sur les performances environnementales et la charge de travail au sein de l'exploitation suite à l'introduction de scénarios de conduites alternatives aux TH, une nécessité de faire des compromis entre performances techniques, économiques, environnementales et la charge de travail lors de la mise en place de méthode alternatives aux TH en élevage OVL est soulevée par les résultats de ce chapitre. Ils suggèrent aussi l'importance d'évaluer l'impact des changements de pratiques annexes envisagés pour améliorer les performances technico-économiques sur les autres aspects de la durabilité du système de production, et ce, afin d'introduire des pratiques durables sur le long terme.

Chapitre VI :

Étude de scénarios d'introduction de nouvelles conduites de la reproduction sans hormones dans une diversité d'exploitation ovine laitière du Bassin Nord Occitanie

Chapitre VI- Étude de scénarios d'introduction de nouvelles conduites de la reproduction sans hormones dans une diversité d'exploitations ovines laitières du Bassin Nord Occitanie

VI-1. Introduction du chapitre

Au chapitre précédent, la simulation de la seule introduction de conduites alternatives de la reproduction dans une exploitation OVL en AC a montré des effets collatéraux (majoritairement négatifs) sur les indicateurs de performances technico-économiques simulés de l'exploitation (cf. Chapitre V). Ces résultats suggèrent une nécessité de modifier certaines pratiques associées à la gestion du troupeau (ex : allongement de la période de traite ou encore redéfinition des périodes d'alimentation) afin de maintenir de bonnes performances technico-économiques dans un contexte sans hormones, tout en conservant les mêmes périodes de reproduction et en perturbant ainsi le moins possible le calendrier de production de l'exploitation. Les résultats de simulations ont également mis en évidence des effets collatéraux négatifs sur les indicateurs de performances environnementales de l'exploitation ainsi que sur la charge de travail pendant les deux périodes d'astreinte que sont l'agnelage et la traite. Ceci pose la question de l'impact des changements de conduite annexes proposés sur l'ensemble des indicateurs de la durabilité de l'exploitation. Le modèle REPRIN'OV développé au chapitre précédent est un bon outil pour appréhender ces questionnements puisqu'il permet de simuler différents scénarios de changements de gestion de la reproduction (associés ou non à d'autres changements de gestion du troupeau) sur une diversité d'indicateurs de la durabilité d'exploitations OVL.

Nous faisons l'hypothèse que selon la configuration de l'exploitation considérée, la mise en place de pratiques alternatives de gestion de la reproduction devrait nécessiter plus ou moins d'ajustements annexes et induire différentes conséquences sur ses performances globales. En effet, l'efficacité de l'effet mâle est variable selon la saison de reproduction, son efficacité étant limitée sur des brebis déjà cycliques (Delgadillo et al., 2009). Ainsi, les effets sur les performances de reproduction du troupeau et donc sur les performances globales de l'exploitation risquent de différer quand nous comparons un élevage qui reproduit son troupeau durant la saison naturelle de reproduction des brebis ou proche de celle-ci (Été-Automne ou période dite « tardive » ; c'est-à-dire à un moment où un grand nombre de brebis sont déjà naturellement cycliques), avec un élevage qui reproduit son troupeau hors saison (Printemps ou période dite « hâtive » ; c'est-à-dire à une période où la majeure partie du troupeau est en anœstrus saisonnier). Il semble également évident que les exploitations en AB qui fonctionnent déjà sans TH n'auront pas à subir de changements aussi forts en termes d'organisation que les exploitations en AC, ce qui laisse supposer des effets moindres sur

leurs performances globales. De même, en termes de scénarios alternatifs aux TH possibles, on suppose de potentielles différences de résultats entre un scénario incluant l'IA sur chaleurs naturelles ou pas.

L'objectif du travail présenté dans ce chapitre était donc de simuler et de comparer les résultats de l'introduction de nouveaux scénarios innovants de gestion de la reproduction dans plusieurs exploitations représentatives du BNO ; ces scénarios comprenant des changements de la conduite de la reproduction couplés (ou non) avec des adaptations d'autres pratiques associées. Ces exploitations ont été modélisées sur la base de données de cas-types d'exploitations du BNO (De Boissieu and Morin, 2022) et les scénarios simulés ont été construits sur la base des résultats obtenus aux chapitres précédents. Le modèle d'exploitation REPRIN'OV a été utilisé pour simuler les différents scénarios et évaluer la diversité de conséquences possibles selon les types exploitations sur cinq campagnes de production après le passage à une conduite alternative de la reproduction.

VI-2. Establishing hormone-free reproduction strategies in dairy sheep farms: a diversity of consequences on farm's long-term sustainability depending on the production system type

VI-2.1. Description of the scenarios

To cover the diversity of dairy sheep farms that could be found in the North Occitania Basin (or Roquefort Basin; **RB**), four farms (named *Early_conv, Late_conv, Early_org and Late_org* respectively) were selected and modelled using the information provided by the latest database of the Inosys Network (De Boissieu and Morin, 2022) on real representative dairy sheep farming systems of the RB. Farm typology differed by i) their agricultural model [conventional or organic, hence by their use (or not) of HT and AI] 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 built: one corresponding to a management with HT followed by AI practice (**HAI**) in conventional farms (*Early_conv* and *Late_conv*) or a HF management scenario (**HFM**) corresponding to the use of the ME followed by direct mating only in organic farms (*Early_org* and *Late_org*). Then, alternative scenarios were designed depending on the initial farm situation to simulate new HF reproduction management practices for the modelled farms. Table VI.1 details the farms characteristics under each simulated scenario. The alternative reproduction management strategies scripted included the use of the ME followed or not by AI (Figure VI.1). When AI was simulated following the use of the ME, it was only performed on the adult ewes' batch. Indeed, performing AI on ewes following a ME is labour intensive as it implies individual heat detection of ewes (see Chapter I, paragraph I-3.4). In addition, it has been shown that

young ewes generally respond poorly to ME, mainly due to the fact that they are mated between 7 and 9 months (during their puberty; thus exhibiting a lack of sexual experience) and are easily affected by stress (Chanvallon et al., 2010). On the other hand, in most RB farms, ewe lambs kept for replacement are generally the first born (i.e. from the adult flock). Thus, a scenario including the use of the ME followed by AI only on the adult batch (**HFAI**) was simulated, as a trade-off between AI conservation in a HF context and the potentially expected workload. This HFAI scenario was simulated for all modelled farms. For the conventional farms only (*Early_conv* and *Late_conv*) a supplementary HFM alternative scenario was also designed in order to simulate an extreme but plausible scenario where AI practice would stop along with stopping the use of HTs due to the complexity to perform AI without HTs.

In addition, it has been suggested that introducing HF practices in conventional farms should be combined with a modulation of the whole flock management to minimize the negative effects linked to an increased variability in the reproductive performances due to the use of ME (see Chapters IV and V). An extension of the farm's milking period and a consequent adaptation of flock's feeding practices 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. Based on this, for each conventional farms, a first simulation of each HF scenario (HFAI and HFM) without any changes in the farm milking and feeding periods was run to monitor distribution of the flock milk production over time (see Chapters IV and V). If the highest peak of milk production occurrence was delayed in HF, milk production and feeding periods per batch during milking were arbitrarily extended by 10 days in the HF scenarios for the conventional farms (Table VI.1).

Table VI. 1. Characteristics of the simulated farms in each scenario.

Farm name	***Early_conv***			***Late_conv***			***Early_org***		***Late_org***	
Scenario	**HAI (Baseline)**	**HFAI**	**HFM**	**HAI (Baseline)**	**HFAI**	**HFM**	**HFM (Baseline)**	**HFAI**	**HFM (Baseline)**	**HFAI**
Production system type	Conventional			Conventional			Organic		Organic	
Flock size *(N° 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, n – July 7th , n			June 9th, n – September 25th , n			April 30th, n – October 15th , n		July 1th, n – October 30th , n	
Reproduction season	"Early"			"Late (Summer)"			"Early"		"Late (Summer)"	
Gap between the start of reproduction of the adult and young batches (days)	51	50	54	15	15	18	48	44	19	16
Start of the milking of the flock	Sep 1th, n			Dec 15th, n			Nov 5th, n		Dec 15th, n	
Milk sales price (€/1000L)	994			918			1330		1216	
Milking period length (days)	272	Baseline +10 days	Baseline	217	Baseline +10 days		223		228	
Pasture period	Mars 15th, n – Sep 10th, n	Baseline +10 days	Baseline	March 1th, n – Nov 15th, n			March 15th, n – Sep 30th, n		March 25th, n – Nov 15th, n	
Changes in feeding program	No	Yes	No	No	Yes	Yes	No	No	No	No
Hormonal treatment	Yes	No	No	Yes	No	No	No	No	No	No
Use of male effect practice	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Number of rams	7	15	15	6	14	14	18	18	14	14
Artificial insemination	Yes	Yes (Adult ewes only)	No	Yes	Yes (Adult ewes only)	No	No	Yes	No	Yes

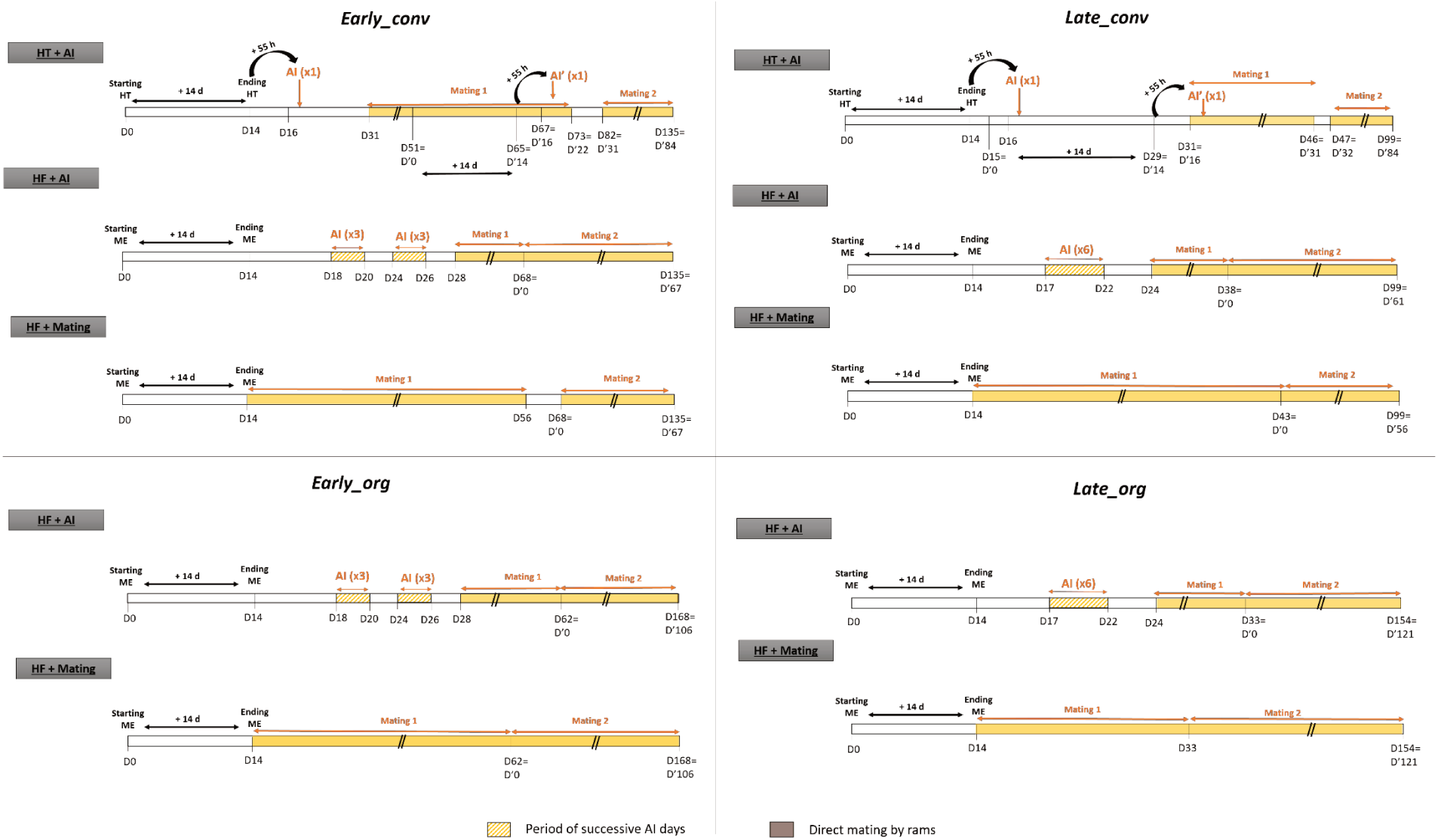

Figure VI. 1. Main steps of the modelled reproduction management strategy from the start of the synchronization protocol until the end of mating in both hormonal and non-hormonal contexts (including AI or not). The direct mating periods illustrated here are specific to each of the farms modelled.

D0= Day of reproduction start for the adult batch; Di= i days after the start of reproduction for the adult batch; D'0= Day of reproduction start for the young batch; D'i= i days after the start of reproduction for adult batch. AI= Artificial insemination; HF= Hormone-Free; HT= Hormonal Treatment; ME= Male effect. AI (x1)= One AI day for the adult batch; AI' (x1)= One AI day for the young batch; AI(x3)= Three successives AI days for the flock; AI(x6)= Six successives AI days for the flock. In the HF+AI scenario only ewes detected in estrus are inseminated.Mating 1= Mating of the adult batch only; Mating 2= Mating of young batch and adult ewes in heat.

VI-2.2. Statistical analysis methods

For each farm, 18 annual (Table VI.2) and 2 dynamic outputs (Figures VI.3 and VI.4) were simulated and analysed. For each individual farm annual indicator, comparisons of results from the first (N1) and fifth (N5) production cycles were performed by using two-factors ANOVAs. The effects of scenario (HAI, HFAI or HFM) and the production cycle on each indicator were evaluated. Mixed ANOVAs with the production cycle as a random factor were also performed for each annual indicator to analyse effects of the scenario on their average indicator values over the five simulated campaigns (see Appendix 5). In addition, the distribution of the farm's lambing events and the milk production over time were plotted by scenario to perform a descriptive analysis of their dynamic progression. For each campaign, the values of the indicators are expressed as the averages of 75 simulation repetitions (threshold value to manage the stochasticity of the flock performance simulated through the flock sub-model; see Chapter III). All statistical analyses were performed using R 3.6.2 software (R. Core Team, 2019).

VI-2.3. Simulation results

Fertility rates and lambing events distributions over time

For both conventional farms, the fertility rate was significantly lower in HF scenarios compared to their baseline scenario over the five production cycles; with the most important differences found in the *Early_conv* farm (-30 and -29 % for HFAI and HFM in *Early_conv* vs. -4 % for both HFs scenarios in *Late_conv*, respectively; $P< 0.05$; Figure VI.2). The HFAI also led to a slightly lower fertility rate compared to baseline in the *Early_org* farm (-1; Figure VI.2) whereas no differences were found between scenarios in the *Late_org* farm. Moreover, for both *Late_conv* and *Late_org* farms, the fertility rate in the HFs remained equivalent between N1 and N5, similar to their baseline scenario, whereas it decreased significantly in the HF scenarios of both *Early_conv* and *Early_org* farms (Table VI.2).

In addition, for all farms, the lambing events distribution over the lambing period was more staggered in the HFs than in their baseline scenarios with an equivalent staggering between N1 and N5 (Figure VI.3). For instance, it took longer to reach 25 % of the total of lambing in HFs regimes (Table A5.2). When comparing to baseline, a lower maximum number of daily lambing events was also observed when using HFs strategies in every farm, except for the *Late_org* in which the maximum number of daily lambing events was slightly higher in HFAI (Table A5.2 and Figure VI.3).

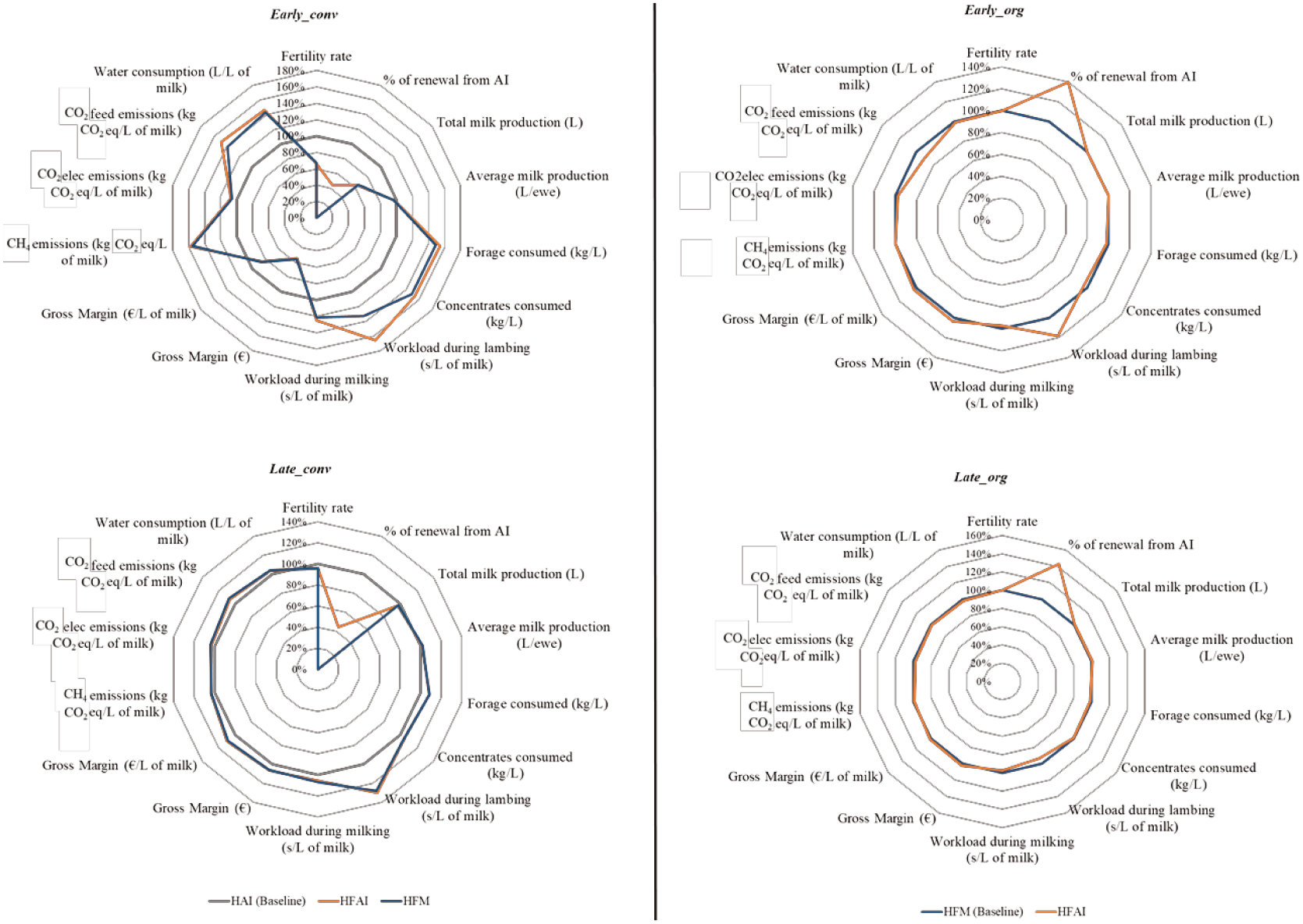

Figure VI. 2. Radar diagrams of the main farm's functioning sustainability indicators values (mean over five successive production cycles), according to each scenario. For each farm, each indicator value in the baseline scenario corresponds to 100 % on the radar scale. HAI= Hormones + Artificial Insemination; HFAI= Hormone-free + Artificial Insemination on adult ewes; HFM= Hormone-free+ Mating only.

Table VI. 2. Mean values of the simulated farms sustainability indicators at the first (N1) and fifth (N5) production cycles (mean of 75 repetitions of simulations *per* scenario).

Farm	***Early_conv***						***Late_conv***						***Early_org***				***Late_org***			
Production cycle	**N1**			**N5**			**N1**			**N5**			**N1**		**N5**		**N1**		**N5**	
Scenario	**HAI (Baseline)**	**HFAI**	**HFM**	**HAI (Baseline)**	**HFAI**	**HFM**	**HAI (Baseline)**	**HFAI**	**HFM**	**HAI (Baseline)**	**HFAI**	**HFM**	**HFM (Baseline)**	**HFAI**	**HFM (Baseline)**	**HFAI**	**HFM (Baseline)**	**HFAI**	**HFM (Baseline)**	**HFAI**
Fertility rate (%)	87^{c}	59^{b}	59^{b}	87^{c}	57^{a}	59^{b}	93^{b}	89^{a}	89^{a}	93^{b}	89^{a}	89^{a}	90^{b}	90^{ab}	89^{ab}	89^{a}	88^{a}	88^{a}	88^{a}	88^{a}
Insemination rate (%)	85^{b}	26^{c}	0^{a}	85^{d}	25^{b}	0^{a}	88^{c}	30^{b}	0^{a}	88^{c}	30^{b}	0^{a}	0^{a}	28^{c}	0^{a}	26^{b}	0^{a}	29^{bc}	0^{a}	29^{b}
% of renewal from AI	97^{d}	45^{c}	0^{a}	96^{d}	42^{b}	0^{a}	98^{c}	44^{b}	0^{a}	98^{c}	44^{b}	0^{a}	0^{a}	41^{c}	0^{a}	39^{b}	0^{a}	43^{b}	0^{a}	43^{b}
% of the flock born from AI	98^{e}	82^{d}	71^{c}	97^{e}	44^{b}	2^{a}	99^{e}	84^{d}	72^{c}	99^{e}	55^{b}	19^{a}	0^{a}	11^{b}	0^{a}	29^{c}	0^{a}	12^{b}	0^{a}	41^{c}
Average age at first reproduction (months)	9.0^{e}	8.5^{a}	8.8^{c}	9.0^{e}	8.6^{b}	8.9^{d}	7.7^{cd}	7.5^{a}	7.7^{b}	7.8^{d}	7.5^{a}	7.7^{bc}	8.6^{c}	8.3^{a}	8.6^{c}	8.3^{a}	7.6^{b}	7.4^{a}	7.7^{b}	7.4^{a}
Average milk production (L/ewe)	312^{c}	313^{c}	312^{c}	326^{d}	310^{b}	308^{a}	301^{a}	305^{b}	307^{c}	314^{d}	317^{e}	318^{e}	285^{b}	284^{a}	289^{c}	292^{d}	275^{a}	275^{a}	286^{b}	293^{c}
Total milk production of the flock (tonnes)	121.2^{d}	83.1^{c}	82.6^{c}	126.4^{e}	78.6^{a}	80.7^{b}	108.2^{b}	105.3^{a}	106.1^{a}	113.1^{d}	109.5^{c}	109.3^{c}	135.5^{b}	133.8^{a}	136.3^{b}	137.7^{c}	959.3^{a}	956.6^{a}	996.1^{b}	102.0^{c}
% of ewes milked	84^{c}	58^{b}	58^{b}	84^{c}	56^{a}	57^{b}	89^{b}	85^{a}	85^{a}	89^{b}	85^{a}	85^{a}	86^{ab}	86^{a}	86^{a}	86^{a}	81^{a}	81^{a}	81^{a}	81^{a}
Forage distributed (kg/L)	2.50^{a}	3.61^{c}	3.55^{b}	2.39^{a}	3.81^{d}	3.63^{c}	2.08^{b}	2.25^{d}	2.24^{d}	2.00^{a}	2.17^{c}	2.18^{c}	2.17^{c}	2.15^{b}	2.14^{b}	2.08^{a}	2.06^{c}	2.05^{c}	1.98^{b}	1.92^{a}
Concentrates distributed (kg/L)	0.87^{a}	1.25^{c}	1.23^{b}	0.83^{a}	1.32^{d}	1.26^{c}	0.85^{b}	0.89^{d}	0.89^{d}	0.82^{a}	0.86^{c}	0.86^{c}	0.80^{d}	0.78^{b}	0.79^{c}	0.75^{a}	0.78^{c}	0.79^{c}	0.75^{b}	0.74^{a}
Gross Margin (€/L of milk)	0.97^{c}	0.84^{b}	0.84^{b}	0.97^{c}	0.82^{a}	0.84^{b}	0.79^{a}	0.87^{d}	0.86^{c}	0.80^{b}	0.87^{d}	0.86^{c}	1.32^{a}	1.36^{c}	1.33^{b}	1.37^{d}	1.20^{a}	1.21^{b}	1.20^{a}	1.22^{c}
Gross Margin (1000 €)	117.5^{d}	70.1^{c}	69.6	122.9^{e}	64.2^{a}	67.7^{b}	85.5^{a}	91.5^{c}	91.7^{c}	90.2^{b}	95.5^{e}	94.5^{d}	179.0^{a}	182.2^{b}	180.9^{b}	188.9^{c}	115.1^{a}	116.0^{a}	119.7^{b}	124.8^{c}
Workload during milking (s/L)	19.7^{b}	23.1^{d}	22.8^{c}	18.9^{a}	24.3^{f}	23.5^{e}	18.7^{b}	19.6^{e}	19.8^{f}	17.9^{a}	18.9	19.2	17.3^{c}	17.0^{b}	17.1^{b}	16.5^{a}	22.5^{d}	22.1^{c}	21.5^{b}	20.8^{a}
Workload during lambing (s/L)	20.3^{b}	31.6^{e}	25.7^{c}	19.3^{a}	32.8^{f}	26.3^{d}	21.0^{b}	27.0^{e}	26.7^{e}	19.9^{a}	26.2^{d}	25.8^{c}	26.8^{a}	32.1^{c}	26.7^{a}	31.1^{b}	31.6^{c}	30.2^{b}	30.3^{b}	28.1^{a}
CH_4 emissions (kg CO_2eq/L of milk)	1.90^{b}	2.79^{c}	2.81^{c}	1.8^{a}	3.0^{e}	2.9^{d}	1.94^{a}	2.01^{b}	1.99^{b}	1.9^{a}	1.9^{b}	1.9^{ab}	2.02^{b}	2.05^{c}	2.01^{b}	1.99^{a}	1.88^{c}	1.89^{c}	1.81^{b}	1.77^{a}
CO_2 electricity emissions (kg CO_2eq/L of milk)	0.0138^{b}	0.0141^{c}	0.0141^{c}	0.0134^{a}	0.0146^{e}	0.0144^{d}	0.0135^{a}	0.0138^{cd}	0.0140^{e}	0.013^{b}	0.0135^{c}	0.0137^{d}	0.0132^{d}	0.0130^{b}	0.0131^{c}	0.0127^{a}	0.0154^{d}	0.0152^{c}	0.0150^{b}	0.0146^{a}
CO_2 feed emissions (kg CO_2eq/L of milk)	0.365^{b}	0.514^{e}	0.487^{c}	0.350^{a}	0.541^{f}	0.499^{d}	0.163^{b}	0.174^{d}	0.174^{d}	0.157^{a}	0.167^{c}	0.169^{c}	0.229^{d}	0.210^{b}	0.225^{c}	0.202^{a}	0.236^{c}	0.236^{c}	0.227^{b}	0.221^{a}
Water consumption (L/L of milk)	9.3^{b}	12.8^{c}	12.7^{c}	8.9^{a}	13.4^{e}	13.0^{d}	8.8^{c}	9.1^{d}	9.2^{d}	8.4^{a}	8.8^{b}	8.8^{c}	9.4^{c}	9.4^{c}	9.3^{b}	9.1^{a}	10.5^{c}	10.4^{c}	10.2^{b}	9.9^{a}

a, b, c, d, e, f: For each farm and simulated indicator, values with a separate letter differ at P-*value< 0.05*

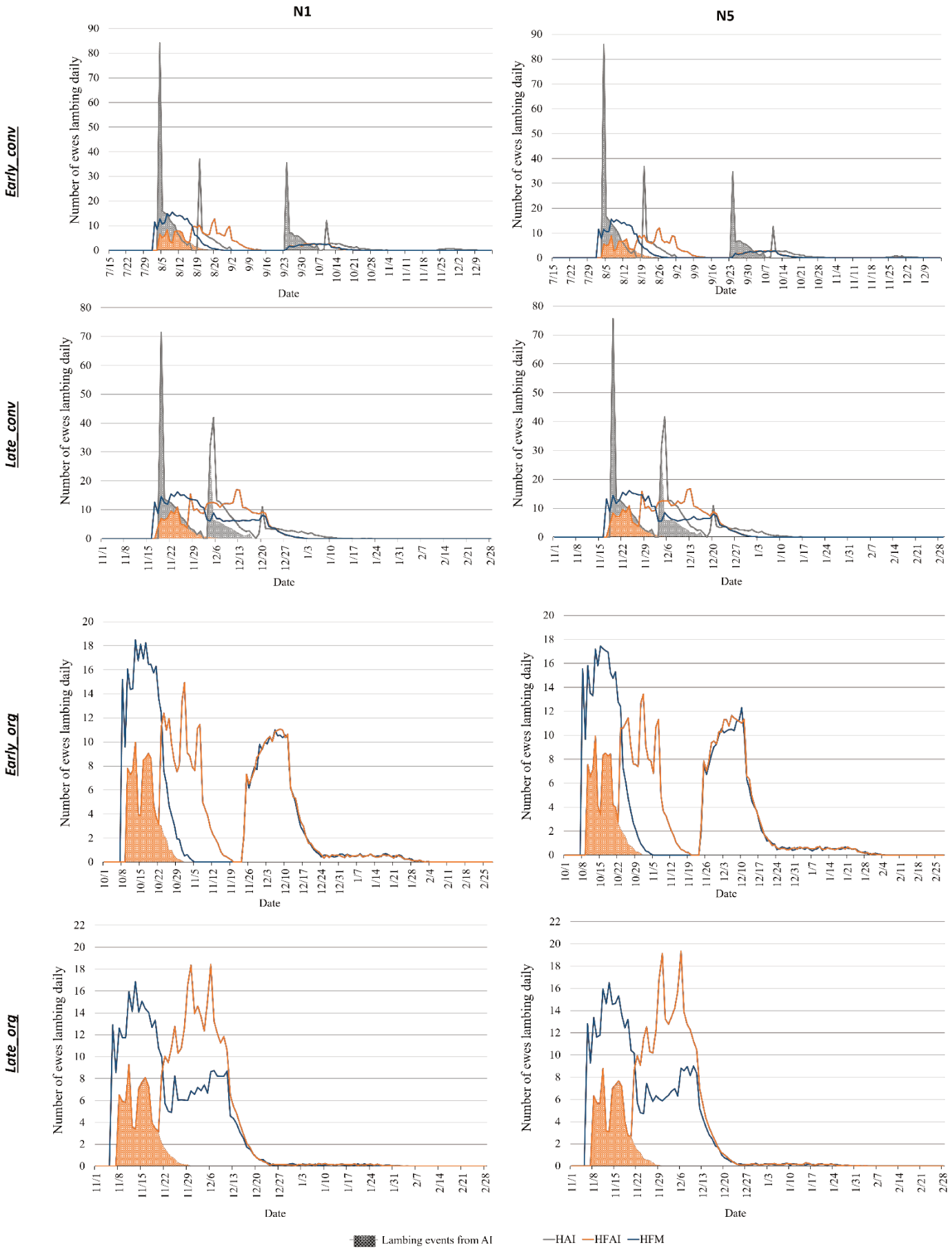

Figure VI. 3. Average daily number of ewes lambing (including the number of ewes lambing from AI) for each scenario in each farm (n= 75 repetition of simulations *per* scenario) during the first (N1) and fifth (N5) production cycles.

HAI= Hormones + Artificial Insemination; HFAI= Hormone-free + Artificial Insemination on adult ewes; HFM= Hormone-free+ Mating only.

AI rates and proportions of ewes born from AI

For both conventional farms flocks, the AI rate was significantly lower in HFAI than in HAI baseline throughout all production cycles, especially in *Early_conv* (Table A5.1). As a consequence, lower proportions of ewes born from AI in the renewal batch were simulated in HFAI during all production cycles (-54 % of the renewal batch, on average for both farms; $P<$ 0.05; Figure VI.2). 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 obviously significantly higher in HFAI than in their HFM baseline (+40 and +43 % of the renewal batch born from AI, on average in *Early_org* and *Late_org*, respectively; $P<$ 0.05; Figure VI.2). In addition, it was found that the AI rates and the proportions of ewes of the renewal batch born from AI were stable between N1 and N5 in all cases; except in the *Early_conv*'s and the *Early_org*'s HFAI scenario in which they decreased over time (Table VI.2).

At the end, when looking at the evolution of the proportion of ewes born from AI in the whole flock over production cycles, while it remained stable in every baseline scenario (almost 100 % in conventional farms and 0 % in organic farms), it decreased over time in both conventional farms HFAI, especially in *Early_conv* (-37 and -29 % in *Early_conv* and *Late_conv*, respectively; $P<$ 0.05; Table VI.2). By the contrary, it increased over time in both organic farms HFAI, especially in *Late_org* (+19 and +29 % in *Early_org* and *Late_org*, on average respectively; $P<$ 0.05; Table VI.2).

Age at first mating

For all farms, the HF strategies led to ewes being incorporated to their first mating slightly (but significantly) earlier than in the baseline, especially in HFAI (Table VI.2). The most important diminution of the age at first mating was in the *Early_conv* and *Early_org* farms. In terms of progression over production cycles, this parameter remained stable whatever the type of farm and scenario (Table VI.2).

Proportion of ewes milking and milk production of the flock

As a consequence of the obtained fertility rates, for both conventional farms, the proportion of milking ewes was significantly lower over the five production cycles in HFs compared to their baseline (Table VI.2 and A5.1). It was especially the case in *Early_conv* for which the proportion of ewes milked decreased between N1 and N5 (Table VI.2). In contrast, for the two organic farms the proportion of ewes milked was equivalent and stable over time in all scenarios (Table VI.2).

Looking at the flock's average annual individual milk production (in L/ewe), it was found to be significantly higher in all HF farms over the five production cycles, except in the *Early_conv* farm (Figure VI.2) for which HFs led to a milk production decrease over time

whereas in every other context it increased (Table VI.2). For both organic farms the increase of the flock's average annual individual milk production through production cycles was more important in their HFAIs compared to HFM baseline scenarios, its increase in HFAI being around twice of that HFM for both farms (Table VI.2). In *Late_conv* however, its increase was still more important in the HAI baseline (+13, +12 and +11 L/ewe in HAI, HFAI and HFM, respectively; $P < 0.05$; Table VI.2). As a result, even though the total milk production of the flock increased over the five production cycles for all contexts (except in the *Early_conv* HFs), lower values for the total milk production of the flock (in tons) were simulated in both HF conventional farms scenarios (Figure VI.2). On the contrary, in both organic farms the total milk production of the flock was significantly higher in HFAIs than in their HFM baselines over time (Figure VI.2).

In addition, for both conventional farms a delay in the occurrence of the highest peak of the flock's daily milk production was observed in HFAI (11 days on average). A similar delay was also observed in the HFM scenario for *Late_conv* only, a tendency that remained stable over time (Figure VI.4). Meanwhile, in the organic farms, no delays were observed in the HFAI scenarios. However, for both of these 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 (Figure VI.4).

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 the HFs; especially in the *Early_conv* farm (Figure VI.2). On the contrary, the HFAI scenarios of both organic farms led to a reduction of this parameter compared to their HFM baseline scenario (Figure VI.2). In addition, a decrease between N1 and N5 in every farm and scenario was observed, except in the *Early_conv*'s HFs for which an increase was obtained (Table VI.2).

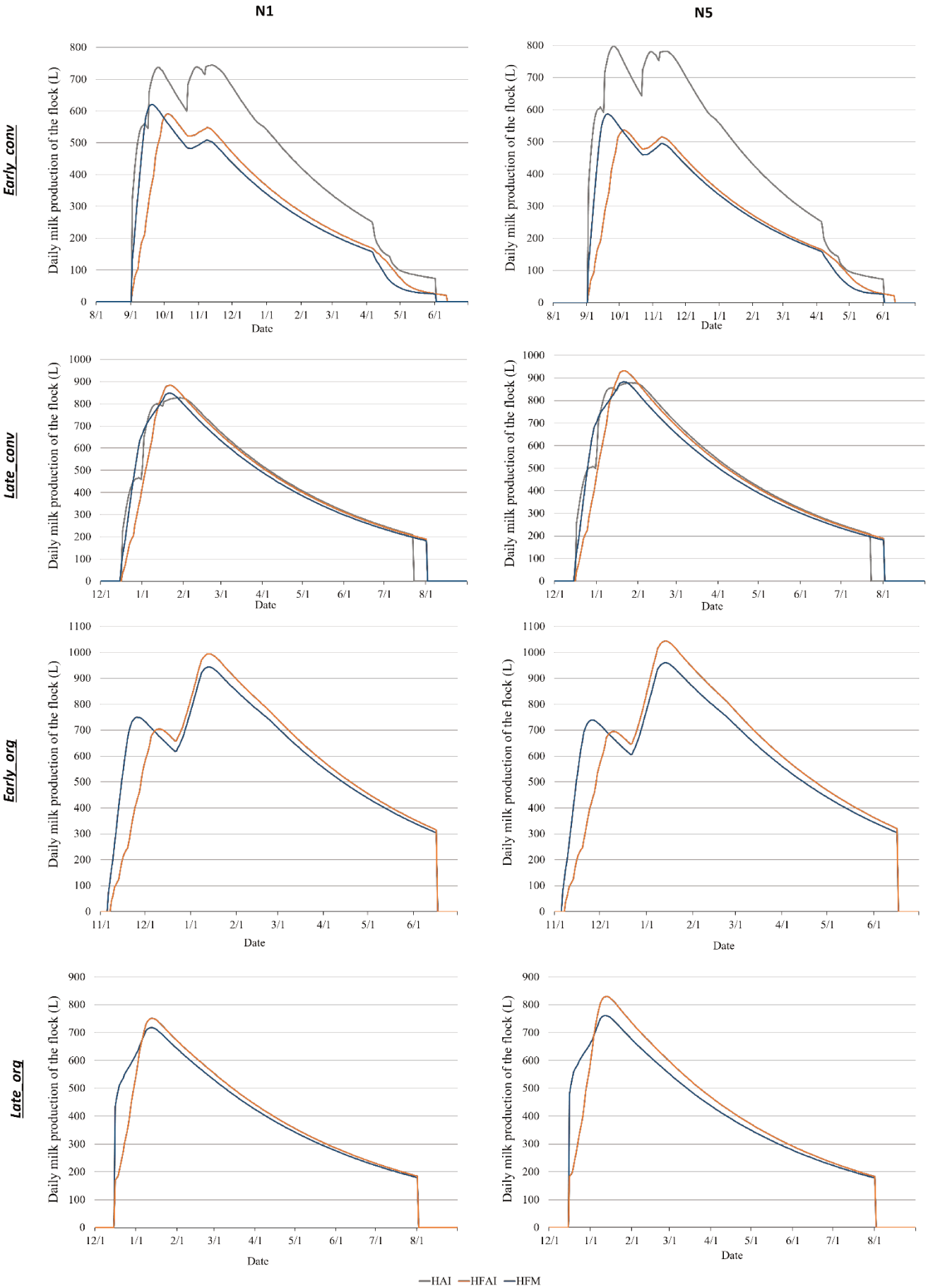

Figure VI. 4. Average daily daily milk production of the flock for each scenario in each farm (n= 75 repetition of simulations *per* scenario) during the first (N1) and fifth (N5) production cycles.

HAI= Hormones + Artificial Insemination; HFAI= Hormone-free + Artificial Insemination on adult ewes; HFM= Hormone-free+ Mating only.

Workload indicators

For both conventional farms and during all production cycles, the workload during lambing and milking periods (work times in s/L of milk produced) were significantly higher in HFs than in HAI baseline strategies; with a bigger difference in the *Early_conv* farm (i.e. up to 66 % of workload increase during lambing in *Early_conv*'s HFAI; Figure VI.2). In contrast, HFAI led to diminish workload during milking in both organic farms. However, regarding workload during lambing it led to lower the amount of time of work per litre in *Late_org*, whereas in the *Early_org* farm, it was increased compared to the HFM baseline scenario (+18 %; $P< 0.05$; Figure VI.2).

In addition, looking at the workload progression over time, for both lambing and milking operations it decreased between N1 and N5 in all farms except in the *Early_conv* where an increase was performed (Table VI.2).

Farm's economy indicators

Over the five production cycles, the gross margin per litre of milk produced (**GM per L,** in €/L) was significantly higher in HFs for all farms except for the *Late_conv* one in which HFs reduced compared to HAI baseline scenario. A similar trend was observed when examining the farm's total GM (Figure VI.2). The GM per L was observed to be stable, or slightly increasing, between N1 and N5 in all farms and scenarios (between 0 and +0.1 €/L; Table VI.2); with the exception of the *Early_conv*'s HFAI in which it significantly decreased (-0.2 €/L over time; Table VI.2). The total GM increased in every farm and scenario between N1 and N5, except in both *Early_conv* HF scenarios.

Farm environmental indicators: GHG 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 GHGs (in kg CO_2eq/L of milk) were significantly higher in HFs compared to HAI scenarios, with the most important differences found in the *Early_conv* farm (Figure VI.2). Similar results were observed for water consumption per litre of milk produced (Figure VI.2). On the contrary, these environmental indicators were significantly lower in HFAIs than in the HFM baselines for both organic farms. The amount of CO_2 emitted due to the feed purchases were particularly lowered in the *Early_org*'s HFAI compared to its HFM baseline (-9 %; $P< 0.05$; Figure VI.2).

In addition, the water consumed and GHG emitted per litre of milk produced decreased in all HF contexts between N1 and N5. The exception was in *Early_conv*'s HF scenarios for which these indicators were improved over time (Table VI.2). Whether these environmental

indicators values were increasing or decreasing over time, their progression was more important when applying the HFAI strategy (Table VI.2).

VI-2.4. Discussion: Consequences of introducing new hormone-free reproduction strategies for a diversity of dairy sheep farms in the Roquefort Basin

Consequences on the flock's reproductive performances

Overall, the simulation results showed that the introduction of HF reproduction strategies (HFAI and HFM) negatively affected most of the biotechnical performances for both conventional farms, especially in the *Early_conv*, whereas applying HFAI induced mostly neutral or positive consequences on the biotechnical performances of organic farms whatever the reproduction season (Figure VI.2).

First, in the conventional farms (*Early_conv* and *Late_conv*), the introduction of HF alternatives resulted in a diminution of the fertility rate. As previously identified (see Chapter V), 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 estrus induction and synchronization preclude more variable responses from ewes compared to HTs, as it is highly affected by ewe's individual characteristics(e.g. BCS or age; Laclef et al., 2021; Debus et al., 2022). The fertility rate was also much more reduced in *Early_conv* than in *Late_conv*. Indeed, introducing HF reproduction management 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 deploy both puberty and strong seasonal anoestrus in addition with their lack of experience (Chanvallon et al., 2010), and are therefore more unlikely to be cyclic (i.e. to fall in estrus and ovulate). As a result, few ewe lambs were detected in estrus and consequently a low number were covered in *Early_conv*, leading to a significant fertility rate diminution compared to *Late_conv*.

In contrast, for the organic farms that were already not using HTs (*Early_org* and *Late_org*), the HFAI scenarios did not affect the fertility rates. Moreover, for the two "early" farms (*Early_conv* and *Early_org)* the HFAI reproduction strategy led to a fertility rate decrease between N1 and N5, different to the trend observed when using the HFM strategy. Since the REPRIN'OV model used here represents 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), this pattern could be due to the fact that the conservation (or introduction) of the AI practice, allowed to improve the flock's production level faster than in HFM, leading at the same time to a decrease in the fertility rates in the HFAI strategy. In addition, when performed during the ewes natural reproduction season (as it was the case in the "late" farms) the ME is less effective to induce estrus because most ewes are already

naturally cyclic (Delgadillo 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" HFAI farms was not extreme over time (-1 % in *Early_org* compared to -2 % in *Early_conv*) but it would be interesting to check outcomes on a longer time span. We hypothesize that this phenomenon could be reduced by improving the estrus synchronization in the flock during the first mating (or AI) cycle. It could limit late parturition situations during the lambing period, and therefore late milking starts leading to ewes starting their next reproductive cycle while still in a high milk production phase.

Lambing events distributions were also affected by the alternative HF scenarios as they were more staggered in all farms. In conventional farms, it was mainly due to the increased variability in estrus onsets compared to HAI. In addition, for all farms, the shape of these lambing events distribution also differed between the two HF reproduction strategies due the modelled AI protocol in HFAI. Indeed, this protocol targeted six specific days, where only ewes in estrus could be effectively inseminated, while delaying the direct mating start compared to HFM. This led to an extension of the lambing 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. Surprisingly, for the "late" farms, the AI protocol in HFAI led to a higher maximum number of ewes lambing daily compared to HFM. This was because for these farms who managed their reproduction during the ewes' natural reproduction season, the AI protocol paradoxically led to a better synchronization 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 heat 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)]. Therefore, under a different situation the lambing distribution could be even more disturbed.

Because of the lambing events staggering in most of the HF scenarios, age at first mating was also lowered for all farms. This diminution wasn't extreme and didn't increase over time. However, more production cycles should be simulated to confirm this observation since a bigger decrease in the age at first mating could negatively affect the reproductive performance of the flock (Hernandez et al., 2011; Corner et al., 2013).

As expected, the introduction of AI in HF context (HFAI) allowed to increase the AI rate and thus the proportion of ewes born from AI in organic farms. On the contrary, it led to a reduction of these rates in conventional farms due to the increased variability in estrus onset

and the restricted AI protocol. In addition, in both "early" farms 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 the "early" farms had a negative retroactivity on the ewes' responses to the ME. It would be interesting to simulate more production cycles to see if this decrease is persisting or if a threshold is reached at some point. 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 organized 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 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 a good genetics through the use of selected rams of good genetic background (Barillet et al., 2001), combined with the flock renewal strategy that favors keeping ewes with good milk performance. As a consequence, the milk production of the flock increased over time in the majority of the farms. In *Early_conv*, however, the milk production of the flock decreased over time following the introduction of a HF reproduction strategy, suggesting that the very low fertility rate (and therefore number of milking ewes) observed in this HF context didn't 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 in milk production was also observed in the HFAI scenarios for both conventional farms whereas no effects were observed in the organic farms' HFAI. This was due to the more important lambing staggering compared to the baseline scenario in the conventional farms which caused to have more staggered milking entries. As a result, the highest peak of milk production was delayed but was higher than in the baseline, as the delay in milking entries paradoxically 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. This is consistent with previous simulations that showed also a similar delay in the milk production highest peak under HF context (see Chapter V). However, when comparing HFM scenarios to the baseline HAI in conventional farms, there was not systematically a delay in the occurrence of the highest peak of milk production. It especially

did not occur in *Early_conv*. This is probably due to the fact that less ewes produced in this scenario and the ones that did were those directly mated following the ME and that consequently lambed and started producing milk first. It also suggests that the AI protocol of HFAI makes it more likely to have a delay in the peak of milk production whereas it is not always the case under HFM.

An adjustment of the milking period (+10 days) was introduced in all HF scenarios showing a shift in their highest peak of milk production in order to compensate for this delay. Indeed, in a previous simulation of the *Late_conv* farm without adjusting the milking dates for the HF scenarios, this delay led to an overall loss of milk marketable (see previous Chapters IV and V). Therefore, increasing the milking duration by 10 days allowed to increase the amount of milk produced in *Late_conv* compared to the results obtained in the previous chapters. Consequently, despite a decrease in the proportion of ewes milked, the ewes average annual individual milk production level (in L/ewe) was higher than in the equivalent baseline scenario. In *Early_conv*, however, the extension of the milking period did not compensate for the lower rates of ewes milked in the HF scenarios. Furthermore, in *Late_conv*, the ewes average annual individual milk production level at the end of the five production cycles was equivalent in HFAI and HFM suggesting that in such farm configuration, the introduction of AI without HTs does not necessarily provide any added value to the milk production level compared to a HFM management. However, the increase of the ewes average annual individual milk production level in HFAI was greater than in HFM, which suggests that it should overcome that of the later in the longer term. Nevertheless, this increase in the ewes average annual individual milk production level was still higher in the HAI baseline than in HFs over the five production cycles. With the extension of the milk production period in HFAI, it would however be interesting to check if it is still the case over a longer period of time.

In the organic farms, the milk production periods were the same between HFAI and HFM. However, an increase in the flock's total milk production was also observed in HFAI compared to that of these farms' HFM baseline. This suggests that the introduction of AI accelerated the genetic progress of the flock resulting in a higher increase in milk performances in HFAI for these organic farms.

Consequences on feed consumption

The farm's feed consumption (forages and concentrates) was lower in the alternative HFAI than in HFM in organic farms mainly due to the total feed quantities distributed in these farms were equivalent between scenarios whereas the flock's milk production was higher. On the contrary, in conventional farms farm feed consumption was higher in the

alternative HFs than in HAI baseline mainly due to the reduced total milk production of the flock while the diets remained the same and more rams were fed over the production cycles.

Consequences on farm's economy

The consequences of introducing alternative HF strategies were positive for both organic farms whereas they were contrasted for conventional farms, depending on the reproduction season (Figure VI.2).

In organic farms, HFAI led to an increase of both GM per L and total GM of the farm, mainly because the quantity and quality of milk produced was increased thanks to the better genetic background introduced through AI. It also suggests that the positive economic benefit of introducing AI into farm's reproduction management routine compensated for the additional economic cost of the AI. In addition, the GM increase over time was higher in HFAI than in HFM due to the increase in the proportion of ewes born from AI in the flock. In conventional farms, results differed according to the reproduction season. Indeed, for *Late_conv*'s HF, stopping the HTs use (and AI in HFM) had a positive impact on the farm's GM per L and total GM. In addition, similarly to organic farms, the GM increase over time was higher in HFAI for *Late_conv*. In *Early_conv*, however, the potential benefit of stopping HTs and/or AI was impeded by the lower flock productivity (in milk and lambs).

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 take into account the fact that inseminators will have transport fresh semen on several successive days for a same farm), the conclusion drawn here might have to be nuanced depending on the price fixed to do AI without HTs. Moreover, we chose to simulate only the farm's GM. However, the introduction of HF strategies also implies structural costs, especially for conventional farms that have to adjust their number of rams and possibly make changes to their buildings in order to practice the male effect. Indeed, despite the need to have a sufficiently high ratio of ewes to rams to achieve an effective male effect (Oldham et al., 1990), it is also commonly admitted that ewes must be isolated from rams at some point to achieve an effective male effect (Delgadillo et al., 2009). Therefore, it could be necessary to add a sufficiently large space to isolate rams from ewes on the farm depending on the farm configuration.

Consequences on workload

The consequences of introducing alternative HF strategies on the farmer's workload during lambing and milking were negative for both conventional farms whereas they were contrasting for organic farms depending on their reproduction season (Figure VI.2).

First, in all conventional farms the workload during the lambing period was considerably increased in the alternative HFs due to the bigger spread of lambing events observed in these scenarios compared to their HAI equivalent baseline. Nevertheless, it should be noted that this 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 better care for ewes and lambs during the lambing period, reduce the lambs' mortality and limit additional labor demand during lambing. In *Early_org's* HFAI, 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 HFAI had a positive impact on the workload during lambing as it became slightly lower than in HFM due to a higher maximum number of ewes lambing daily.

For the workload during milking, in all organic farms it was lower in HFAI compared to their equivalent HFM baseline as a paradoxical consequence of the staggering of milking entries that led to a better concentration of lactation stages in the flock during milking and thus a higher peak of milk production in HFAI. In contrast, for the conventional farms, the workload was higher in HF scenarios compared to the HAI baseline. Indeed, in *Early_conv*, it was mostly due to the fact that 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 due to the fact that the milking period was extended.

Consequences on environmental footprint

Introducing alternative HF strategies negatively impacted farm's GHG emissions and water consumption for both conventional farms, whereas positive trends were observed in organic farms (Figure VI.2).

In the conventional farms, the simulated GHG emissions as well as the water consumption were higher in the alternative HF scenarios, especially in HFAI. For *Early_conv*, this was once again, due to the lower quantity of milk produced in HFs while the total emissions values of most GHG and the total quantity of water consumed were reduced in lower proportions or increased (for the CH_4) due to the increase in the number of animals permanently present in the flock in these scenarios. For *Late_conv,* GHG emissions values and water consumed were increased. The CO_2 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.

On the contrary, in the organic farms' HFAI scenarios, the simulated GHG emissions and water consumption were lower 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 CH_4 emitted as well as the quantity of water and feed consumed was equivalent between HFAI and HFM while milk production was increased in HFAI leading to lower values per L of milk for the CH_4 and CO_2 feed emissions as well as for the water consumption. For the CO_2 emissions linked to electricity use, the lower values observed were the result of the better concentration of lactation stages in the flock during the milking in HFAI that led to a more efficient use of the milking parlour and thus reduced the electricity use per litre of milk produced.

VI-3. Conclusion du chapitre

Les résultats du travail présenté dans ce chapitre ont confirmé l'hypothèse selon laquelle les conséquences de l'introduction de nouvelles pratiques non hormonales de gestion de la reproduction sur la durabilité d'une exploitation OVL devraient différer en fonction de sa configuration initiale. Des différences entre les types d'agricultures (AB ou AC) pratiquées avant l'introduction d'un changement de gestion de la reproduction et entre les périodes de reproduction des troupeaux (« hâtive » ou « tardive ») ont notamment été confirmées. Les exploitations en AC modélisées ont en effet fait face à de nombreuses conséquences négatives sur les différents indicateurs simulés de la durabilité du système suite à l'introduction d'alternatives aux TH (c'est-à-dire diminution des performances de reproduction, augmentation des émissions de certains GES ou encore augmentation de la charge de travail), tandis qu'à l'inverse, pour les exploitations en AB, des effets plutôt neutres à positifs ont été observés sur ces mêmes indicateurs. Des différences en fonction de la saison de reproduction du troupeau dans les exploitations modélisées ont également été identifiées puisqu'au sein de chaque type d'agriculture, les exploitations en reproduction « hâtives » ont présenté plus de retombées négatives, ou alors des retombées négatives plus fortes, que les exploitations « tardives » et ce, en raison de la plus grande complexité à induire un retour de la cyclicité chez les brebis hors saison.

Ces résultats ont également montré que les modifications supplémentaires d'autres pratiques de gestion du troupeau, envisagées au chapitre précédent pour accompagner les changements de gestion de la reproduction (allongement de la période de traite et des périodes d'alimentation du troupeau ; cf. Chapitre V), ne peuvent être appliquées de la même manière dans toutes les exploitations et doivent être ajustées à chaque contexte. En effet, un allongement de la durée de la traite (+10 jours), ainsi qu'un ajustement en conséquence des périodes d'alimentations du troupeau, ont été introduits en accompagnement des

modifications de gestion de la reproduction dans les scénarios alternatifs pour les exploitations en AC. Cependant, selon les saisons de reproduction pratiquées dans ces exploitations, cela n'a pas nécessairement permis d'améliorer les résultats technico-économiques. Dans le cas de l'exploitation « tardives » cela a permis d'augmenter ses performances laitières et d'améliorer ses indicateurs de performances économiques tandis que dans le cas de l'exploitation « hâtive », cela n'a pas eu d'effet. Par ailleurs, les résultats obtenus confirment qu'au regard des conséquences contrastées sur les différents aspects de la durabilité du fonctionnement des exploitations (ex : introduction de l'IA, amélioration des performances biotechniques et économiques, mais augmentation de la charge de travail pendant l'agnelage pour l'exploitation de type AB en période « hâtive »), des compromis par rapport aux objectifs principaux des éleveurs devront probablement être faits lors du choix des stratégies à mettre en place dans le cadre de l'introduction d'alternatives aux TH en élevage OVL.

En définitive, les résultats de ce chapitre donnent un premier aperçu des changements que pourraient subir un système de production OVL au cours des cinq campagnes de production suivant l'introduction de nouvelles stratégies alternatives aux TH pour gérer la reproduction de son troupeau et offrent des premiers éléments pour penser la reconception des systèmes d'élevage OVL dans le nouveau contexte et dans le cadre spécifique de l'introduction d'alternatives durables à l'utilisation de TH. Il serait cependant intéressant de simuler davantage de campagnes de production pour voir si les tendances observées ici se confirment sur un plus long terme et pour les différents systèmes.

Chapitre VII :
Discussion générale

Chapitre VII- Discussion générale

Ce travail de thèse avait pour objectif de **concevoir un modèle de simulation du fonctionnement d'une exploitation OVL** et de l'utiliser pour **étudier les effets des changements de pratiques** associés à l'introduction de nouvelles conduites, n'incluant pas l'utilisation d'hormones pour gérer la reproduction, sur le fonctionnement global des exploitations OVL du BNO. Ainsi, les différents chapitres de ce manuscrit ont présenté tour à tour les étapes de construction du modèle multi-agent d'exploitation OVL (REPRIN'OV) ainsi que les principaux résultats obtenus suite à la simulation et l'évaluation de différents scénarios d'introduction de pratiques alternatives.

Cette discussion générale vient compléter les discussions des précédents chapitres. Elle aborde dans un premier temps la démarche générale du travail réalisé et expose ensuite les principales originalités du modèle d'exploitation REPRIN'OV. Puis, en résumant l'ensemble des principaux résultats obtenus, nous apportons des éléments de réponses à la question de recherche « *Comment concevoir des élevages ovins lait durables, utilisant des méthodes alternatives aux TH de synchronisation dans leur gestion de la reproduction* ? » pour le cas du BNO.

VII-1. Démarche générale

Un modèle de simulation pour accompagner le changement de pratiques en élevage OVL

La problématique de la gestion de la reproduction sans TH est assez délicate car elle suppose des changements importants en termes d'organisation pour les exploitations (notamment en AC) mais laisse aussi entrevoir des changements d'organisation à l'échelle de la filière. Ainsi, face à cette question sensible, il y a extrêmement de prudence et bien que la nécessité de réfléchir à des moyens alternatifs aux TH pour la gestion de la reproduction en élevage OVL soit aujourd'hui admise, très peu d'éleveurs OVL du BNO sont prêts à implémenter les pratiques alternatives proposées par manque de vision des impacts collatéraux potentiels sur le fonctionnement de leurs exploitations (Lurette et al., 2016). Le processus d'adoption de pratiques nouvelles est en effet très complexe car il est influencé par les caractéristiques du système social dans lequel il se déroule et peut parfois nécessiter l'intervention d'autres acteurs que les adoptants *stricto sensu* de ces nouvelles pratiques (Ingrand et al., 2014). Par ailleurs, le modèle sociologique de la diffusion d'innovations développé par Rogers et al. (2008) montre que la diffusion et l'adoption de l'innovation dans un groupe sont des processus qui prennent du temps. L'innovation ou le changement de pratiques induisent en effet un manque de stabilité et une incertitude qui limite la rationalité

de l'adoptant et peut ainsi ralentir ou inhiber le processus d'adoption (Alter, 2010; Ingrand et al., 2014). Dans ce contexte, les modèles de simulation interviennent comme facilitateurs de l'adoption et de la diffusion d'innovations ou de changements de pratiques. Comme cela a déjà été énoncé au Chapitre I, paragraphe I-4.1, les modèles de simulation permettent en effet de tester un grand nombre de scénarios d'évolution d'un système virtuel, c'est-à-dire sans mettre en péril la durabilité du système en place dans la réalité, tout en limitant l'emploi de méthodes coûteuses en argent et en temps (Bernard, 2010). Nous avons donc choisi de développer le modèle REPRIN'OV, un modèle de simulation visant à apporter, par le biais de simulation de scénarios, des premiers éléments pour faciliter la réflexion autour de l'introduction de conduites alternatives aux TH dans les élevages OVL et accompagner ainsi la filière vers la mise en place et la diffusion de méthodes alternatives durables dans un contexte de transition agroécologique. Ce modèle appartient à la catégorie des modèles de type « what if ? » (« qu'est-ce qui se passe si ? »), très majoritairement utilisée pour étudier et accompagner les changements de pratiques en élevage (Vayssières, 2008; Bernard, 2010; Gouttenoire et al., 2011; Lurette et al., 2018), et qui ont pour objectifs de tester différents scénarios d'évolution d'un même système et de les comparer entre eux (Börjeson et al., 2006).

Choix des processus représentés et généricité de REPRIN'OV

L'objectif du travail étant d'observer l'impact de l'introduction d'alternatives aux TH de synchronisation des chaleurs sur le fonctionnement des exploitations OVL du BNO, beaucoup des processus modélisés ont été construits sur la base de données spécifiques au BNO. En effet, la saisonnalité de la reproduction ainsi que les performances de reproduction et de production laitière des brebis étant corrélées à la race considérée (Chanvallon et al., 2011), il a été choisi d'intégrer des représentations des processus de reproduction et de production laitières spécifiques à la race Lacaune (race majoritaire du BNO). De même, la modélisation des choix de gestion de l'éleveur (concernant le renouvellement et la réforme notamment) ainsi que la temporalité de ces choix sont fortement corrélées au contexte du BNO. La validation faite des sorties du modèle a montré qu'il simule correctement les performances pour des exploitations du BNO. Cependant, toutes les spécificités énoncées dans la formalisation des processus modélisés réduisent le niveau de généricité du modèle développé et il n'est pas certain que les résultats soient totalement similaires pour d'autres bassins de production OVL (tels que les Pyrénées Atlantiques ou la Corse par exemple). Malgré tout, REPRIN'OV représente de nombreuses relations biotechniques classiquement observées en élevage OVL quelle que soit la race de brebis et le contexte du bassin. La représentation de la réponse à l'effet mâle par une équation dressant des relations entre l'âge, la NEC et le niveau de production laitière des brebis peut tout à fait être considérée comme universelle

au vu des précédentes études montrant l'impact de différents facteurs des brebis sur leur capacité de réponse à l'effet mâle (cf. Chapitre I, paragraphe I-3.2). Cela suggère que le modèle développé reste intéressant pour observer des tendances générales liées à l'introduction d'alternatives aux TH en élevage OVL, mais suppose que hors contexte de ferme classique du BNO les coefficients des équations construites pour modéliser la réponse à l'effet mâle des brebis devront être adaptés aux systèmes étudiés. Le modèle REPRIN'OV ne peut donc pas être utilisé dans un autre contexte (autre environnement et /ou autre race) sans ajustement des coefficients des équations et des règles de décisions représentées pour la gestion de l'élevage.

Par ailleurs, il a été choisi de n'étudier que des scénarios impliquant l'utilisation de l'effet mâle comme alternative aux TH de synchronisation. Pour intégrer l'utilisation d'autres méthodes (ex : photopériodisme seul ou couplé à l'effet mâle), un travail de caractérisation de la réponse du troupeau par rapport à ces méthodes est nécessaire et devra être intégré au modèle en place.

Simplification des processus représentés

Afin de ne pas requérir un trop grand nombre de données pour son paramétrage et son utilisation, le modèle a été construit dans une optique de simplification. Plusieurs processus intervenant dans le fonctionnement d'une exploitation OVL ont donc été simplifiés.

Premièrement, au niveau de la modélisation du processus de reproduction, l'impact démontré des caractéristiques des béliers tels que leur état corporel, leur libido ou encore leur âge sur les performances de reproduction (cf. Chapitre I, paragraphe II-3.2) n'a pas du tout été représenté. Le choix a été fait de considérer que les béliers utilisés pour l'effet mâle et la monte naturelle étaient des béliers en bon état à tout instant. Il serait pourtant pertinent d'intégrer les règles principales de variation de performances de reproduction associées aux caractéristiques des béliers, car en contexte non hormonal utilisant l'effet mâle, la maîtrise de ces caractéristiques devient d'autant plus importante et pourrait être une cause de variabilité de performances entre exploitations. En outre, le taux de réussite à l'IA a été considéré comme étant constant au cours du temps ; or, on sait qu'il peut évoluer en fonction de plusieurs facteurs (entre autres, l'intervalle dernier agnelage-IA, l'âge des femelles, la qualité de la semence (Arranz et al., 2008) ou encore la technicité de l'inséminateur (Palacín et al., 2012)). Rajouter une représentation de l'effet de ces facteurs sur le taux de réussite à l'IA permettrait d'introduire de la variabilité et du réalisme dans les résultats obtenus pour les scénarios avec TH et leur évolution au cours du temps selon les choix de gestion de l'éleveur. Enfin, la représentation des gains phénotypiques laitiers associés à une naissance issue d'IA ou de monte naturelle est très théorique dans le modèle

développé. Elle se base en effet sur des niveaux de gains phénotypiques (issus de gains génétiques) actuels, c'est-à-dire dans un contexte de schéma de sélection basé sur une utilisation massive de TH dans les élevages sélectionneurs. En réalité, si l'ensemble des exploitations du BNO arrêtent l'utilisation de TH, les évolutions des gains génétiques et donc phénotypiques risquent d'être beaucoup plus variables que ce qui a été représenté. En effet, l'évolution des caractéristiques génétiques des principales races utilisées dans le BNO se base aujourd'hui sur un schéma de sélection qui nécessite d'avoir assez de béliers issus d'IA dans le noyau de sélection pour pouvoir créer du progrès génétique (Barillet et al., 2016). Cela suppose qu'il y ait assez de béliers nés d'IA dans l'ensemble des élevages sélectionneurs. Les récents travaux de simulation génétique menés par Raoul et Elsen (2020) pour les schémas de sélection ovin allaitants français ont montré que diminuer, voire complètement arrêter l'IA aurait des conséquences négatives sur le progrès génétique des populations sélectionnées en réduisant la valeur de leur gain génétique annuel par rapport au contexte actuel. Il serait intéressant de faire le même type d'évaluation pour les schémas de sélections des principales races OVL du BNO. Dans ce cadre, une extrapolation à l'échelle du territoire des taux d'IA simulés avec REPRIN'OV dans les principaux types d'exploitations du BNO permettrait de préciser les scénarios d'évolution de taux d'IA (à l'échelle de la population) à simuler via des modèles génétiques. Cela permettrait d'estimer l'évolution du gain génétique dans différents scénarios d'introduction d'alternatives aux TH en élevage OVL. Rétroactivement, il serait alors possible d'utiliser ces nouvelles valeurs de gains génétiques pour ajuster l'évolution du gain phénotypique laitier dans le troupeau au sein de REPRIN'OV et être plus précis dans l'estimation de l'évolution dans le temps des performances laitières des différents troupeaux simulés.

La représentation du processus d'alimentation a aussi été largement simplifiée. En effet, bien que l'utilisation de DAC pour ajuster les apports alimentaires aux besoins individuels des brebis se développe de plus en plus dans les élevages OVL, les troupeaux du BNO sont généralement alimentés en lot avec une seule ration calculée sur les besoins de la brebis moyenne du lot, et sans la prise en compte de la progression des stades physiologiques (ex : début, milieu et fin de gestation ou lactation). De fait, une grande partie du troupeau est alimentée au-dessus de ses besoins (Hassoun et al., 2018) pendant une grande partie de l'année. Ainsi, sachant l'évolution annuelle modérée du gain phénotypique laitier dans le BNO (+4 L/an en moyenne sur la production laitière totale/brebis en contexte classique (Barillet et al., 2016)) et le nombre de campagnes simulées (n= 5), nous avons fait le choix de ne pas faire évoluer les rations au cours du temps (ni en quantité, ni en qualité) par soucis de simplification. Il convient tout de même de noter que dans la réalité, dans un souci de

recherche d'autonomie alimentaire (De Boissieu et al., 2021), les rations sont régulièrement ajustées en fonction notamment des performances laitières du troupeau, ce qui a des conséquences sur les charges opérationnelles et donc l'économie de l'exploitation. Dans ce sens, REPRIN'OV gagnerait à intégrer la possibilité de faire évoluer les rations au fil des années en fonction des résultats laitiers du troupeau. Inversement, les performances laitières ainsi que les états corporels des brebis sont liés aux rations distribuées et de nombreux liens sont connus entre rations distribuées, acquisition des nutriments et minéraux, et évolution de l'état corporel et des performances laitières des individus d'un troupeau de ruminants (Inra et al., 2018). Cependant, n'ayant pas pour objectif dans cette thèse de tester des évolutions du fonctionnement des troupeaux dans le cadre de rations alimentaires contrastées, il a été décidé de ne pas représenter ces liens. Seules des représentations théoriques et simplifiées de l'évolution de la NEC des individus et de l'évolution de la production laitière (représentée à partir des équations de Lagriffoul et al. (2003) qui ne varient entre individus que par rapport à leur numéro de lactation et à leur niveau de production laitière initiale) ont ainsi été faites.

La représentation de l'évolution des rendements des surfaces fourragères et cultivées a été aussi très simplifiée puisque les rendements sont identiques au fil des années. Il s'agit encore là d'une simplification importante qui devrait être ajustée pour mieux tenir compte de la disponibilité des ressources au cours du temps et plus généralement des impacts du changement climatique sur l'évolution des rendements et donc la disponibilité des ressources, notamment dans les régions méditerranéennes comme le BNO (Aguilera et al., 2020). Cela permettrait en effet d'apporter du réalisme à la fois dans la simulation de l'évolution des ressources au cours du temps, mais aussi dans celle des impacts économiques (ex : en périodes de manque de fourrage, nécessité d'acheter de l'aliment en supplément, ce qui impacterait le niveau des charges opérationnelles de l'exploitation).

Enfin, seuls quelques indicateurs de performances économiques, environnementales et sociales du fonctionnement d'un élevage OVL ont été modélisés car il aurait été trop fastidieux de chercher à simuler l'ensemble des nombreux indicateurs de durabilité existants et possibles. De manière générale, dans les évaluations multicritères ou les études de durabilité de systèmes agricoles, des choix sont faits pour étudier quelques indicateurs pertinents par rapport à l'objet d'étude. Le choix d'un nombre restreint, mais diversifié d'indicateurs simulés par REPRIN'OV a ainsi été fait pour permettre une vision complète en termes de dimensions de la durabilité du fonctionnement des exploitations modélisées. Il faut tout de même noter que sur le plan de l'évaluation économique, les charges de structures (c'est-à-dire les charges liées à la mise en œuvre du fonctionnement de l'exploitation : terres,

bâtiments, équipements et main d'œuvre permanente, etc.) ne sont pas simulées par REPRIN'OV. De ce fait, l'impact d'investissements potentiels pour l'achat de matériaux nécessaires à la réalisation de l'effet mâle (outils de détections des chaleurs ou encore aménagements de bâtiments) n'ont pas été pris en compte. Sur le plan environnemental, seules les émissions de méthane et de CO2 émis par des postes d'émissions considérés comme importants en élevage OVL ont été simulées (Escribano et al., 2020) mais cela ne permet pas par exemple d'avoir une vision d'ensemble (holistique) sur l'empreinte carbone des différents systèmes. L'impact environnemental associé à la production et l'utilisation de TH n'a en particulier pas été quantifié (ex : « coût » environnemental associé à la synthèse de FGA ou au rejet de perturbateurs endocriniens dans l'environnement, impact de l'élevage de juments nécessaire à la production de PMSG, etc.). Une prise en compte de tous ces aspects permettrait une meilleure comparaison des effets d'une gestion de la reproduction avec ou sans TH sur l'environnement. Sur le plan social, seul le temps de travail nécessaire pendant les deux périodes d'astreinte principales a été observé, mais sans faire de liens ni avec la quantité de main d'œuvre allouée pour chaque type d'exploitation ni avec la charge de travail associée aux autres tâches quotidiennes. Cela mériterait d'être pris en compte pour faire une meilleure évaluation de la charge de travail globale à l'échelle de l'exploitation.

En définitive, plusieurs processus ont été simplifiés et mériteraient une représentation plus détaillée (et compris dans une approche dynamique spatio-temporelle) afin d'apporter du réalisme et permettre ainsi de tester d'autres changements de conduites ou d'adaptations de conduites existantes au cours du temps. Toutefois, l'intégration de nombreux processus détaillés tels que la représentation du processus individuel de reproduction des brebis ou encore l'intégration du plan d'alimentation des animaux détaillé par catégorie physiologique rendent déjà le modèle complexe en l'état puisque cela nécessite de fournir de nombreuses informations spécifiques en entrée. À ce stade, rajouter des processus complexes tels que les processus d'acquisition et d'allocation des nutriments en fonction de l'alimentation ou encore le processus d'évolution des ressources fourragères disponibles en fonction du climat pourrait donc rallonger les durées de simulation et affecter la généricité du modèle selon le type de données nécessaires. De plus, pour modéliser les différents processus discutés plus haut, il faut un grand nombre d'informations à différentes échelles et ces dernières ne sont pas toujours disponibles. Ainsi, si des modifications sont envisagées à l'avenir pour REPRIN'OV, il faudra s'assurer qu'elles soient nécessaires en fonction des attendus du modèle et qu'elles ne complexifient pas à outrance son utilisation.

Paramétrage du modèle

Afin de répondre correctement à notre objectif de simulation des conséquences associées à un changement de conduite de la reproduction aussi bien à l'échelle du troupeau qu'à celle de l'exploitation OVL, plusieurs jeux de données d'origines diverses ont été nécessaires pour paramétrer le modèle. Tout d'abord, des données expérimentales [données du troupeau OVL de la ferme expérimentale de La Fage et données de travaux expérimentaux en élevage commercial (Debus et al., 2022)] ont été utilisées pour représenter la composition d'un troupeau OVL et ont permis de développer un modèle capable de représenter le fonctionnement de troupeau très détaillé. Pour pouvoir passer à l'échelle de l'exploitation, des données techniques de cas-type et d'enquêtes ont été utilisées pour représenter le fonctionnement de l'exploitation dans son ensemble. Parfois, comme c'est souvent le cas pour les modèles de type « what if » qui simulent des situations inédites (Caurla et al., 2021), les données disponibles dans la littérature étaient insuffisantes voire inexistantes (ex : pour représenter la saisonnalité spécifique des cycles ovariens des agnelles). Dans ces cas, l'avis d'expert a été sollicité pour le paramétrage des processus représentés.

Par ailleurs, nous avons choisi de simuler les cinq campagnes successives de reproduction faisant suite à l'introduction d'un changement de gestion de la reproduction, en considérant que cinq campagnes étaient suffisantes pour observer un effet du changement de conduite de la reproduction sur le long terme. En effet, il faut traditionnellement 4 à 5 ans pour renouveler entièrement un troupeau OVL dans le BNO avec le taux de renouvellement annuel moyen de 28 % pratiqué dans les élevages OVL de la région (De Boissieu et Morin, 2022). Les résultats de simulation obtenus dans ce travail de thèse montrent cependant que ce temps d'observation gagnerait à être allongé pour pouvoir confirmer certaines tendances observées (ex : diminution du taux d'IA au fil des campagnes de production pour certaines exploitations, dans le cadre d'une gestion sans TH de synchronisation).

Calibration et validation du modèle

Lors de la construction d'un modèle, les étapes de calibration et de validation sont essentielles pour assurer sa cohérence et permettre son utilisation. Les modèles informatiques possèdent en effet plusieurs sources d'incertitude qui peuvent conduire à des erreurs de prévisions importantes (ex : les variables et paramètres d'entrée ou encore les équations des processus représentés). Ces étapes de calibration et de validation permettent ainsi de vérifier que le modèle construit produit des sorties acceptables par rapport à ses objectifs. Elles font partie intégrante de la construction d'un modèle (Sargent, 2015) puisque son élaboration est un processus itératif présentant une série d'alternances entre codage, calibration et validation des sorties de simulations pour vérifier les sorties obtenues et le

comportement du modèle. La validation recoupe notamment un vaste ensemble d'étapes et de méthodes possibles (validation de la cohérence entre le modèle conceptuel et les théories sur lesquelles il se base, vérification de la bonne traduction du modèle en code informatique et/ou évaluation de la cohérence des sorties de simulation par rapport à ses objectifs et son domaine d'applicabilité ; Caurla et al., 2021). Par ailleurs, dans le cas de modèles multi-agents comme REPRIN'OV, qui combine un grand nombre de sous-modèles de processus spécifiques à chaque entité représentée ainsi qu'un grand nombre de sorties à différentes échelles (individuelle, troupeau, ferme), le processus de calibration et la validation est particulièrement complexe. Le caractère stochastique du modèle REPRINO'V a d'autant plus complexifié cette vérification puisqu'il a impliqué de lancer plusieurs répétitions des simulations afin de prendre en compte l'aléa qui en découle et obtenir des sorties de simulations robustes. Une estimation du seuil minimum de répétitions nécessaires pour avoir des résultats robustes a montré qu'il fallait au moins 75 répétitions par simulation (cf. Chapitre III). Cela suppose un long temps de simulation et oblige à faire des choix dans le nombre de scénarios à simuler. Malgré cela, une calibration et validation complète des sorties du modèle troupeau en contexte non hormonal ont été faites à partir de données de terrain et de discussions avec des acteurs du terrain ainsi que des experts (cf. Chapitre III). En revanche, les sorties du modèle en contexte classique (avec TH) ainsi que les autres sorties à l'échelle globale de la ferme ont uniquement été validées à dire d'expert faute de temps et/ou de données de référence. Un travail plus approfondi de calibration et de validation reste donc à accomplir avec des méthodologies adaptées aux modèles tels que REPRIN'OV. Les résultats de simulation obtenus ont tout de même été jugés satisfaisants dans le cadre des objectifs de ce travail de thèse, qui visaient à étudier et à comparer les différences de comportements d'une exploitation OVL gérant sa reproduction avec ou sans TH ; et non pas à prévoir des valeurs exactes de performances d'exploitations, tel que le ferait un outil d'aide à la décision.

VII-2. Originalités du modèle REPRIN'OV

Représentation du processus de reproduction dans un contexte de gestion sans hormones

La complexité de la gestion de la reproduction sans TH de synchronisation réside dans l'anticipation et la maîtrise de la variabilité individuelle de l'entrée en chaleur des individus présents dans un troupeau. Le modèle développé prend donc en compte cette variabilité d'entrée en chaleur caractéristique du contexte sans hormones via l'intégration d'équations individuelles de réponses à l'effet mâle pour les brebis de race Lacaune. Cela constitue l'une des principales originalités du modèle développé. En effet, parmi les modèles ovins de la littérature qui intègrent une représentation de la réponse du troupeau à une gestion sans

hormones de la reproduction, les performances de reproduction du troupeau sont principalement modélisées via des taux de conception ou de fertilité fixés ou calculés à partir de valeurs moyennes de caractéristiques du troupeau, sans prise en compte des individualités (Benoit, 1998; Gebre et al., 2014). À notre connaissance, seul le modèle d'exploitation OVL de Villalba et al. (2019) fournit une représentation du processus de reproduction d'un troupeau OVL en contexte sans hormones. Dans leurs travaux, ils intègrent de la variabilité individuelle via une probabilité individuelle de conception qui dépend pour chaque brebis de sa NEC et du nombre de chaleurs effectuées avant d'aboutir à une fécondation. Le modèle REPRIN'OV se distingue donc par une représentation de la variabilité entre individus non pas au niveau de l'étape de conception (ou fécondation), mais avant cela, au niveau de l'étape de manifestation de chaleurs (donc des ovulations) des brebis à la suite d'un effet mâle.

Le travail expérimental mené par Debus et al. (2022) a en effet permis d'identifier et de mesurer les effets simultanés de plusieurs caractéristiques des brebis sur la réponse ovarienne à court terme des brebis laitières de la race Lacaune à la suite d'un effet mâle. Les résultats de ce travail ont ainsi permis d'intégrer les probabilités de cyclicité avant et après un effet mâle. Dans REPRINOV, ces probabilités sont influencées par l'intervalle dernier agnelage-mise à la reproduction, la NEC, l'âge et le potentiel de production laitière de chaque brebis (production totale et niveau de production juste avant la reproduction, caractérisé par la valeur du dernier contrôle laitier). Cela constitue également une originalité du modèle, car il existe très peu de modèles de reproduction ovine (qu'ils soient à l'échelle de l'animal ou du troupeau) qui tiennent compte de l'effet simultané de plus de deux caractéristiques des brebis dans leur estimation des performances de reproduction. Généralement, seul le lien avec la NEC et/ou l'âge (ou d'autres facteurs associés tels que la parité) est représenté (Cournut et Dedieu, 2004; Gebre et al., 2014; Villalba et al., 2019); ces deux caractéristiques ayant largement été présentées comme étant des facteurs présentant une forte influence sur les performances reproductives des brebis (Hight et Jury, 1970; Abegaz et al., 2002; Rosa et Bryant, 2003; Kenyon et al., 2014). En revanche, il n'existe pas à notre connaissance de modèle de troupeau ou d'élevage ovin qui intègre dans sa représentation du processus de reproduction des liens avec l'intervalle dernier agnelage-mise à la reproduction et/ou la production laitière des brebis. Il existe pourtant un lien entre le moment d'introduction du bélier par rapport à l'agnelage précédent et la cyclicité des brebis (Ungerfeld et al., 2004; Debus et al., 2022). De même, il existe un lien entre les performances laitières et les performances reproductives des brebis laitières (Gootwine et Pollott, 2000; David et al., 2008; Debus et al., 2022) qu'il est d'autant plus important de prendre en compte dans un contexte de gestion de la reproduction sans TH. Ainsi, dans REPRINOV le rendement laitier total de

la dernière campagne de production et le rendement observé au dernier contrôle laitier avant la mise à la reproduction affectent la probabilité d'entrée en chaleur des brebis suite à un effet mâle. Par ailleurs, la prise en compte de l'intervalle dernier agnelage-mise à la reproduction, de même que celle des indicateurs individuels de performances laitières dans la détermination de l'entrée en chaleur des brebis offrent également la possibilité de faire des liens indirects avec les performances de reproduction de la campagne précédente (ex : un échec de la reproduction se traduit par une production laitière nulle, ce qui affecte la probabilité d'entrée en chaleur de la brebis à la campagne suivante). En définitive, la prise en compte simultanée de tous ces différents facteurs dans les équations de probabilité d'entrée en chaleur suite à un effet mâle donne la possibilité de relier plus finement la composition du troupeau étudié (notamment les caractéristiques des brebis qui le composent) et ses performances de reproduction.

Modélisation de dynamiques issues des différentes interactions entre les entités du système de production OVL

Grâce à l'utilisation de la méthode de modélisation multi-agent (cf. Chapitre II, paragraphe II-2), le modèle REPRIN'OV permet également de faire le lien entre réponses individuelles des brebis à la stratégie de gestion de la reproduction, performances du troupeau et de l'exploitation au cours du temps. Il représente en effet les comportements simultanés de diverses entités composant un élevage OVL (brebis et éleveur notamment), ce qui permet de modéliser les interactions dynamiques entre différents processus biophysiques et organisationnels intervenant à diverses échelles (de temps et d'espace) et les performances globales de l'exploitation. Les résultats des travaux menés dans cette thèse montrent en effet que des changements de gestion de la reproduction ont eu des conséquences sur les performances individuelles des brebis puis, par des jeux d'interactions entre processus individuels au sein du troupeau et décisions de l'éleveur, ont eu des répercussions sur les performances dynamiques du troupeau (notamment sur l'évolution des courbes de distribution des agnelages et de production laitière), affectant ainsi (ou pas) les performances de l'exploitation en fonction du contexte. Par ailleurs, les différentes échelles temporelles représentées dans REPRIN'OV (de la demi-journée à plusieurs années) favorisent l'observation de l'évolution de ces dynamiques d'interaction dans le temps.

Une attention particulière a également été portée sur la modularité du modèle [conceptuel et implémentation avec la plate-forme GAMA (https://gama-platform.org)] de façon à faciliter l'ajout de nouveaux éléments tels que, par exemple, l'ajout de nouvelles règles de gestion du troupeau dans la représentation de la gestion de l'éleveur, l'ajout de processus individuels supplémentaires comme l'acquisition de nutriments et la mobilisation des

réserves corporelles au cours du temps pour les brebis et les béliers, ou encore l'ajout de lois d'évolution de la croissance de l'herbe en fonction du climat pour les surfaces fourragères. Cela fait de REPRIN'OV un outil de simulation potentiellement intéressant pour tester l'impact de changements simultanés de pratiques en élevage OVL (qu'ils concernent la gestion de la reproduction ou pas) sur l'évolution dynamique des performances de l'exploitation. En effet, outre son intérêt pour étudier l'effet de l'introduction de conduites non hormonales de la reproduction sur les performances du troupeau, cet outil semble intéressant pour simuler par exemple les interactions qui découlent de différents choix simultanés de gestion au niveau de la reproduction et au niveau de la gestion de l'alimentation du troupeau. La gestion de l'alimentation détermine en effet l'état corporel des animaux ainsi que leur dynamique de production laitière. Elle peut donc avoir des conséquences sur ses performances de reproduction, conséquences qui pourraient plus ou moins différer selon la méthode de gestion de la reproduction. Ainsi, REPRIN'OV pourrait par exemple servir à étudier l'impact de l'introduction d'une conduite non hormonale de la reproduction dans un contexte de variabilité de la disponibilité de l'herbe au pâturage (en lien avec le changement climatique) qui affecterait plus ou moins les états corporels et/ou la production laitière des individus d'un troupeau OVL avec des impacts possibles à étudier au cours des saisons climatiques ou en réponse par exemple aux effets du changement climatique.

Prise en compte des trois dimensions de la durabilité dans l'évaluation des performances de l'exploitation

De manière générale, comme l'indique la récente revue de la littérature faite par Van der Linden et al. (2020), la plupart des modèles d'élevages européens développés pour explorer les conséquences multidimensionnelles d'innovations, ou encore de changement de politiques publiques, sur la durabilité des élevages représentés ne couvrent pas simultanément les trois dimensions de la durabilité (économique, environnementale et sociétale). Cela ne leur permet donc pas d'évaluer des synergies ni de réfléchir à des compromis entre l'ensemble des aspects de la durabilité d'un système. Si les aspects économiques et environnementaux de la durabilité des systèmes représentés sont souvent pris en compte, la dimension sociale est plus rarement modélisée principalement du fait de la difficulté de quantifier les indicateurs sociaux (Van der Linden et al., 2020). Lorsqu'on s'intéresse spécifiquement à l'élevage OVL, il n'existe pas à notre connaissance de modèles d'exploitations qui permettent d'appréhender les trois dimensions de la durabilité en sortie. Le modèle REPRIN'OV se distingue donc également par la prise en compte de ces trois dimensions dans l'évaluation de ses systèmes simulés. Même simplifiée, la prise en compte de l'aspect social de la durabilité du système

via la simulation de la charge de travail lors des périodes d'astreintes principales (l'agnelage et la traite) a notamment permis de constater que pour trois des quatre cas-types d'exploitations OVL modélisées dans ce travail de thèse, l'introduction de conduites alternatives aux TH a eu des implications négatives très importantes sur leur charge de travail pendant l'agnelage en comparaison avec les effets observés sur d'autres indicateurs technico-économiques ou encore environnementaux de leur durabilité. Cela a permis de dresser des conclusions et de suggérer des compromis qu'il n'aurait pas été possible d'envisager si la charge de travail n'avait pas été évaluée en parallèle des autres indicateurs de la durabilité des exploitations. Cela illustre l'importance de s'intéresser à tous les aspects de la durabilité d'une exploitation dans le cadre de réflexions visant à introduire des changements de pratiques.

VII-3. Principaux apports des résultats de simulation dans le cadre de la réflexion autour de l'introduction d'alternatives à l'utilisation de traitements hormonaux dans le Bassin Nord Occitanie

Principales conséquences associées à l'introduction de nouvelles conduites de la reproduction utilisant des alternatives aux hormones dans les élevages OVL du BNO

En se basant sur les connaissances concernant les méthodes alternatives aux TH utilisables en élevage ovin (cf. Chapitre I-3) ainsi que sur des discussions avec des experts et des acteurs du fonctionnement de la filière OVL du BNO, plusieurs scénarios théoriques de gestion alternative de la reproduction ont été identifiés (cf. Chapitre II, II-3.3). Pour rappel :

- *Pour les exploitations en AC* (qui utilisent actuellement des TH) *:* Un premier scénario (SHIA) représentant une conduite de la reproduction avec utilisation de l'effet mâle comme alternative aux TH de synchronisation couplée à la conservation de la pratique de l'IA pour le lot de brebis adultes uniquement. Et, un deuxième scénario (SHMN) représentant une conduite de la reproduction avec utilisation de l'effet mâle comme alternative aux TH de synchronisation couplée à l'arrêt complet de l'IA du troupeau (donc monte naturelle exclusive).
- *Pour les exploitations en AB* qui fonctionnent déjà sans hormones : Uniquement un scénario (SHIA) représentant une conduite de la reproduction avec utilisation de l'effet mâle comme alternative aux TH de synchronisation couplée à l'introduction de la pratique de l'IA pour le lot de brebis adultes uniquement.

Les résultats obtenus pour les simulations de ces différents scénarios d'introduction de méthodes alternatives de gestion de la reproduction dans plusieurs cas-types d'exploitations OVL représentatives du BNO, ont montré des effets contrastés entre les exploitations sur les

différents indicateurs de durabilité simulés (cf. Chapitre V et VI). Des différences ont en effet été observées selon la configuration initiale des exploitations et notamment selon les types d'agriculture (AB ou AC) et les saisons de reproduction (« hâtive » ou « tardive ») des exploitations. En effet, les scénarios alternatifs de gestion de la reproduction (SHIA et SHMN) évalués ont globalement montré des conséquences négatives sur les indicateurs de durabilité simulés pour les exploitations en AC, tandis que le scénario alternatif SHIA a eu des effets positifs sur ces mêmes indicateurs pour les exploitations en AB. En parallèle, il a été observé qu'à type d'agriculture équivalent, les exploitations dont la saison de reproduction se situait « hors saison » (c'est-à-dire en dehors de la saison naturelle d'activité sexuelle des brebis) ont présenté plus de conséquences négatives ou alors des conséquences négatives plus fortes sur les indicateurs de durabilité simulés dans les scénarios alternatifs sans TH. Ces résultats étaient attendus puisque pour les exploitations en AB, il n'y a pas eu de modification de leur pratique d'induction/synchronisation des chaleurs, tandis que pour les exploitations en AC, nous avons simulé un passage de l'utilisation de TH à une pratique d'induction/synchronisation des chaleurs plus variable (l'effet mâle) ce qui a conduit à une distribution des agnelages plus étalée par rapport au contexte classique avec TH. Cet étalement de la distribution des agnelages s'est par ailleurs traduit en une perturbation de la courbe de production de lait du troupeau, et a en conséquence négativement impacté une grande partie des indicateurs économiques et environnementaux évalués. D'autre part, les effets négatifs simulés étaient d'autant plus forts pour les exploitations « hâtives » (c'est-à-dire dont la saison de reproduction se situait « hors saison ») et particulièrement dans celle où les agnelles ont été mises à la reproduction « hors saison », du fait de la plus grande difficulté à induire l'œstrus chez les agnelles sans TH à ce moment de l'année.

Les résultats de ce travail de thèse confirment ainsi notre première hypothèse de départ selon laquelle les changements de pratique associés à l'introduction de nouvelles conduites de la reproduction devraient différer selon la structuration des exploitations. Ils suggèrent notamment que l'introduction de pratiques alternatives aux TH (qu'elles intègrent ou non la pratique de l'IA) doit être réfléchie différemment selon le type d'agriculture et la saison de reproduction de l'exploitation OVL considérée. Ils supposent notamment que des changements dans la gestion et l'organisation de l'exploitation sont strictement nécessaires dans les exploitations en AC pour introduire de manière durable une gestion de la reproduction sans utilisation de TH, alors que ce n'est pas obligatoirement le cas pour les exploitations en AB. Ils supposent également plus d'adaptations pour les exploitations « hâtives » que pour les exploitations « tardives » (Figure VII.1).

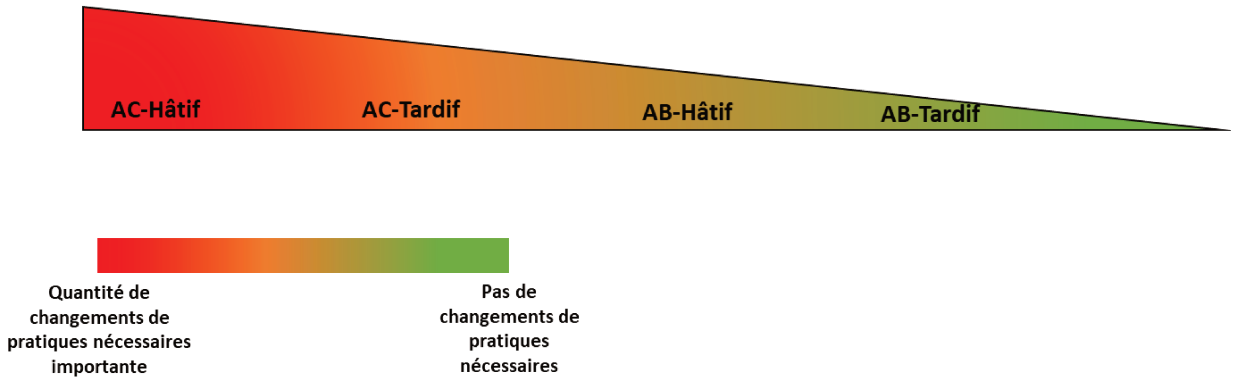

Figure VII. 1. Schématisation de la quantité de changements de pratiques à introduire pour mettre en place une conduite alternative de la reproduction sans perturber le fonctionnement actuel de l'exploitation en fonction du type d'agriculture et de la saison de reproduction des différents cas-types d'exploitations OVL simulées dans la thèse.

En ce qui concerne les scénarios alternatifs incluant l'introduction de l'IA sur chaleurs naturelles (SHIA) les résultats obtenus au terme de cinq campagnes de production ont montré, qu'il s'agit effectivement d'un bon moyen d'éviter une diminution importante du pourcentage d'individus ayant la meilleure génétique dans les exploitations en AC puisque la pratique de l'IA sans hormones a permis de conserver un patrimoine génétique issu d'IA pour plus de 40 % des individus du troupeau contre moins de 20 % sans la pratique de l'IA (scénarios SHMN) dans les exploitations en AC. Inversement, l'IA sur chaleurs naturelles a permis de faire profiter d'un patrimoine génétique issu d'IA à 30-40 % des brebis du troupeau dans les exploitations en AB. Cependant, pour tous les types d'exploitations, les rendements laitiers simulés dans les scénarios SHIA ont montré des différences significatives mais pas extrême avec les scénarios SHMN (ex : entre -0,5% et +1% pour la production laitière totale par brebis sur cinq campagnes, selon les exploitations) tandis qu'ils ont conduit dans la plupart des cas à des charges de travail quasi équivalentes à supérieures. Cela vient nuancer l'idée souvent avancée selon laquelle il est nécessaire de conserver la pratique de l'IA pour maintenir des performances biotechniques et notamment un progrès génétique laitier élevé dans les troupeaux en AC. De même, l'idée selon laquelle l'introduction de l'IA dans les exploitations en AB permet d'apporter un progrès génétique et donc amélioration des traits laitiers plus rapide peut sembler discutable au vu des résultats obtenus. Cependant, il faut noter que les niveaux génétiques des troupeaux OVL du BNO, en AC comme en AB, sont déjà très élevés du fait du travail de sélection qui a été réalisé pour la race Lacaune pendant plusieurs dizaines d'années (Barillet et al., 2001). Les élevages qui ne font pas d'IA aujourd'hui (majoritairement ceux en AB) ont en effet la possibilité d'acheter des béliers reproducteurs nés d'IA dans les CIA, ce qui leur permet de profiter malgré tout du progrès génétique par ce biais. On peut donc supposer qu'une observation des conséquences du passage à l'IA sans hormones sur cinq campagnes de production correspond à un nombre trop

faible de campagnes pour pouvoir observer des différences majeures entre des scénarios alternatifs avec et sans IA. Barillet et al. (2016) estiment en effet que le régime de croisière en termes de gain génétique ne peut généralement être espéré que 10 à 15 ans après le démarrage d'un programme de sélection dans le cadre de l'organisation actuelle des schémas de sélection des races ovines françaises. Il semble ainsi nécessaire de simuler un plus grand nombre de campagnes de production, mais, comme dit précédemment (cf. paragraphe VII-2 de ce chapitre), cela nécessite dans le même temps d'estimer de manière plus précise les évolutions probables du gain annuel génétique sur le territoire dans un contexte de réduction de l'utilisation des TH.

Pistes pour une intégration durable d'alternatives aux hormones dans les élevages OVL du BNO à partir des résultats de simulations

Les résultats de simulations obtenus dans ce travail ont également souligné l'existence d'une vraie difficulté à proposer des stratégies alternatives de gestion de la reproduction qui n'impactent pas négativement au moins une des dimensions de la durabilité du fonctionnement dans les exploitations OVL. Cela suppose donc que de manière générale, des compromis devront forcément être faits en fonction des principaux objectifs d'évolution des agriculteurs pour leurs systèmes de production et selon le poids qu'ils donnent aux différentes dimensions de la durabilité. Les travaux menés et les résultats obtenus permettent tout de même de proposer des pistes générales à explorer pour limiter les retombées négatives simulées sur certains des indicateurs de durabilité des différents types d'exploitations modélisées.

Premièrement, une solution pour limiter la diminution des taux de fertilité simulée dans les exploitations en AC pourrait être de **prolonger la durée de la période d'accouplement direct (et donc la période de reproduction)** afin que les brebis qui n'ont pas exprimé d'œstrus au printemps (ou au début de l'été pour les élevages de type « tardif ») aient une chance de le faire plus tard à l'approche de la saison de reproduction naturelle. Par ailleurs, pour les élevages en AC de type « hâtif » au sein desquelles les agnelles sont aujourd'hui mises à la reproduction en pleine contre saison, un décalage du début de leur reproduction en saison pourrait être fait en complément afin d'éviter une baisse générale de la fertilité du troupeau due à la difficulté de reproduire les jeunes femelles « hors saison ». Les résultats des travaux de Debus et al. (2022) et l'exploration des sorties du modèle de troupeau OVL présenté au chapitre III ont également permis d'identifier des **leviers individuels à l'échelle des brebis** (NEC, âge et production laitière notamment) qui, lorsqu'ils sont optimisés, permettent d'améliorer l'induction des cycles ovariens et donc la synchronisation dans les troupeaux OVL du BNO. Cependant, si favoriser une bonne NEC

moyenne ou encore une bonne production laitière moyenne du troupeau semble réalisable de manière indépendante à l'échelle de l'exploitation (ex : en optimisant le plan d'alimentation du troupeau), augmenter l'âge moyen du troupeau ou l'intervalle moyen entre le dernier agnelage et la mise à la reproduction sont des solutions qui nécessitent de revoir des choix de gestion de troupeau eux-mêmes liés à l'organisation de la filière à l'échelle du territoire (ex : augmenter l'âge moyen du troupeau suppose de revoir la politique de réforme et de renouvellement dans les exploitations, ce qui pourrait avoir des conséquences à l'échelle de la filière sur la vitesse du progrès génétique). Ces leviers proposés à l'échelle du troupeau doivent donc être discutés à l'échelle de la filière afin de trouver des compromis acceptables.

Une autre solution pour limiter la diminution des taux de fertilité simulée dans les exploitations en AC pourrait aussi être de combiner l'utilisation de l'effet mâle avec d'autres pratiques non hormonales pour induire et synchroniser l'apparition des cycles ovariens dans un troupeau OVL. **Des protocoles photopériodiques en complément de l'effet mâle** sont notamment envisagés pour essayer d'améliorer l'induction de la cyclicité dans le troupeau (Pellicer-Rubio et al., 2019) en particulier hors saison pour les agnelles. Cependant, l'utilisation de traitements photopériodiques n'était jusqu'à maintenant pas plébiscité dans les élevages ovins, car considérée comme trop coûteuse (Lurette et al., 2016; Pellicer-Rubio et al., 2019). Elle nécessite par ailleurs une réorganisation du travail afin de respecter strictement les protocoles d'éclairage pour les animaux traités. Cela suggère une fois de plus que des compromis devront être envisagés si cette technique est introduite en complément de l'effet mâle, et ce, afin de permettre une amélioration des performances de reproduction sans mettre en péril la santé économique de l'exploitation. La représentation du processus de reproduction entreprise dans le modèle REPRIN'OV a d'ailleurs soulevé l'existence de manquements dans la littérature scientifique concernant les fondements de la saisonnalité des agnelles et leur capacité à répondre à l'effet mâle en fonction de leur âge. Or, les résultats obtenus dans ce travail de thèse ont montré que le faible taux d'entrée en chaleur des agnelles hors saison impacte beaucoup la production laitière du troupeau et donc ses performances globales. Il est donc nécessaire dans un premier temps de développer les connaissances fondamentales sur ce sujet pour permettre de proposer des solutions efficaces pour favoriser l'induction et la synchronisation des chaleurs hors saison pour l'ensemble des animaux du troupeau.

Afin de compenser la réduction du taux de fertilité (et donc du pourcentage de brebis traites) ainsi que la perturbation de la dynamique de production laitière du troupeau observée en exploitation AC (avec TH) dans les scénarios alternatifs conservant les mêmes périodes de reproduction que celles pratiquées pour une gestion classique (Chapitres IV et

V), une proposition **d'allonger la période de traite de quelques jours** a aussi été faite. Une extension de 10 jours de la période de traite a donc été simulée en parallèle des changements de conduites de la reproduction dans les scénarios alternatifs simulés au chapitre V pour les exploitations en AC. Cette modification complémentaire de la gestion du troupeau a en effet conduit à une quantité de lait produit et à une marge brute d'exploitation plus élevées que dans le cas de la gestion actuelle du troupeau pour l'exploitation tardive en AC. Cela suggère que l'extension de la période de traite d'une dizaine de jours pourrait être un moyen simple d'introduire les conduites alternatives aux TH simulées dans les exploitations en AC de type tardives, tout en conservant un bon niveau de production laitière et en soutenant l'économie de l'exploitation. Cependant, l'extension de la période de traite s'est aussi accompagnée d'une augmentation des émissions des GES simulées et de la consommation d'eau par litre de lait produit, ainsi que d'une augmentation de la charge de travail (en s/L de lait). Par ailleurs, l'extension de la période de traite doit être associée à un ajustement équivalent des périodes d'alimentation du troupeau. Cela pourrait donc conduire à prolonger la durée de la période de pâturage dans certains cas, ce qui pourrait être un défi en fonction du contexte climatique, en particulier dans les régions méditerranéennes comme le BNO où la production et la disponibilité de l'herbe sont de plus en plus affectées par le changement climatique (Iglesias et al., 2012). De plus, l'extension de la traite à l'échelle d'une exploitation ne peut être intéressant d'un point de vue économique que si le lait produit pendant cette période de traite supplémentaire est collecté par sa laiterie. Cela suppose une révision des contrats de collecte de lait signés avec les laiteries pour pouvoir mettre en place cette stratégie.

Enfin, le taux d'IA sur chaleurs naturelles pourrait être amélioré en **augmentant le nombre de jours d'IA prévu dans le protocole d'IA sans hormones** modélisé. Cependant, cela devrait aussi conduire à une augmentation de la charge de travail pendant la période de reproduction et pourrait créer des coûts financiers supplémentaires pour l'exploitation. En effet, bien qu'il soit difficile de fixer un coût actuellement pour la réalisation de l'IA sans hormones, il est possible que les centres d'IA répercutent les charges supplémentaires liées à la nécessité de se déplacer plusieurs fois de suite pour inséminer les brebis d'une même exploitation sur le prix de l'IA.

De manière générale, si ces pistes de pratiques et/ou changements de pratiques proposées pour faciliter une introduction durable des alternatives aux TH s'envisagent assez facilement à l'échelle de l'exploitation, des conséquences sont également attendues à l'échelle de la filière en fonction du nombre d'exploitations choisissant de passer à des conduites alternatives pour la gestion de la reproduction de leur troupeau au sein du territoire du BNO. L'allongement

proposé de la période de reproduction pourrait par exemple entraîner un étalement de la période de traite du troupeau dans chaque exploitation, ce qui pourrait entraîner une perturbation de la collecte de lait à l'échelle de la filière. De même, l'évolution des taux d'IA dans les différentes exploitations conditionnera le progrès génétique à l'échelle du territoire. Par ailleurs, il est important de noter la spécificité de la pratique de l'IA ovine qui est encore aujourd'hui limitée à l'utilisation de semence fraîche. Cette contrainte, couplée aux protocoles proposés d'IA sans hormones, risque de complexifier l'organisation du travail dans les CIA si l'IA sans hormones venait à se développer largement en élevage OVL (ex : difficulté à organiser des plans d'accouplement à l'avance ou encore nécessité pour les inséminateurs de faire plusieurs trajets pour inséminer les brebis en chaleurs dans un même élevage). Il serait intéressant, dans ce sens, de continuer à développer les travaux de recherche pour un protocole d'IA ovine en semence congelée qui faciliterait la pratique de l'IA sans hormones pour les CIA (Buckrell et al., 1994; Druart et al., 2009). En parallèle, le développement de dispositifs pour automatiser la transmission d'informations entre les élevages et les CIA concernant le suivi des entrées en chaleur des brebis [par exemple via des dispositifs de transmission d'informations connectés aux outils de détection automatisée des chaleurs en développement (Bocquier et al., 2006; Alhamada et al., 2016)] permettrait de faciliter l'implémentation de l'IA sans hormones dans la filière OVL. De plus, des stratégies de compensations financières (via des primes) ou de revalorisation du prix du lait payé aux exploitants pourraient être envisagées en fonction du type d'exploitation et de la quantité d'ajustements nécessaires pour maintenir des performances biotechniques acceptables en contexte sans hormones. Ceci, afin de valoriser la mise en place de méthodes de gestion de la reproduction n'utilisant pas de TH en réponse à la demande sociétale. Ces exemples et suggestions montrent une fois de plus la nécessité de penser les solutions proposées non seulement à l'échelle de l'exploitation, mais également à celle de la filière et soulignent l'importance de discuter des solutions envisagées avec l'ensemble des acteurs de la filière OVL du BNO.

Conclusions et perspectives

Conclusions et perspectives

Une bonne maîtrise de la gestion de la reproduction est essentielle au bon fonctionnement d'un élevage puisqu'elle détermine entre autres le nombre et l'état des animaux en production à chaque campagne ainsi que l'organisation temporelle de leur production. Tout changement dans la gestion de la reproduction pourrait donc affecter fortement le fonctionnement global de l'exploitation ainsi que sa durabilité sur le long terme. Il est donc nécessaire, avant d'introduire une innovation et/ou un changement de conduite de la reproduction, d'explorer leurs effets sur la durabilité du système de production dans lequel ils s'intègrent.

Dans cette optique, le travail mené dans cette thèse a permis la construction d'un modèle d'exploitation OVL, REPRIN'OV, qui simule les conséquences de l'introduction de conduites innovantes de la reproduction, utilisant des alternatives aux TH pour la synchronisation des cycles ovariens des brebis, sur plusieurs indicateurs de la durabilité d'exploitations OVL du BNO. Bien qu'il nécessite encore un travail de calibration et de validation afin de pouvoir simuler plus précisément les valeurs des indicateurs modélisés, il semble être un outil intéressant pour imaginer et évaluer des scénarios d'évolutions possibles de la gestion de la reproduction sans hormones dans les élevages OVL du BNO.

Le modèle développé a ainsi été utilisé pour explorer les conséquences de l'introduction de conduites alternatives dans quelques cas-types d'exploitations OVL représentatives du BNO. Les résultats des simulations obtenus ont permis d'observer une diversité de conséquences biotechniques, économiques, environnementales et sociales (charge de travail) selon la configuration de départ des exploitations concernées et notamment selon leur type d'agriculture et leur choix de saison de reproduction. Ils ont également souligné la nécessité d'extrapoler les résultats obtenus pour chaque type d'exploitation à l'échelle du territoire du BNO. L'évolution au cours du temps de plusieurs paramètres du modèle ayant été identifiée comme directement liée à leur évolution à l'échelle du territoire. La méthode de la modélisation multi-agent utilisée pour le développement du modèle REPRIN'OV permet de facilement envisager ce type d'évolution. Il s'agirait d'intégrer la modélisation faite dans ce travail de thèse à l'échelle de l'exploitation dans un modèle de fonctionnement de la filière OVL du BNO à l'échelle territoriale, où les exploitations, mais aussi l'industrie laitière ou encore les centres d'inséminations seraient des entités (ou agents) du système d'élevage OVL du BNO et où une représentation des règles de fonctionnement de chaque entité ainsi que des interactions entre elles seraient faites.

Par ailleurs, les scénarios d'alternatives aux hormones développés dans ce travail étaient simplifiés de manière à pouvoir les appliquer à tous types d'exploitations OVL. De même, les

pistes de solutions proposées pour faciliter l'intégration durable d'alternatives aux traitements hormonaux en élevage OVL supposent des compromis entre les principales dimensions de la durabilité d'un système de production. Afin de proposer des solutions qui correspondent aux besoins actuels de la filière, il serait intéressant de poursuivre la démarche de construction de scénarios de pratiques alternatives, mais aussi d'analyse des résultats en impliquant plus fortement les experts locaux et des éleveurs. Le modèle développé semble en effet intéressant, pour simuler d'autres changements et ajustements dans les conduites de la traite ou l'alimentation en fonction des contraintes de chaque exploitation, afin de proposer aux éleveurs des conduites optimisées par rapport à leur système. À l'instar d'autres modèles de simulations interactives présentés dans la littérature pour raisonner des changements de pratiques dans des agrosystèmes, l'idée serait de pouvoir proposer des scénarios, mais aussi de réfléchir à des solutions qui correspondent plus spécifiquement aux attentes de la filière. Cela permettrait en effet d'avoir des sorties de simulations plus facilement appropriables par les éleveurs et leur permettrait d'envisager des changements de leur système en profondeur afin de supporter efficacement la reconception des systèmes d'exploitation en place et tendre vers une intégration durable de pratiques alternatives à l'utilisation d'hormones pour la gestion de la reproduction en élevage OVL.

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Annexes

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Annexe 1 : High body condition score combined with a reduced lambing to ram introduction interval improves the short-term ovarian response of milking Lacaune ewes to the male effect 188
Annexe 2 : Supplementary data 1 of Article 3 199
Annexe 3 : Supplementary data 2 of Article 3 204
Annexe 4 : Main parameters used to model the individual reproduction process in each simulated farm 209
Annexe 5 : Supplementary tables presenting results of the simulation of alternative scenarios to the use of TH in a diversity of farms of the Roquefort basin (see Chapter VI) 210

Annexe 1 : High body condition score combined with a reduced lambing to ram introduction interval improves the short-term ovarian response of milking Lacaune ewes to the male effect

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High body condition score combined with a reduced lambing to ram introduction interval improves the short-term ovarian response of milking Lacaune ewes to the male effect

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ABSTRACT

The male effect is an effective natural technique to induce off-season ovulation and ultimately mating or artificial insemination in small ruminants. It constitutes an alternative to hormonal treatments in conventional breeding systems and, to shift and organise the yearly production cycle, is currently the only solution complying with European organic standards. However, its associated performances are still heterogeneous, both in terms of the global response and the extent of reproductive synchronisation of the females, due to complex interactions with environmental factors that limit its use on commercial farms. This study was carried out on a French organic farm under commercial conditions to investigate, in the field and across five consecutive years, the main parameters affecting the early ovarian response to a ram effect on Lacaune dairy ewes. While the within-year binary logistic regressions yielded contrasting results, the cross-year mixed-effect binary logistic regression models clearly showed that parameters associated with the nutritional state of the animals have a profound influence on the ovarian response of the ewes. Indeed, the probabilities of a spontaneous resumption of ovarian activity before the ram effect and of an early ovarian response to the ram effect were positively associated with the body condition score, total milk production and the age of the animals, while being negatively associated with the milk production level at the 3rd milk recording. The probabilities of a spontaneous resumption of ovarian activity before the ram effect were positively associated with the interval between lambing and the introduction of the rams. Altogether, these results indicate that the ovarian performances in response to a male effect follow a bell-curve pattern with optimal performances depending upon a complex combination between photoperiodic and nutritional cues. Regarding these latter, this study highlights the major contribution of body reserves and energy balance dynamics.
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Implications

Reproductive performances in response to a male effect are variable which limits the use of this technique. We addressed this issue by identifying the main factors involved in the spontaneous and male-induced resumption of ovarian activity during a 5-year study conducted on a commercial organic dairy sheep farm. We identified a set of factors associated with the nutritional status of the ewes has having a significant impact on both parameters, which resulted in reproductive performances following a bell-curve pattern. On-farm performances could be improved by adjusting the timing of the male effect relatively to the nutritional status of the ewes.

Introduction

The seasonality of reproduction in sheep is a constraint for breeders even when raising breeds that exhibit less pronounced seasonal patterns of reproductive activities, such as most Mediterranean breeds. In any case, the spring remains a period unfavourable to reproduction. Hormonal treatments were developed to overcome this limitation and allow not only off-season breeding but also the practice of artificial insemination by stimulating the ewes to have synchronised ovarian cycles. This practice grants

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access to faster genetic progress, simplifies the work of breeders and limits the spread of animal sexual diseases. In the Rayon de Roquefort, the main region of French dairy sheep production located in the south-west of France, animal insemination is a keystone of dairy sheep farming. Thus, in this region, the selection scheme based on this practice is particularly efficient, with a dairy genetic gain of approximately 5–7 litres/year, close to the theoretical maximum (Barillet et al., 2001). However, concerns from various representatives of civil society are growing regarding the environmental and health consequences of these hormonal treatments. Globally, French society is asking for alternative techniques that do not require the use of exogenous hormones to manage reproduction (Brice et al., 2002). European organic farming standards have banned the use of these treatments.

The introduction of rams into a flock of seasonally anoestrous ewes results in an increase in the activity of the hypothalamo-pituitary axis, ultimately leading to ovulation and the resumption of oestrus cycles (Delgadillo et al., 2009). This phenomenon, called the ‘‘male effect”, is a simple cost-effective ‘‘clean, green and ethical” technique for breeding ewes during the anoestrus season (Martin et al., 2004). However, the response of ewes to the male effect is still too variable to consider a systematic use of this technique as an alternative to hormonal treatments. Additionally, the percentage of cyclic ewes within one flock during the anoestrus season, which will affect the response to the male effect, is highly variable.

Although the origins of this global variability have been investigated in several studies, the different factors have generally been studied one by one under controlled experimental conditions. These results obtained from controlled experiments, despite enriching our knowledge about reproductive mechanisms, cannot be used directly to provide practical recommendations for farmers.

When considering the performances of the ovarian response to a male effect, two main parameters have to be taken into account, namely, the proportion of females exhibiting a spontaneous resumption of ovarian activity before male introduction and the proportion of females showing an ovarian response to the male effect (i.e., the response to the male effect *per se*). The relationships between these two parameters are relatively complex. Indeed, while an increase in the first automatically decreases the second, it has also been shown that fertility after a male effect is positively correlated with the percentage of spontaneously cycling females (Folch et al., 2000).

Both of these parameters are impacted by various factors, and nutrition can be considered one of those main factors, with major direct effects on both parameters. Thus, it has been demonstrated that nutrition modulates the timing of seasonal reproductive transitions in sheep (Menassol et al., 2012). Moreover, a reduced nutritional status is associated with a longer postpartum anoestrus (Wright et al., 1990), and a greater live weight is associated with more frequent off-season ovulations (Avdi et al., 2003). In terms of the response to the male effect, a lower nutritional status can be associated with a reduction in the occurrence of ram-induced ovulations and oestrus behaviour (Todorov and Nedelkov, 2015) with contradictory results (Scaramuzzi et al., 2014), as well as an earlier cessation of oestrus cycles (Wright et al., 1990). Therefore, timed nutritional supplementation, known as focus feeding and flushing, is often used as a management technique to improve reproductive performance following a ram effect (Johnson et al., 2011; Ben Khlil et al., 2017).

Other factors closely associated or relatively independent of nutrition may also have an impact on these parameters. Concerning the spontaneous resumption of ovarian activity, the age of the ewes has been shown to increase the occurrence of off-season ovarian cycles (Maatoug-Ouzini et al., 2013). Moreover, this parameter also varies with the breed of sheep (Chanvallon et al., 2011). On the other hand, the ovarian response to a male effect is positively impacted by the timing of ram introduction relative to the females' previous parturition (Ungerfeld et al., 2004) and dry-off (Tournadre et al., 2009). This observation is amplified in milking ewes affected by both postpartum and lactation anoestrus (Cappai et al., 1984), suggesting a link between the dynamics of body energy expenditure and the ovarian response to the male effect. More generally, when observing the behavioural oestrus response of ewes to a male effect, parity, age, time of exposure to the male and sex ratio were also factors described as having multiple impacts on reproductive performances (for a review, see: Rosa and Bryant, 2002; Delgadillo et al., 2009).

The aim of this work was to gain a better understanding, under the commercial breeding conditions of an organic dairy sheep farm monitored for five consecutive years, of how various factors interact to impact the spontaneous and male-induced resumption of ovarian activity and to ultimately develop practical recommendations for hormone-free breeding management.

Material and methods

Location

This experiment was carried out at an organic commercial farm located in the Roquefort area in Aveyron, in southern France (44 387N, 2 9623E). This farm and the associated lands have been certified as organic since 2008, in accordance with the European and French organic farming standards. The farm covers around 80% of its feed needs while the other 20% are purchased from other French organic farms. All animals were cared for as specified within the guidelines of the French National Research Institute for Agriculture, Food and the Environment (INRAE) animal ethics committee, and the experiments were compliant with the Animal Research Act of 1985 in accordance with ethical principles that have their origins in the European Union directive 2010/63/EU.2.1.

Animals and management

The experiment was conducted for five consecutive years (2012–2016) at the time of seasonal anoestrus in the spring on 228–269 adult Lacaune dairy ewes (n = 283, 230, 256, 223 and 226 ewes for each year, respectively), aged from 18 months to 10 years (3.4 ± 0.1, 2.7 ± 0.1, 3.0 ± 0.1, 3.0 ± 0.1 and 3.1 ± 0.1 years for each year, respectively). Due to husbandry conditions and the mating plan of the farm, the number of available rams varied between years. Three to twelve entire mature rams (aged from 5 to 8 years) were used, depending on the year, for the ‘‘ram effect” (n = 8; 3; 6; 9 and 12 rams representing a sex ratio of 1/35; 1/77; 1/43; 1/25 and 1/19 rams/ewes for each year, respectively). The rams could not be weighed, but the sexual activity of the rams was individually monitored using an automated electronic oestrus detector (Alhamada et al., 2017), except for 2012. During the 14 days of the ram effect, an average of 197 ± 27 mounts was recorded for each ram, suggesting that each ram could be considered as sexually active. The ewes were kept as a single flock during all of the experiments.

The ewes were maintained on pasture (alternating temporary and permanent grassland) during the day and in the sheepfold at night. Their diet was complemented with a concentrate feed (depending on their physiological state and in accordance with the dietary recommendations established by INRA (2010)) twice a day at the milking parlour manually or by using an automated concentrate feeder since 2015 and they were given free access to water. Two types of concentrate feed were offered: a complete nitrogen-rich concentrate feed (25–30% of nitrogen-rich extract

per kg) and a meslin-based concentrate. The ewes were equally separated into four groups for supplementation as follows:

- Group 1: ewes with the highest milk production, plus ewes in poor body condition and primiparous ewes,
- Group 2: ewes with an average milk production,
- Group 3: ewes with the lowest milk production,
- Group 4: ewes with almost no milk production, plus dry and overweight ewes.

The automated concentrate feeder was programmed to individually deliver mixed amounts of each concentrate according to the average needs of each group.

The rams were kept indoors in a separate building until the start of the experiment. They were maintained under a natural photoperiod and standard husbandry conditions, fed *ad libitum* hay and concentrate feed (depending on their physiological state and in accordance with the dietary recommendations established by INRA (2010)), and were given free access to water. The males were completely isolated from the females for at least 2 months before each male effect.

Experimental design

After the introduction of the rams at Day 0 (**D0**), blood samples were taken from the ewes at D-10, D0 and D+11 and were assayed for plasma progesterone levels to determine the occurrence of cyclicity before (D-10 and D0) and in response (D+11) to the introduction of the rams.

At D0 (23, 18, 17, 17 and 14 April for each year), the rams were equipped with an apron that prevented mating and they were introduced into the flock in the late afternoon, just after milking. They were kept with the ewes for 14 days, only between the daily afternoon and morning milkings (each lasting around 10 hours). After D+14, the ewes were inseminated or mated with one of six different rams.

One week before the introduction of rams, the body condition score (**BCS**, noted on a scale from 0 to 5) (Russel et al., 1969) was evaluated for each ewe by trained technicians. Age, days from previous lambing, litter size, milk yield during the previous lactation (total milk production and milk production level at the third milk recording just before the introduction of the rams) were also collected for each ewe and across each year.

Blood samples and hormone assays

Blood samples (3 mL), taken by jugular venepuncture, were used to determine the concentrations of progesterone. They were collected in the morning after milking and placed in heparinised tubes (17 IU/mL sodium heparin, Vacutainer; Becton Dickinson and Company, Franklin Lakes, NJ). After sampling, the plasma was separated by centrifugation (3 600 rpm for 20 min at 4 °C) and stored at −20 °C.

Progesterone was assayed in duplicate measures of 10 µL of plasma using a double-antibody ELISA (Canépa et al., 2008). The sensitivity of the assay averaged 0.22 ng/mL (28 assays), the intra-assay CV was 14%, and the inter-assay CV was 12%.

Data analysis

Cyclicity determination

A ewe was considered to be cyclic before the introduction of the rams (defined as a spontaneous resumption of ovarian activity) if the plasma progesterone concentration was above 1 ng/mL in at least one of the two blood samples taken before the introduction of the rams (D-10 and D0). Only ewes that were categorised as not cyclic before the introduction of the rams were considered as being able to respond to the male effect. Thus, a given ewe was considered to be responding to the male effect, if categorised as non-cyclic before and cyclic after (plasma progesterone concentration at D+11 > 1 ng/mL) the introduction of the rams. This single blood sampling at D+11 allowed to monitor both main patterns of resumption of ovarian activity in response to a ram effect (Lassoued et al., 1997).

Zootechnical parameters

Four continuous and two categorical explanatory zootechnical variables were included in the data analysis: the age of the animals (age, in days), the interval between lambing and male introduction (**LME** interval, in days), total milk production (**TMP**, in L), milk production at the third milk recording (3rd milk recording, in mL), the size of the last litter (litter size, from 1 to 4 depending on the year) and the category of the body condition score (high: BCS > 3, medium: 2 < BCS $\leq$ 3 and low: BCS $\leq$ 2). These parameters are presented according to the BCS categories and for each year in Table 1.

Statistical models

Within years' model

Binary logistic regressions were performed for each year to determine the contribution of the three categories of BCS and the five other factors listed above (age, LME interval, TMP, 3rd milk recording, litter size) for the probability of being cyclic before the male effect and for the probability of responding to the male effect. The binary variables to be explained each have two modalities: Yes or No, which corresponded to the success and failure of the events "The ewe is cyclic before the male effect" and "The ewe is responding to the male effect". These analyses were performed using the glm function of the glm2 package of R software (Marschner, 2011). Given the large number of explanatory variables, only their simple effects were analysed.

Between years' model

Five years of monitoring resulted in a longitudinal dataset with a repetition of measurements for some individuals in the flock. To analyse the five-year effect of the variables defined above, mixed-effect binary logistic regression models were performed using the glmer function of the lme4 package of R software (Bates et al., 2015). In these models, BCS, age, LME interval, litter size, TMP and 3rd milk recording were fitted as fixed factors, while individual and year were fitted as random factors. Since the sex ratio varied with year, it was fitted within the models as a random factor nested within year. Only the simple effects of the explanatory variables were analysed.

The models took the following form:

$$Log(Odds) = Log\left(\frac{P}{1-P}\right) = Constant + \sum Coeff_i * Variable_i + \varepsilon,$$

where *Odds* is the ratio between the probability of success and the probability of failure of the event "The ewe is cyclic before the male effect" and "The ewe is responding to the male effect", *P* is the probability of being cyclic before the male effect and for the probability of responding to the male effect, *i* is one of the zootechnical parameters, *Coeff* is the regression coefficient associated with each variable *i* and $\mathcal{E}$ *is* the model random error.

The statistical associations between the events to be explained and the explanatory variables were obtained by observing the odds ratio (**OR**). These ORs are equal to the exponential value of the regression coefficients. When referring to a continuous variable, ORs significantly higher (or lower) than 1 (*P*-value < 0.05) indicate an increased (or reduced) probability of the events being explained

Table 1
The zootechnical characteristics of the ewes according to their respective body condition score categories.

		Age (years)			3rd milk recording (mL)			TMP (L)			LME interval (days)			Litter size		
		BCS low	BCS medium	BCS high	BCS low	BCS medium	BCS high	BCS low	BCS medium	BCS high	BCS low	BCS medium	BCS high	BCS low	BCS medium	BCS high
Year	n[1] (nL,nM,nH)	Mean (±SEM)														
2012	283	3.0	3.4	3.9	1 250	1 025	658	218	250	256	105	137	182	1.1	1.2	1.4
	(29,219,35)	(±0.30)	(±0.10)	(±0.20)	(±55.0)	(±25.9)	(±52.1)	(±10.9)	(±5.0)	(±9.5)	(±7.3)	(±3.2)	(±4.9)	(±0.06)	(±0.03)	(±0.09)
2013	230	2.6	2.7	3.8	1 239	979	728	222	250	248	107	146	178	1.2	1.3	1.3
	(14,203,13)	(±0.40)	(±0.10)	(±0.30)	(±95.4)	(±19.5)	(±59.1)	(±11.6)	(±4.8)	(±19.8)	(±2.1)	(±2.7)	(±7.9)	(±0.11)	(±0.03)	(±0.13)
2014	256	2.9	2.9	4.7	1 237	942	486	156	199	162	94	145	181	1.4	1.3	1.3
	(17,232,7)	(±0.40)	(±0.10)	(±0.40)	(±57.2)	(±18.1)	(±41.3)	(±12.2)	(±4.3)	(±21.8)	(±6.5)	(±3.0)	(±8.1)	(±0.12)	(±0.03)	(±0.29)
2015	223	2.9	3.1	3.6	929	790	534	198	231	199	253	195	193	1.1	1.2	1.4
	(18,198,7)	(±0.50)	(±0.10)	(±0.70)	(±77.3)	(±17.7)	(±53.4)	(±10.8)	(±4.1)	(±26.3)	(±34.8)	(±5.8)	(±2.2)	(±0.08)	(±0.03)	(±0.20)
2016	226	7.0	2.9	3.8	1 130	1 057	805	253	248	277	135	151	195	1.5	1.4	1.3
	(2,178,46)	(±0.00)	(±0.10)	(±0.20)	(±230.0)	(±23.8)	(±25.0)	(±66.2)	(±5.6)	(±6.3)	(±40.0)	(±3.7)	(±1.5)	(±0.50)	(±0.04)	(±0.07)

BCS = body condition score; TMP = total milk production; LME interval = lambing to male effect time interval.
BCS low: BCS ≤ 2; BCS medium: 2 < BCS ≤ 3; BCS high: BCS > 3.
[1] n: total number of ewes; nL: number of ewes in the low BCS class; nM: number of ewes in the medium BCS class; nH: number of ewes in the high BCS class.

with each 1-unit increase in the value of the explanatory variable. For the categorical variables, ORs significantly higher (or lower) than 1 (P-value < 0.05) indicate an increased (or decreased) probability of the events being explained when compared with a given level of the explanatory variable. It should be noted that for the categorical variable BCS, the reference category used was the Low class. Thus, for each regression, the OR associated with BCS Low is equal to one.

Statistical analyses were performed using R software (R Core Team, 2021). The data are presented as the mean ± SEM.

Results

Cyclicity before the male effect

The progesterone results showed that the cyclicity before the male effect was highly variable and ranged from 29 to 61% depending on the year (35, 30, 29, 61 and 61% for each year, respectively) and varied with BCS (17, 39 and 71% for low, medium and high BCS, respectively).

Within years' results

The results of the binary logistic regression models performed for each year are presented in Supplementary Table S1.

Within years, the results were highly heterogeneous, with few consistent effects across years. The occurrence of cyclicity before the introduction of rams was positively associated with the LME interval (P < 0.01) only during 2013 and 2014. During 2016, age and TMP were positively associated (P < 0.01 and P < 0.05, respectively) with the proportion of cyclic ewes before the male effect, while the 3rd milk recording was negatively associated (P < 0.05) with this same parameter.

Between years' results

The results of the mixed-effect binary logistic regression model over the 5 years of the experiment are presented in Table 2 and Fig. 1. The contributions of the individual variables to the predicted probabilities of the spontaneous resumption of ovarian cycles are presented in Fig. 2.

The variables BCS (class High), age, 3rd milk recording, TMP and LME interval significantly contributed (P < 0.05 and P < 0.001 for first two and last three variables, respectively) to the probability of being cyclic before the male effect, whereas the contribution of litter size was not significant (Table 2). Among these variables, the high BCS level made the greatest contribution to the outcome of the model. Thus, this model shows that a gain in BCS class multiplied the probability of responding to the male effect by 3.3 (from BCS medium to high; Table 2). As shown in Fig. 1, the ewes that were most likely to be cyclical combined high BCS, low 3rd milk recording and long LME interval values. Age also had a positive linear effect on the probability of being cyclical (Fig. 2).

Cyclicity in response to the male effect

Progesterone results ranged from 31 to 85%, showing that the response of ewes to the male effect was highly variable between years (51, 31, 41, 85 and 52% for each year, respectively). This parameter also varied according to BCS (17, 50 and 90% for low, medium and high BCS, respectively).

Within years' results

The results of the binary logistic regression models performed for each year are presented in Supplementary Table S2.

Once again, the within-year results were highly variable, and consistent results across years could not be found. Among all vari-

Table 2
Five-year logistic regression model for the event "The ewe is cyclic before the Male Effect".

	OR[1]	95% CI[1]	*P*-value
BCS			
Low	Reference		
Medium	1.803	0.830–3.913	0.14
High	3.333	1.307–8.502	<0.05
Age	1.112	1.006–1.230	<0.05
3rd milk recording	0.998	0.998–0.999	<0.001
TMP	1.007	1.004–1.010	<0.001
LME interval	1.008	1.005–1.011	<0.001
Litter size	0.947	0.683–1.313	0.70

BCS = body condition score; TMP = total milk production; LME interval = lambing to male effect time interval.
BCS low: BCS $\leq$ 2; BCS medium: 2 < BCS $\leq$ 3; BCS high: BCS > 3.
[1] OR = odds ratio – CI = confidence interval.

ables, 3rd milk recording (years 2014 and 2015, $P < 0.05$ and $P < 0.01$, respectively) and BCS (class medium: years 2015 and 2016, $P < 0.05$ and $P < 0.01$, respectively; class high: year 2012, $P < 0.05$) more often showed significant contributions to the models (2 out of 5 models). Depending on the year, the variables age (year 2016, $P < 0.01$) and LME interval (2013, $P < 0.05$) were positively associated with the proportion of ewes responding to the male effect, while litter size (year 2014, $P < 0.05$) was negatively associated with this same parameter.

Between years' results

The results of the mixed-effect binary logistic regression model over the 5 years of the experiment are presented in Table 3 and Fig. 3. The contributions of individual variables to the predicted probabilities of the early ovarian response to the male effect are presented in Fig. 4.

The variables BCS (class medium and high), Age, 3rd milk recording and TMP significantly contributed (all $P < 0.001$) to the probability of responding to the male effect, whereas the contribution of LME interval and litter size was not significant (Table 3). Among these variables, BCS made the greatest contribution to the outcome of the model. Thus, this model shows that a gain in BCS class multiplied the probabilities of responding to the male effect by a 6.4 or 19.0 factor (from BCS low to medium and BCS medium to high, respectively; Table 3).

As shown in Fig. 3, the ewes that were most likely to respond to the male effect combined a high BCS and age with low 3rd milk recording values. Moreover, the negative impacts of 3rd milk recording values on the probabilities of responding to the male effect were reduced with age.

Discussion

The results of this study highlight the importance of farm management practices on the short-term ovarian response of milking ewes to a male effect. Two main parameters were considered to characterise this response, *i.e.,* the occurrence of ovarian cycles before and after the introduction of rams, corresponding to a "potential of response" and the response *per se*. Hence, the probability of an early spontaneous resumption of ovarian activity before the introduction of rams was positively associated with BCS, TMP, the interval between LME Interval and the age of the animals,

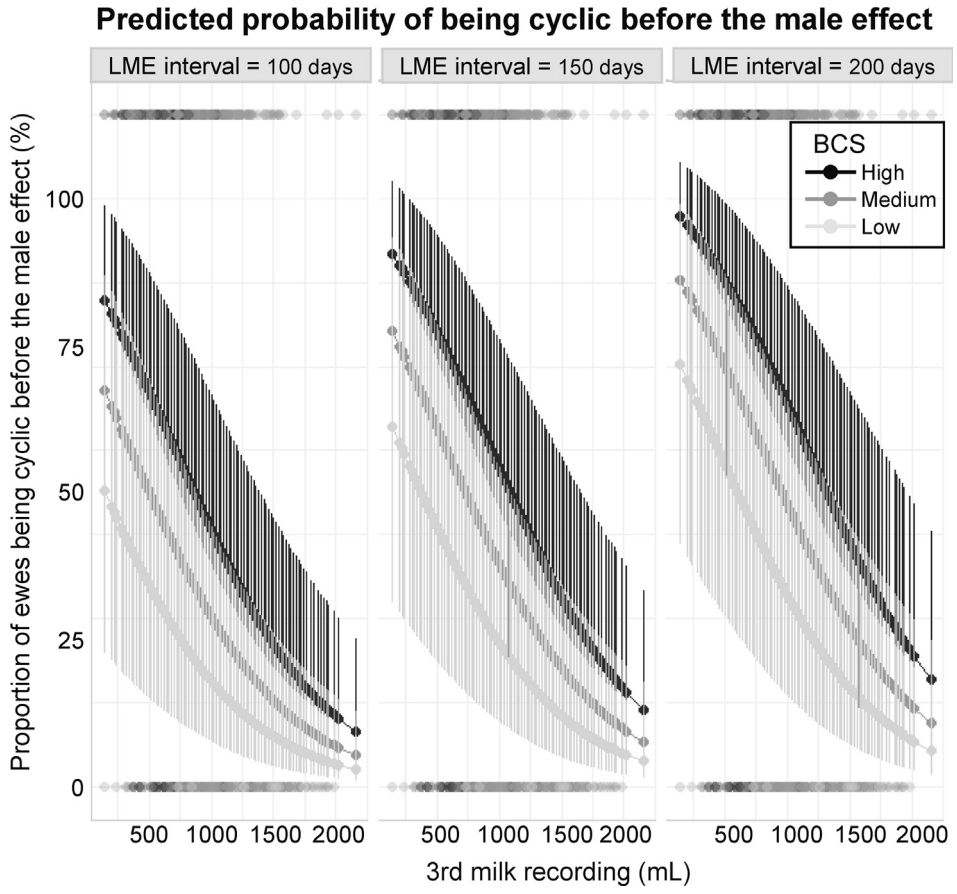

Fig. 1. Predicted probabilities (probabilities ± 0.95 confidence interval) for the ewes of being cyclic before the male effect according to the body condition score class (BCS) (Low: light grey circle, Medium: dark grey circle and High: black circle), the production level at the 3rd milk recording (3rd milk recording) and the lambing to male effect time interval (LME interval). BCS classes: Low $\leq$ 2; 2 < Medium $\leq$ 3; High > 3.

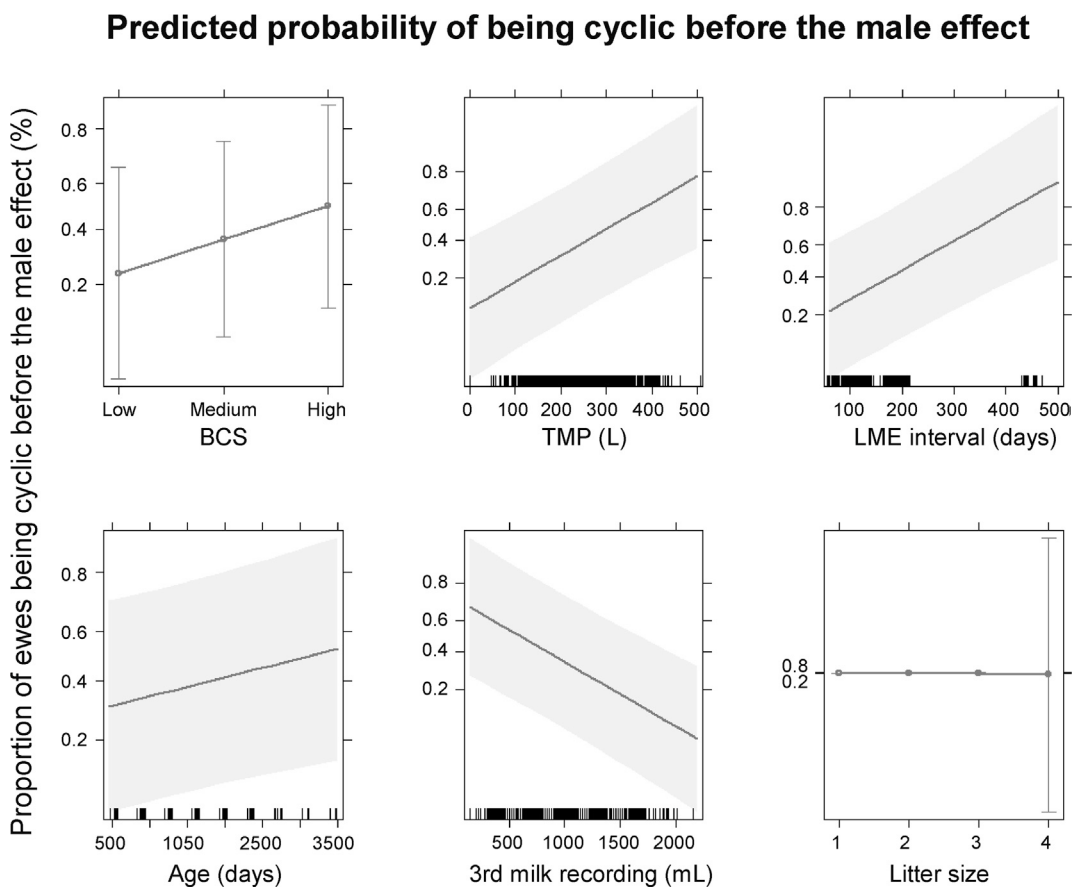

Fig. 2. Predicted probabilities (probabilities ± 0.95 confidence interval) for the ewes of being cyclic before the male effect according to the zootechnical characteristics: body condition score class (BCS), total milk production (TMP), the interval between lambing and the male effect (LME interval), age, milk production at the third milking recording (3rd milk recording) and litter size. BCS classes: Low ≤ 2; 2 < Medium ≤ 3; High > 3.

Table 3
Five-year logistic regression model for the event "The ewe is responding to the male effect".

	OR[1]	95% CI[1]	*P*-value
BCS			
Low	Reference		
Medium	6.402	2.591–15.820	<0.001
High	19.46	3.868–97.880	<0.001
Age	1.326	1.160–1.516	<0.001
3rd milk recording	0.997	0.997–0.998	<0.001
TMP	1.011	1.007–1.014	<0.001
LME interval	1.000	0.996–1.004	0.90
Litter size	0.861	0.542–1.368	0.50

BCS = body condition score; TMP = total milk production; LME interval = lambing to male effect time interval.
BCS low: BCS ≤ 2; BCS medium: 2 < BCS ≤ 3; BCS high: BCS > 3.
[1] OR = odds ratio – CI = confidence interval.

while the milk production level at the 3rd milk recording was negatively associated with this same parameter. The same associations were observed for the probability of a short-term ovarian response to the male effect, except for the LME Interval, which had no significant influence on this parameter.

Concerning the spontaneous acute or persistent resumption of ovarian activity within one flock, both being indistinguishable in our study, our results are in line with previous studies performed in sheep establishing a positive relationship between age, live weight and the time since lambing with spontaneous off-season ovarian activity (Avdi et al., 2003) and between body condition score (Forcada et al., 1992; Menassol et al., 2012) or the time since a previous lambing (Mitchell et al., 2010) and early resumption of ovarian activity. On the other hand, regarding the factors explaining the early ovarian response to a male effect, our results are also in agreement with other studies, such as the experiment reported by Dzabirski and Notter (1989), where the frequency of ovulation after a male effect, realised in spring, was lower for Dorset ewes (meat sheep) that had previously lambed during the winter season in comparison with Dorset ewes that had previously lambed during the fall season (21 ± 9 vs 59 ± 8%, respectively). Therefore, an extended interval between lambing and introduction of the rams (approximately 4 vs 8 months) had a dramatic positive impact on the proportion of ewes exhibiting an early ovarian response. A study performed in a commercial organic farm raising Limousine meat sheep (Tournadre et al., 2009) confirmed these results. Similar conclusions were drawn in a study conducted on the expression of oestrus following a male effect on 22 commercial farms breeding Merino sheep in South Australia (Kleemann et al., 2006).

Body condition score has also been identified as a factor impacting the short-term ovarian response to a ram effect in a Mediterranean breed such as the Barbarine ewe (Khaldi and Lassoued, 1991) as well as in a more seasonal breed such as the Île-de-France ewe (Johnson et al., 2011), both being sheep breeds raised for meat production. In dairy sheep, Luridiana et al. (2015), in a study conducted on two commercial farms, identified BCS and age as factors positively correlated with early oestrus expression in response to a male effect in Sarda ewes. Similar conclusions were drawn in a study conducted on six Bulgarian farms raising dairy, meat and multi-purpose breeds of sheep, where a positive correlation was established between BCS and the percentage of

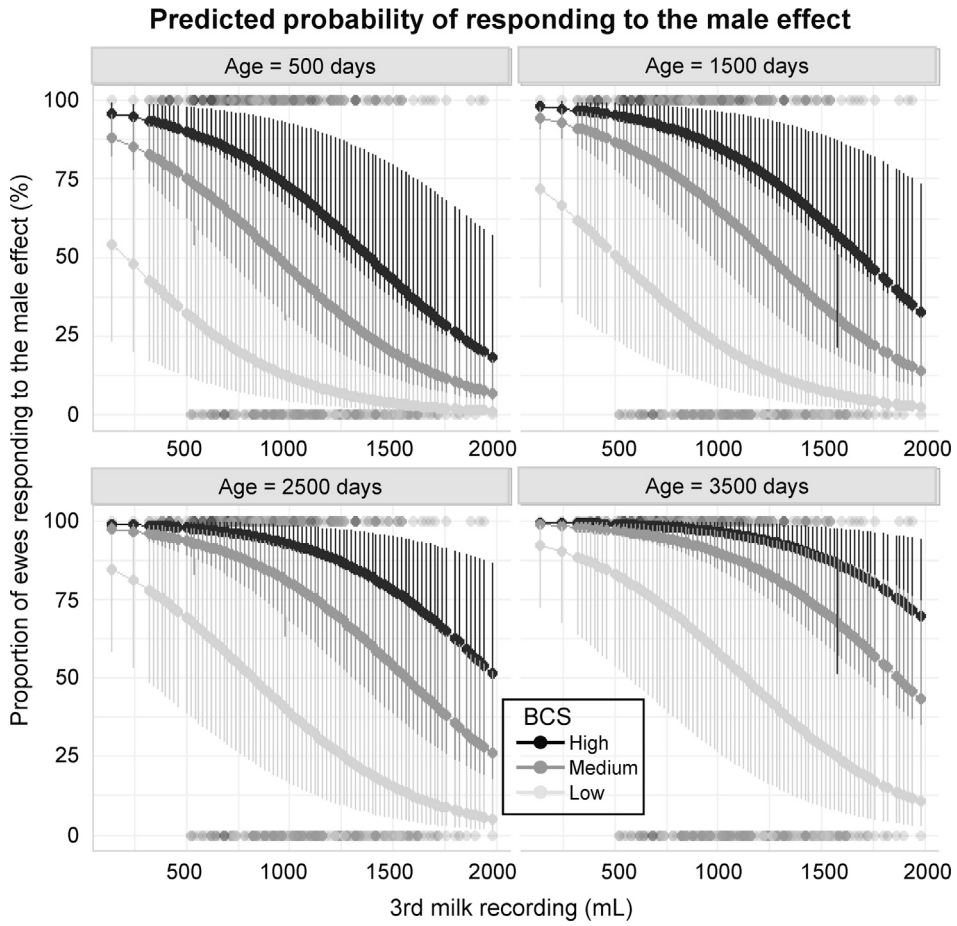

Fig. 3. Predicted probabilities (probabilities ± 0.95 confidence interval) for the ewes of responding to the male effect according to the body condition score class (BCS) (Low: light grey circle, Medium: dark grey circle and High: black circle), the production level at the 3rd milk recording (3rd milk recording) and the lambing to male effect time interval (LME interval). BCS classes: Low $\leq$ 2; 2 < Medium $\leq$ 3; High > 3.

ewes displaying oestrus behaviour in response to a male effect (Todorov and Nedelkov, 2015).

Regarding this matter, it is noteworthy that the effects of nutrition might be mediated on oestrus expression independently of direct effects on the early ovarian response following ram introduction. This was suggested by a study performed on Merino ewes, where low live weight and BCS associated with dietary restriction beginning during mid-pregnancy had negative effects on oestrus expression (77.5 ± 2.5 vs 30.0 ± 22.5%) but not on ovulations in response to a male effect (Wright et al., 1990). Finally, a positive correlation of age with all of the reproductive performances associated with the male effect (early ovarian response, oestrus expression, ovulation and conception rates) was also found but only when comparing 1-year nulliparous ewes with multiparous ewes (Ungerfeld, 2016).

This study confirms that nutrition acts as a major factor modulating the ovarian response to a male effect and that it is one of the main factors to be taken into account when this technique is employed by farmers to maximise reproductive performance on commercial farms. Indeed, each factor having a significant contribution to our statistical model is associated with body reserves and the energy balance of the animals. For instance, it is well known that in ruminants, a negative state of negative energy balance associated with high milk production, especially at the beginning of lactation, has global adverse effects on reproduction (Gootwine and Pollott, 2000). Additionally, there is a negative genetic correlation between total milk production and fertility that induces lower fertility in adult ewes (David et al., 2008). The apparent contradictory effects of milk production variables, total milk production (positively associated) and milk production at the third milk recording (negatively associated), on the probabilities of ewes exhibiting ovarian cycles spontaneously before the introduction of rams and in response to the male effect highlight the importance of the effects of metabolic dynamics on reproductive functions. In accordance with the effects of the interval between lambing and introduction of the rams (LME Interval), this result indicates that the negative effects associated with high milk yields on reproductive functions are time-dependent, with high milk production levels close to the introduction of rams being associated with fewer spontaneous ovarian cycles and a lower proportion of ewes responding to the male effect.

In our study, despite similar manifestations, the effects of nutrition on the resumption of ovarian activity before (spontaneous) or after (induced) the introduction of rams are probably mediated through different pathways. While the timing of the spontaneous resumption of ovarian activity originates from the interaction between nutrition and photoperiodic cues at the central level (Menassol et al., 2012), the integration of nutritional cues along the pathways involved in the interpretation of the sociosexual signals associated with the male stimulus is less known. This interaction acts on the emission and interpretation of these sociosexual signals (Delgadillo et al., 2009) and probably involves both central and peripheral levels (Johnson et al., 2011; Scaramuzzi et al., 2014). These different neurophysiological pathways could explain why there is an effect of the LME interval on the spontaneous resumption of ovarian cycles before the introduction of rams and not in

response to the male effect. From the results of our study, we suggest that the factors associated with nutritional cues have synergetic effects that shape an optimal time window, with interactions with the photoperiodic signal, for the induction of early ovarian cycles in response to the male effect (Fig. 5). In other words, the sociosexual signals associated with the ram stimulus can disrupt the inhibitory photoperiodic signal depending on its amplitude and the nutritional status of milking ewes. This asser-

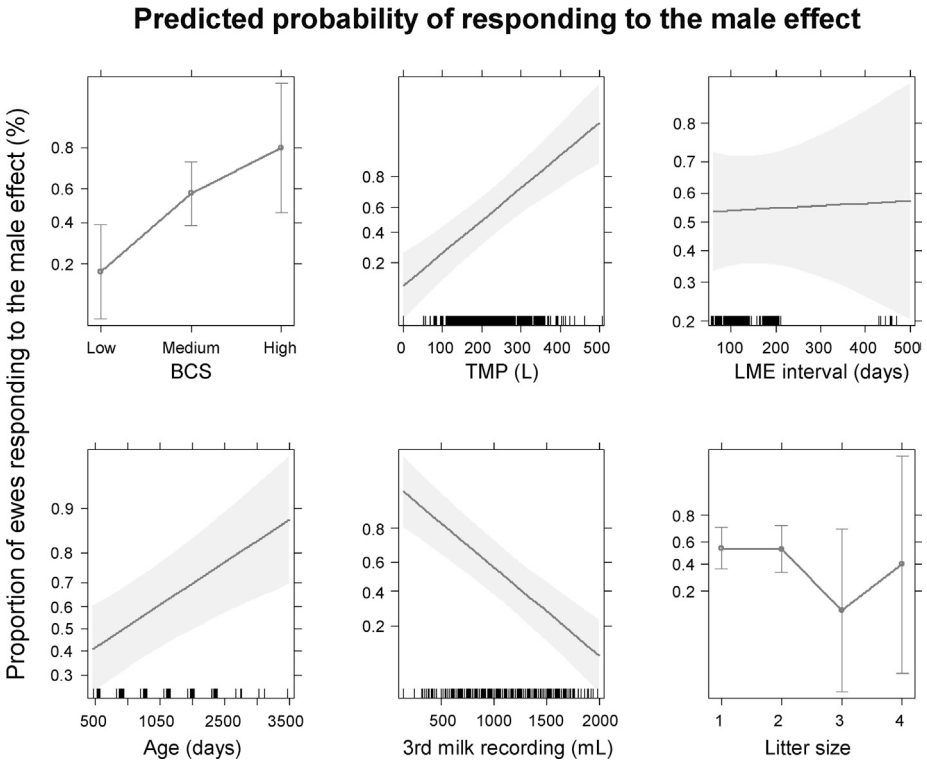

Fig. 4. Predicted probabilities (probabilities ± 0.95 confidence interval) for the ewes of responding to the male effect according to the zootechnical characteristics: body condition score class (BCS), total milk production (TMP), the interval between lambing and the male effect (LME interval), age, milk production at the third milking recording (3rd milk recording) and litter size. BCS classes: Low $\leq$ 2; 2 < Medium $\leq$ 3; High > 3.

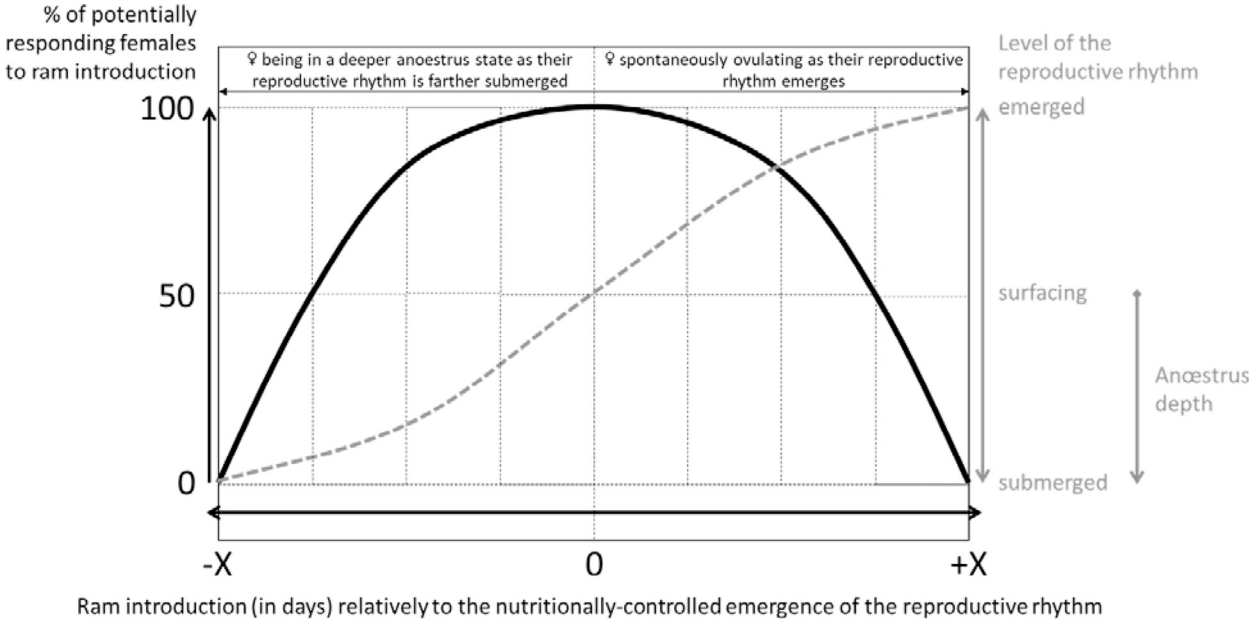

Fig. 5. Schematic representation of the proportion of females potentially responding to a male effect (solid line, primary Y-axis) given the time of introduction of the rams relative to the spontaneous resumption of ovarian cycles. Nutritional and photoperiodic cues interact to control the emergence of each individual reproductive rhythm (dashed line, secondary Y-axis). From [-X; 0] (left side of the figure), the alleviation of the anoestrus deepness gradually allows a greater proportion of ewes to be able to respond to the ram effect until a theoretical maximum is reached. From [0; +X] (right side of the figure), the gradual increase in ewes spontaneously resuming their ovarian cycles limits the proportion of ewes being able to respond to the ram effect. This global pattern illustrates the occurrence of an optimal time window for the realisation of a ram effect associated with greater success in the induction of ovarian cycles.

tion prolongs an earlier observation of a positive correlation between fertility after the male effect and the percentage of ewes exhibiting spontaneous ovarian activity within one flock (Folch et al., 2000), as well as a previous interpretation proposed by Scaramuzzi et al. (2014) suggesting that the photoperiodic signal could override potential nutritional impacts on the reproductive response to a male effect.

In comparison with other studies, some specific conditions in the protocol of realisation of the male effect for our study can be discussed. Regarding the duration of the rams' presence with the ewes, a factor known to impact the performances of the male effect, it is conventionally recommended a continuous presence of the male to maximise the endocrine or ovulatory responses of females to the male stimulus (Oldham and Pearce, 1983; Hawken and Beard, 2009). In our study, the rams were kept with the ewes only between the afternoon and morning milkings, corresponding to a daily average presence of 10 hours. This practice is specific to the dairy systems of the Roquefort production area where rams are usually kept indoor. We found that this management practice did not downgrade the reproductive performances of the ewes in response to a male effect (personal data) and therefore, it was maintained throughout the experiment. On the other hand, it was shown in goats that 1 or 2 daily hours of contact with sexually active males is sufficient to stimulate ovulatory activity in non-cyclic goats (Bedos et al., 2014). The sex ratio, another important factor that can affect the response to the ram effect (Rosa and Bryant, 2002; Delgadillo et al., 2009), was highly variable between years in our study (from 3 to 12 depending on the year). This was due to husbandry conditions and the mating plan of the farm. In order to take into account this variability, this factor was included in each of our statistical models as a random factor nested within the year of the experiment. The contrasted results observed between years could also be explained by other uncontrolled environmental factors and the usual adaptations of management practices by the farmer including sex ratio. We consider that this variability between years is a strong argument in favour of a longitudinal study and cross-year analysis to extract and interpret the significant factors under such on-farm conditions.

In practical terms, the results of this study highlight several factors that have to be prioritised in farm management practices associated with the realisation of a male effect. They highlight that to maximise the reproductive response of ewes to the male effect and the associated objectives of an off-season synchronised reproductive response, a compromise including BCS, milk production and the timing of the introduction of the rams relative to the date of lambing has to be identified. These management issues are particularly important in organic farm conditions where the ban on any hormonal treatment and the legal requirements for local feed production impose a greater sensitivity of the reproductive rhythm to local environmental and nutritional conditions.

In conclusion, we found that a combination of factors linked with body reserves and energy balance defines a time window associated with optimal early reproductive performances of milking ewes in response to a male effect. The originality of this work is that it was conducted on a commercial farm over several years, which allowed us to surpass the variability between years to draw consistent conclusions that prolong previous studies in this field. This confirms the importance of precise nutritional management of farm animals to improve their reproductive performance and limit the variability associated with the male effect, a key technique of hormone-free breeding programmes in small ruminants. The implementation of automated concentrate feeders in milking parlours is a valuable tool that can be used in response to our findings depending on the objectives of the farmer. Complementary investigations are currently being conducted to analyse the factors affecting the behavioural oestrus response and the associated pregnancy rates under similar breeding conditions.

Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.animal.2022.100519.

Ethics approval

All animals were cared for in accordance with the guidelines of Institut national de recherche pour l'agriculture, l'alimentation et l'environnement (INRAE) animal ethics committee and the experiments were compliant with the Animal Research Act of 1985 in accordance with ethical principles that have their origins in the European Union directive 2010/63/EU.2.1.

Data and model availability statement

None of the data were deposited in an official repository.

The data that support the study findings are available to reviewers.

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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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Annexe 2 : Supplementary data 1 of Article 3

Table A2. 1. Description of the main attributes and state variables of the agents represented in the REPRIN'OV model

Attributes and state variables	Definition	Notation	Type	Units	Initial value or range of values	Source	Different in HF scenarios
Age of the ewes[1]	-	Age	Integer[3]	years	0-7	De Boissieu and Morin, 2022 (through csv files)	No
Age of the rams	-	Age	Integer	years	2-4		No
Ewe's body condition score	Score of 0 to 5, based on the level of muscling and fat deposition around the ewe's loin region (Russel et al., 1969)	BCS	Float	-	1-5		No
Initial daily milk yield (for ewes > 1 year old)[2]	Daily milk production of an adult ewe on first day of milking after the suckling period	$IDMY_e$	Float[4]	L	1-5		No
Initial daily milk yield (for ewe-lambs <1 year old)[2]	Daily milk production of a young ewe (<1 year) on first day of milking after the suckling period	$IDMY_{el}$	Float	L	1-5		No
Last milk yield monitoring (of previous lactation)	Last milk yield monitoring (during ewe's previous lactation). Usually, there is monitoring of ewe's milk yield every 1 to 2 months during the milking period of the flock	LMYM	Float	mL	0-2500		No
Last total milk yield[2]	Total milk yield produced during the last lactation of the ewe	LTMY	Float	L	0-500		No
Lactation number	Number of lactations performed by the ewe since the beginning of its productive life	$Lact_{num}$	Integer	-	0-8		No
Mean live weight of ewes	Mean live weight of adult ewes at starting date(i.e. first day of reproduction process)	-	Float	kg	75		No
Mean live weight of ewe lambs	Mean live weight of ewe lambs at starting date(i.e. first day of reproduction process)	-	Float	kg	47		No
Lambing to reproduction interval[1]	Days between last lambing date and the hormonal treatment or the date of rams introduction for male effect	LMEI	Integer	days	0-310		No
Initial milk protein content	Protein content of the milk produced on the first day of milking	MPC	Float	g/L	45.9		No

Initial milk fat content	Fat content of the milk produced on the first day of milking	MFC	Float	g/L	60.7		No
Pregnancy length[2]	-	PL	Integer	days	145-157	Expert	No
Hormonal treatment	If reproduction strategy of the farmer includes hormonal treatment	-	Boolean[5]	-	True		Yes
Anestrus	Ewe at sexual rest and no estrus behavior (mating acceptance or heats) is observed	-	Boolean	-	True		No
Cyclic before male effect	Ewe in estrus before rams arrivals into the flock	CBME	Boolean	-	False		No
Responding to male effect	Ewe that was not cyclic before male effect and became sexually receptive ("in heat" or in estrus) thanks to the 15 days of male effect	RME	Boolean	-	False	-	No
Show first estrus	First ewe's estrus after an anestrus period	-	Boolean	-	False		No
In estrus	Ewe in estrus	-	Boolean	-	False		No
Pregnant	Ewe pregnant	-	Boolean	-	False		No
Abortion	Ewe aborts	-	Boolean	-	False		No
Lambing	Ewe gives birth	-	Boolean	-	False		No
Lactating	Ewe produces milk (i.e. during suckling and milking)	-	Boolean	-	False		No
Active for mating	Ram has the possibility to mate with ewes	-	Boolean	-	False		No

1: Set randomly by a Poisson distribution whose mean and standard deviation are taken from the corresponding source.
2: Set randomly by a normal distribution whose mean and standard deviation are taken from the corresponding source.
3: Integer= whole numbers.
4: Float = values that have potential decimal places.
5: Boolean = Statement that can only be equal to yes or no.
HF: Hormone-free

Table A2. 2. Main parameters used in the REPRIN'OV model

Parameters	Definition	Notation	Type	Units	Initial value/range of values	Source	Different in HF scenarios
Starting date of the simulation	-	-	Date	-	June 9th, n	De Boissieu and Morin, 2022 (through csv files)	No
Ending date of the simulation	-	-	Date	-	July 21th, n+6		No
Starting date of hormonal treatment for adult ewes	-	-	Date	-	June 9th		Yes
Starting date of hormonal treatment for ewe lambs	-	-	Date	-	June 24th		Yes
Ram introduction date for male effect	Date on which the farmer introduces rams into the flock and leaves them for 15 days (without the possibility to mate) in order to stimulate the ovarian cycle of ewes in hormone free context	-	Date	-	-		Yes
Rams 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	-	July 10th		Yes
Rams introduction date for the mating of ewe lambs and adult latecomers	Date on which the farmer introduces rams to mate young ewes (<1 year old) and the adult ewes that did not get pregnant during the previous mating periods	-	Date	-	July, 25th		No
Dry-off date	Limit date set by the farmer to dry-off all ewes of the flock that are still milking	-	Date	-	July 20th		No
Minimum milk yield accepted at milking	Daily milk production value below which the farmer decides to dry off the ewe	MMYA	Float[2]	L/day	0		No
Probability of abortion	Probability for a pregnant ewe to lose the foetus(es) before term	Pa	Float	-	0.01		No
Probability of an easy lambing	Probability to lamb without complications preventing the milking or leading to a health problem	Pel	Float	-	0.97		No

Probability of synchronization rate	Probability for a ewe (or a ewe lamb) to start ovulating following hormonal treatment	$P_{SYNCHRONIZATION\ SUCCESS}$	Float	-	0.85 (for adult ewes) and 0.95 (for young ewes)	Yes
Detection rate	Heat detection rate in hormone free scenarios	-	Float	%	100	No
Probability of AI success for ewes	Probability for a ewe to be pregnant following AI	$P_{AI\ SUCCESS}$	Float	-	0.67	No
Probability of AI success for ewe lambs	Probability for a ewe lamb to be pregnant following AI	$P_{AI\ SUCCESS}$	Float	-	0.75	No
Ewes AI rate	Percentage of ewes inseminated	-	Float	%	100	Yes
Ewe lambs AI rate	Percentage of ewe lambs inseminated	-	Float	%	100	Yes
Male/female ratio for the adult ewes batch	-	-	Float	-	1/50	Yes
Male/female ratio for the ewe lambs batch	-	-	Float	-	1/18	Yes
Probability of health problem	Probability for a ewe to have health problem preventing milking (e.g. mastitis)	P_{hp}	Float	-	0.04	No
Probability for the ewe to expect a twin litter	-	P_{L2}	Float	-	0.4	No
Probability for the ewe to expect a multiple litter (≥ 3 lambs)	-	P_{L3}	Float	-	0.1	No
Selected culling age	Age after which an ewe is considered by the farmer for culling	-	Integer[3]	years	1	No
Duration of the first free mating period for adult ewes	Period set by the farmer during which rams can mate freely with ewes	-	Integer	days	66 days (for adult ewes); 52 days (for ewe lambs)	Yes
Mean suckling length	From lambing to weaning. Minimum period during which the ewes must suckle their newborns	SL	Integer	days	28	No
Selected turnover rate	Percentage of ewes to be renewed each year to keep a constant flock population	-	Float	%	27	No
Feed plan	Quantity of feed to be distributed to ewes and rams according to their physiological stages and according to the time of the year	-	Float	Kg of dry matter (DM)	Depends on the feed	No
Sales and purchases prices of farm products	-	-	Float	€/product unit	-	No

Emission factors for CO_2 and CH_4 emission estimation	Average greenhouse gas emission rate of a given source, relative to units of activity or processes	-	Float		*cf. Annexe 3*		No
Reference values for energy and water consumption	Reference values for energy and water consumption in a dairy sheep farm of the Roquefort Basin	-	Float		*cf. Annexe 3*		No
Probability to cyclic during season[1]	Probability that the ewe is in a spontaneous period of heat and accept mating	PC	Float	-	0.8-1	Adapted from Chanvallon et al. (2011)	No
Probability to by cyclic out of season					*f(Age,BCS,LMYM,LTMY,days since last lambing)*	(Laclef et al., 2021)	No
Probability to respond to the male effect	Probability that a non-cyclic ewe is in a period of heat and accept mating following the male effect	PREM	Float	-	*f(Age,BCS,LMYM,LTMY)*		No
Probability for a successful mating	Probability for a ewe to become pregnant after mating	Pms	Float	-	0.5	Expert	No

1: 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).
2: Float = values that have potential decimal places.
3: Integer= whole numbers.
HF: Hormone-free

Annexe 3 : Supplementary data 2 of Article 3 Detail of the calculation of the economic, environmental and workload indicators simulated by the REPRINOV model

Economic indicators:

The gross margin (in €) of the farm (without taking into account the potential subsidies) is the main economic indicator simulated with the model. They were simulated based on the following equations:

$$Gross\ margin = Gross\ \ income\ - Operating\ costs \qquad [1]$$

The gross income (in €) is the money income generated by the sale of the products of the different workshops (animal and vegetal) of the farm. In this study, it was calculated as follow:

$$Gross\ income\ = Gross\ income\ _{animal\ workshop} + Gross\ income\ _{vegetal\ workshop} \qquad [2]$$

Where:

$$Gross\ income_{animal\ workshop} = \sum_{j} Milk\ produced_j * \ price\ of\ milk_j\ + Number\ of\ youngs\ sold * price\ sale\ youngs + Number\ of\ culled\ ewes * price\ culled\ female + Number\ of\ culled\ rams * price\ culled\ male - Number\ of\ renewal\ female\ bought * price\ renewal\ female - Number\ of\ renewal\ male\ bought * price\ renewal\ male \qquad [3]$$

$j = Month$

$$\text{price of milk}_j = \frac{\text{milk reference price}}{2} * \left(\frac{\text{Average milk fat content of the flock}_j}{\text{Reference milk fat content}} + \frac{\text{Average milk protein content of the flock}_j}{\text{Reference milk protein content}}\right) \qquad [4]$$

with the monthly price of milk and the milk reference price in €/L, the milk and protein content values in g/L and the prices of the various animal sales in €/animal.

and,

$$Gross\ income_{vegetal\ workshop} = Quantity\ of\ forages\ sold * price\ of\ forages + Quantity\ of\ cereals\ sold * price\ of\ cereals + Quantity\ of\ straw\ sold * price\ of\ straw \qquad [5]$$

with the quantities of vegetal productions in Tons and the prices associated in €/Ton.

The operating costs correspond to the annual expenses necessary for the maintenance and proper functioning of the various workshops (animal and plant) of the farm. They are calculated as follow:

$$Operating\ costs = Operating\ costs_{animal\ workshop} + Operating\ costs_{vegetal\ workshop} \qquad [6]$$

Where:

$$Operating\ costs_{animal\ workshop} = price\ of\ hormonal\ treatment * Number\ of\ ewes\ treated + price\ of\ insemination * (Number\ of\ ewes\ inseminated) + AEP * (price\ mineral\ and\ vitamin\ supplement + price\ veterinary\ services + price\ of\ milk\ control + other\ fees) + \sum quantity\ of\ feed_i\ bought * price\ of\ feed_i \quad [7]$$

with AEP=Average number of ewes in production; Quantity of each feed bought in Tons; Prices in €/animal (or €/Tons for each of the feed purchased).

$$Operating\ costs_{vegetal\ workshop} = size\ of\ production\ parcel_i * price\ of\ maintenance\ inputs\ (fertilzer, seed\ and\ other\ treatments)\ the\ parcel_i \quad [8]$$

with the size of each parcel in ha and the prices of inputs in €/ha.

<u>Calculation of environmental indicators:</u>

- ***GreenHouse Gases (GHG) emissions of the farm:***

The model uses a combination Tier1 and Tier 2 methods of the IPCC (2019) guidelines for inventories of GHG to simulate the yearly CH_4 and CO_2 emissions.

- *CH_4 emissions:*

According to IPCC guidelines, all emissions are expressed in kg of CO_2eq. Thus the Global Warming Potential (GWP) based on the 4th Assessment Report of the IPCC (Solomon et al., 2007) was used to convert CH_4 to CO_2eq terms. Therefore, 1kg of CH_4 equals 25 kg CO_2eq.

Emissions from livestock vary depending on animal type, weight, physiological state and feeding situation. Three animal categories are thus taken in consideration to estimate GHG emissions: adult dairy ewes (> 1-year-old), mature rams (>1-year-old) and young ewes and rams (> 4 months old).

The total CH_4 emission (in kg CO_2eq/year) is simulated using the following equations:

$$CH_4\ emission = \sum_T CH_4\ ent\ (T) + \sum_T CH_4\ mm\ (T) \quad [9]$$

CH_4ent(T) is the methane emissions from enteric fermentation in each animal category T (in kg of CH_4/year) and is calculated using a Tier 2 method ([10],IPCC (2019)) which supposes the calculation of an Emission Factor (EF) for CH_4 enteric fermentation of each animal category. This EF is calculated using the equation [11] which is based on the gross energy intake (GE, in MJ/head/year) for each animal category. In this study, GE is estimated using

reference values from Hassoun and Bocquier (2010) for each of the feed present in the feed plan of the flock.

$$CH_{4\ ent}(T) = N(T) * EF_{CH_4\ ent}(T) \quad [10]$$

$EFCH_4ent(T)$= emission factor for CH_4ent emissions in kg CH4/head/year

N(T)= number of head of livestock species for a giving category (T)

$$EF_{CH_4\ ent}(T) = \frac{GE*\left(\frac{Ym}{100}\right)}{55.65} \quad [11]$$

GE= gross energy intake for a giving category (T) in MJ/head/year

The factor 55.65 (MJ/kg CH_4) is the energy content of CH_4

Y_m=methane conversion factor, per cent of gross energy in feed converted to CH_4 for a given species= 6.7 for sheep IPCC (2019).

CH_4mm (T) are the emissions from manure management (in kg CH_4/year). They depend on the animal category considered and on the type of manure storage system (solid storage, dry lot, or on pasture). In this study, two types of manure storage are considered: solid storage and pasture. For CH_4mm estimation, the Tier 1 method is applied using reference values of the IPCC (2019) guidelines. Thus:

$$CH_{4\ mm}(T) = \sum_S \frac{\left(N(T)*VS(T)*AWMS(T,S)*EF_{CH_4\ mm}(T,S)\right)}{1000} \quad [12]$$

N(T)= number of head of livestock species for a giving category (T)

AWMS (T, S) = fraction of total annual VS(T) for each livestock species/category (T) that is managed in manure storage system (S) = 0.21 for building manure storage/ management and 0.78 for pasture manure storage/management, for all sheep category

$EFCH_{4\ mm}$ (T, S) = emission factor for direct CH_4 emissions from manure storage system S, by animal species/category T, in g CH_4 / kg VS= 5.1 for building manure storage/ management and 0.6 for pasture manure storage/management, for all sheep category

VS(T) is the annual average volatile solid excretion per head /category T, in kg VS/animal/year. It is calculated using the following equation:

$$VS(T) = \left(VS_{rate} * \frac{TAM(T)}{1000}\right) * 365 \quad [13]$$

VS(T) = annual VS excretion for livestock category T in kg VS/ animal/year

VS_{rate} = default VS excretion rate in kg VS/1000 kg animal mass/ day =8.2 IPCC (2019)

TAM(T) = typical animal mass for livestock category T in kg/animal

- *CO_2 emissions:*

The CO_2 emissions from electricity use during milking and feed input (in kg CO_2eq/year) purchases are calculated for every simulated year using the following equations:

$$CO_2\ feed_{input} = Quantity\ of\ feed\ purchased\ * EF_{CO_2 feed_input} \quad [14]$$

$$CO_2\ electricity = Quantity\ of\ electricity\ consumed * EF_{CO_2 electricity} \quad [15]$$

Quantity of electricity consumed= ∑Daily fixed electricity consumption + ∑Daily fluctuating electricity consumption [16]

*Daily fixed electricity consumption = Daily quantity of milk produced * 0.0136, in kwh. Where 0.0136 is a reference of fixed electricity consumed per L of milk produced in the Roquefort basin, from (Hassoun et al., 2013).*

Daily fluctuating electricity consumption=2.06 Integer (number of ewes milked/48), in kwh. Where 2.06 is a reference of fluctuating electricity consumption per day for a milking machine of 48 places in the Roquefort basin, from (Hassoun et al., 2013).*

$EF_{CO2electricity}$ *= 0.308 kg* CO_2*eq/kWh from Bochu et al. (2013)*

$EF_{CO2feed_input}$ *= 0.655 kg* CO_2*eq/kg from Bochu et al. (2013)*

- ***Water consumption of the farm:***

Every year, the model simulates the consumption of water on the farm (in L of water/ year). This consumption corresponds to the water used for milking material and for animals watering. Thus:

Water consumption = Water consumption for milking + Water consumption for animal watering [17]

*Water consumption for milking = Number of milking days of the flock * 500, in L. Where 500 is a reference value (in L/day of milking) of water consumption by milking material in dairy sheep farms of the Roquefort basin where ewes are milked two times a day (Hassoun et al., 2013).*

Water consumption for animal watering = $\sum Daily\ individual\ water\ consumption\ (T)$ [18]

Where, daily individual water consumption(T) is the consumption value per animal category (T). They are being calculated according to the physiological stage of the animals and the period of the year (winter or summer (20-25°)), using the reference values of Roussel et al. (2012).

- ***Calculation of workload indicators:***
  - *Workload during milking*

Based on the observations of the working time during milking (in h) in a dairy sheep farm in the Roquefort basin made by Hassoun et al. (2013), the working time during milking is calculated as follow:

$$Working\ time\ during\ milking = (\sum Daily\ fixed\ milking\ working\ time + \sum Daily\ fluctuating\ milking\ working\ time)/60 \quad [19]$$

Daily fixed working time (in min) corresponds to the working time dedicated to the milking parlour start-up and the cleaning of the milking parlour = 42 min based on (Hassoun et al., 2013).

Daily fluctuating working time (in min) corresponds to the milking itself. It is calculated as follows: 15 Integer (number of ewes milked/48), in kwh. Where 15 min is a reference of fluctuating milking work time per day for a milking machine of 48 places in the Roquefort basin, from (Hassoun et al., 2013).*

- *Workload during lambing*

Every production season the model simulates the total working time during lambing (in h) as follow:

$$Lambing\ working\ time\ = \sum Daily\ working\ time\ during\ lambing \quad [20]$$

Daily working time during lambing(h/day) =Number of ewes lambing per day 3. Where 3 is a reference number of hours of work per ewe during lambing (IDELE, 2021). No matter how many ewes are lambing per day, the number of hours of work is limited to 24 hours.*

Annexe 4 : Main parameters used to model the individual reproduction process in each simulated farm

Table A4 1. Values of the main parameters used to model the ewe's individual reproduction process in REPRIN'OV for each farm.

Parameters	**Values (or range of values)**				**Sources**
Farm	***Early_conv***	***Late_conv***	***Early_org***	***Late_org***	
P_c	*f (Age, milk yield, BCS, lambing to ME interval) for adult ewes;* 0.2 for ewe lambs	0.8 (summer) - 1.0 (autumn)	*f (Age, milk yield, BCS, lambing to ME interval) for adult ewes;* 0.2 for ewe lambs	0.8 (summer) - 1.0 (autumn)	(Laclef et al., 2021) (Chanvallon et al., 2011) + Expert
P_{RME}	*f(Age, milk yield, BCS)*				(Laclef et al., 2021)
Estrus detection rate	100%				Expert
$S_{synchronisation\ success}$	1.0		0		
P_{ms}	0.5				
$P_{AI\ success\ for\ adult\ ewes}$	0.7	0.67	0.67	0.67	(De Boissieu and Morin, 2022)
$P_{AI\ success\ for\ young\ ewes}$	0.75	0.75	0.75	0.75	
P_a	0.01	0.01	0.01	0.05	
P_{el}	0.99	0.97	0.95	0.98	

AI= Artificial Insemination; 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 complication); P_{ms}= Probability of mating success; P_{RME}= Probability to respond to Male Effect.

Annexe 5 : Supplementary tables presenting results of the simulation of alternative scenarios to the use of TH in a diversity of farms of the Roquefort basin (see Chapter VI)

Table A5. 1. Mean values of the simulated sustainability indicators of the farms functioning over the five production cycles following the introduction of a HF reproduction management strategy (i.e. mean of the 5 × 75 repetitions of simulations *per* scenario).

	Early_conv			***Late_conv***			***Early_org***		***Late_org***	
	HAI[1]	**HFAI**	**HFM**	**HAI[1]**	**HFAI**	**HFM**	**HFM[1]**	**HFAI**	**HFM[1]**	**HFAI**
Fertility rate (%)	87[c]	57[a]	59[b]	93[b]	89[a]	89[a]	90[a]	89[a]	88[a]	88[a]
Insemination rate (%)	85[c]	25[b]	0[a]	88[c]	30[b]	0[a]	0[a]	27[b]	0[a]	29[b]
% of renewal from AI	97[c]	43[b]	0[a]	98[c]	44[b]	0[a]	0[a]	40[b]	0[a]	43[b]
% of the flock born from AI	97[c]	58[b]	28[a]	99[c]	66[b]	39[a]	0[a]	23[b]	0[a]	28[b]
Average age at first reproduction (months)	8.9[c]	8.5[a]	8.8[b]	7.7[c]	7.5[a]	7.7[b]	8.6[a]	8.3[a]	7.6[b]	7.4[a]
Average milk production (L/ewe)	319[c]	310[b]	309[a]	307[a]	311[b]	313[c]	287[a]	288[b]	281[a]	285[b]
Total milk production of the flock (tonnes)	124.0[c]	79.4[a]	80.6[b]	110.9[c]	107.5[a]	108.0[b]	136.1[a]	136.0[a]	97.7[a]	98.8[b]
% of ewes milked	84[c]	56[a]	57[b]	89[b]	85[a]	85[a]	86[a]	86[a]	81[a]	81[a]
Forage distributed (kg/L of milk)	2.44[a]	3.77[c]	3.63[b]	2.04[a]	2.21[b]	2.21[b]	2.15[b]	2.11[a]	2.02[b]	1.99[a]
Concentrates distributed (kg/L of milk)	0.85[a]	1.30[c]	1.26[b]	0.83[a]	0.87[b]	0.87[b]	0.79[b]	0.76[a]	0.77[b]	0.76[a]
Gross Margin (€/L of milk of milk)	0.97[c]	0.83[a]	0.84[b]	0.79[a]	0.87[c]	0.86[b]	1.32[a]	1.37	1.20[a]	1.22[b]
Gross Margin total (1000 €)	120.5[c]	65.7[a]	67.6[b]	88.0[a]	93.6[c]	93.2[b]	180.3[a]	187.0[b]	117.3[a]	120.4[b]
Workload during lambing (s/L of milk)	19.7[a]	32.6[c]	26.2[b]	20.5[a]	26.5[c]	26.2[b]	26.7[a]	31.6[b]	31.0[b]	29.0[a]
Workload during milking (s/L of milk)	19.3[a]	24.1[c]	23.5[b]	18.2[a]	19.3[b]	19.5[c]	17.2[b]	16.7[a]	22.0[b]	21.4[a]
CH_4 emissions (kg CO_2eq/L of milk)	1.9[a]	2.9[c]	2.9[b]	1.9[a]	2.0[b]	2.0[b]	2.0[a]	2.0[b]	1.85[b]	1.83[a]
CO_2electricity emissions (kg CO_2eq/L of milk)	0.0136[a]	0.0145[c]	0.0144[b]	0.0133[a]	0.0137[b]	0.0139[c]	0.0131[b]	0.0128[a]	0.0152[b]	0.0149[a]
CO_2 feed emissions (kg CO_2eq/L of milk)	0.357[a]	0.531[c]	0.497[b]	0.160[a]	0.171[b]	0.172[c]	0.227[b]	0.206[a]	0.232[b]	0.229[a]
Water consumption (L/L of milk)	9.1[a]	13.3[c]	13.0[b]	8.6[a]	8.9[b]	9.0[b]	9.3[b]	9.2[a]	10.3[b]	10.1[a]

1: Baseline scenario of the corresponding farm;

a, b, c: Pour chaque exploitation et pour chaque indicateur simulé, les valeurs présentant une lettre distincte diffèrent avec un $P<0,05$.

Table A5. 2. Indicators of each farm's daily milk production and lambing distribution over time *per* scenario.
(See Figures VI.3 to VII.6 of Chapter VI for the graphical representations of these dynamic changes).

Farm	***Early_conv***						***Late_conv***						***Early_org***				***Late_org***			
Production cycle	**N1**			**N5**			**N1**			**N5**			**N1**		**N5**		**N1**		**N5**	
Scenario	**HAI [2]**	**HFAI**	**HFM**	**HAI [2]**	**HFAI**	**HFM**	**HAI [2]**	**HFAI**	**HFM**	**HAI [2]**	**HFAI**	**HFM**	**HFM [2]**	**HFAI**	**HFM [2]**	**HFAI**	**HFM [2]**	**HFAI**	**HFM [2]**	**HFAI**
Daily lambing events distribution indicators																				
Q1 (day when 25 % of the lambing events have occurred)[1]	D2	D11	D6	D2	D12	D6	D3	D12	D7	D3	D12	D7	D7	D16	D8	D17	D8	D15	D8	D16
Median (day when 50 % of the lambing events have occurred)[1]	D17	D21	D11	D16	D22	D11	D16	D20	D14	D16	D20	D13	D17	D30	D17	D30	D14	D23	D14	D23
Q3 (day when 75 % of the lambing events have occurred)[1]	D52	D29	D17	D52	D30	D17	D21	D27	D25	D21	D27	D25	D59	D57	D59	D57	D28	D29	D28	D30
Maximum number of daily lambing events	84	13	15	86	12	16	71	17	16	76	17	16	18	15	17	13	17	18	17	19
Flock's daily milk production evolution indicators																				
Delay in the occurrence of the highest peak of milk production ?		Yes	No		Yes	No		Yes	Yes		Yes	Yes		No		No		No		No
Delay length (days)		10	0		11	0		10	10		11	11		0		0		0		0

1: D = Days; D1= First day of the lambing period; 2: Baseline scenario of the corresponding farm.