



HAL
open science

Saisir la diversité des systèmes d'élevage de ruminants à travers le monde pour accompagner leur intensification durable : proposition d'un cadre d'évaluation de leurs impacts environnementaux et socio-économiques

Lucie Perin

► To cite this version:

Lucie Perin. Saisir la diversité des systèmes d'élevage de ruminants à travers le monde pour accompagner leur intensification durable : proposition d'un cadre d'évaluation de leurs impacts environnementaux et socio-économiques. Environnement et Société. Université Paris-Saclay, 2023. Français. NNT : 2023UPASB006 . tel-04207267

HAL Id: tel-04207267

<https://pastel.hal.science/tel-04207267v1>

Submitted on 14 Sep 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Capturing the diversity of ruminant farming
systems around the world to support their
sustainable intensification : a proposed
framework for assessing their environmental
and socio-economic impacts

*Saisir la diversité des systèmes d'élevage de ruminants à travers le monde pour
accompagner leur intensification durable : proposition d'un cadre d'évaluation
de leurs impacts environnementaux et socio-économiques*

Thèse de doctorat de l'université Paris-Saclay

École doctorale n°581 : agriculture, alimentation, biologie, environnement, santé (ABIES)
Graduate School : Biosphera. Référent : AgroParisTech

Thèse préparée dans l'unité de recherche **CIRED**
(Université Paris-Saclay, AgroParisTech, CNRS, Ecole des Ponts ParisTech, Cirad, EHES)
sous la direction de **Patrice DUMAS**, chercheur (HDR)
et le co-encadrement de **Mathieu VIGNE**, chercheur.

Thèse soutenue à Paris-Saclay, le 22 mars 2023, par

Lucie PERIN

Composition du Jury

Membres du jury avec voix délibérative

Philippe LESCOAT Professeur, AgroParisTech (Université Paris-Saclay)	Président
Gilles BRUNSCHWIG Professeur, VetAgro Sup	Rapporteur & Examineur
Charles-Henri MOULIN Professeur, L'Institut Agro Montpellier	Rapporteur & Examineur
Anne MOTTET Livestock Development Officer, FAO	Examinatrice

Titre : Saisir la diversité des systèmes d'élevage de ruminants à travers le monde pour accompagner leur intensification durable : proposition d'un cadre d'évaluation de leurs impacts environnementaux et socio-économique

Mots clés : système d'élevage, ruminants, évaluation des impacts, typologie, anticipation

Résumé : Les activités d'élevage de ruminants jouent un rôle crucial dans le monde, en termes de nutrition et de santé, de moyens de subsistance, d'emploi et de culture. Les systèmes d'élevage sont actuellement confrontés au défi de produire suffisamment de produits d'origine animale pour répondre à la demande croissante tout en étant durable et en respectant l'environnement. L'objectif global de cette thèse est de saisir la diversité des systèmes d'élevage de ruminants pour développer des outils pour soutenir leur intensification durable, en proposant un cadre conceptuel pour évaluer les impacts économiques et environnementaux. Après une analyse des différentes voies d'intensification, un nouveau cadre conceptuel et des typologies des systèmes d'élevage bovin dans le monde sont proposés, sur la base d'une revue de la littérature et de la connaissance des experts. Ce cadre devrait permettre de saisir et de comparer les multiples caractéristiques et fonctions de l'élevage de ruminants, y compris les impacts économiques et environnementaux, ces derniers étant actuellement un problème majeur pour le secteur de l'élevage. Pour évaluer ces impacts, un modèle conceptuel est ensuite présenté pour comparer les systèmes de production, représentés par leurs pratiques. Un gradient d'intensification est présenté,

correspondant aux objectifs d'intensification. Les limites de ce gradient sont représentées par une intensification motivée par une maximisation du bénéfice privé (par exemple, l'augmentation de la production, la production de fumier, la force de traction, la possession d'une assurance ou d'un capital financier grâce aux animaux), et une intensification motivée par une maximisation du bénéfice social incluant des bénéfices socio-économiques (par exemple, le cycle de l'azote, la réduction des émissions de gaz à effet de serre, la gestion du paysage, la réduction de la pollution, la cohésion de la communauté, etc). Enfin, une étude prospective sur les systèmes d'élevage bovin laitier au Kenya et au Sénégal est présentée pour tester la pertinence du cadre conceptuel à représenter la diversité des systèmes d'élevage laitier à l'échelle du pays. Dans cette dernière partie, les voies d'intensification et leurs impacts potentiels sont ensuite étudiés pour comprendre comment les systèmes actuels évoluent face aux différents défis (changement climatique, augmentation de la population, insécurité et conflits). Cette thèse ouvre la voie à de futures études sur l'évaluation des impacts et les voies d'intensification afin d'atteindre l'objectif d'avoir des systèmes de production de ruminants résilients, et en trouvant le bon équilibre entre productivité et durabilité.

Title : Capturing the diversity of ruminant farming systems around the world to support their sustainable intensification: a proposed framework for assessing their environmental and socio-economic impacts.

Keywords : farming systems, ruminants, impact assessment, typology, foresight

Abstract : Ruminant farming activities play a crucial role in the world, in terms of nutrition and health, livelihoods, employment, and culture. Farming systems are currently facing the challenge to produce enough animal-based products to supply the increasing demand while being sustainable and respecting the environment. The global objective of this thesis is to capture the diversity of ruminant farming practices and systems by developing tools to support their sustainable intensification, and by proposing a conceptual framework for assessing economic and environmental impacts. Following an analysis of various intensification pathways, a new conceptual framework and typologies of cattle farming systems over the world are proposed, based on a literature review and expert knowledge. This framework should render it possible to capture and compare the multiple characteristics and functions of cattle farming, including economic and environmental impacts, the latter currently being a major issue for the global livestock sector. To assess these impacts, a conceptual model is then presented to compare production systems, represented by their practices.

An intensification gradient is presented, corresponding to the intensification objective. The limits of this gradient are represented by an intensification motivated by a private benefit maximization (e.g., increase in production, manure production, draught power, possession of walking insurance or financial capital), and an intensification motivated by a social benefit maximisation including socio-economic benefits (e.g., nitrogen cycling, greenhouse gases emissions reductions, landscape management, pollution reduction, community cohesion, etc). Finally, a foresight study on dairy farming systems in Kenya and Senegal is presented to test the relevance of the conceptual framework to represent the diversity of cattle dairy farming systems at the country scale. In this last part, intensification pathways and their potential impacts are then investigated to understand how current systems are evolving and facing various challenges (climate change, increase of population, and insecurity and conflicts). This thesis opens the way for future studies on impact assessment and intensification paths to reach the goal of having resilient ruminant production systems, by reaching the right balance between productivity and sustainability.

In addition to the four jury members, Armelle Gac (Engineer, EVEA-Conseil) will be sitting as a guest during the PhD defence, without participating in the deliberations.

This PhD was funded by CLAND (Convergence Institute on land-management solutions for managing the ecological and energy transitions) and carried on under the employment of AgroParisTech (Institut National des Sciences et Industries du Vivant et de l'Environnement).



This PhD was carried on at CIRED (Centre International de Recherche sur l'Environnement et le Développement), as well as ILRI (International Livestock Research Institute).



RÉSUMÉ DE LA THÈSE

Depuis la domestication, les humains et le bétail ont évolué ensemble (Laca et Demment, 2009), de sorte que le bétail est devenu une partie intégrante de nos sociétés et de nos moyens de subsistance. Aujourd'hui, cependant, les systèmes de production animale sont confrontés à d'importants défis pour répondre à la demande sans cesse croissante en protéines animales (Derner et al., 2017). En effet, la demande de produits d'origine animale augmente en raison de divers facteurs: croissance démographique, urbanisation, augmentation des revenus et changement des habitudes, entre autres (Pfeifer, Morris et Mose, 2018). Les systèmes d'élevage sont aussi responsables de nombreux impacts sur l'environnement: pollution de l'eau, émissions de gaz à effet de serre (GES), menaces sur la biodiversité, dégradation des sols, ainsi que des perturbations du cycle naturel de l'azote (Pfeifer, Morris et Mose, 2018). Pour répondre à cette demande croissante à l'échelle mondiale sans avoir d'impact négatif sur l'environnement, il est absolument nécessaire de concevoir des systèmes de production animale durables.

Les ruminants - bovins, buffles, chèvres, moutons, chameaux - sont essentiels dans de nombreuses régions du monde. Les populations dépendent de leurs produits, tels que le lait, la viande et le sang, pour leurs revenus et leur autoconsommation. Les ruminants peuvent valoriser et occuper des terres qui ne conviennent pas à la production végétale (Mottet et al., 2017), ainsi qu'accroître l'efficacité de la production agricole en déposant du fumier (FAO, 2018b). Cependant, ils contribuent aussi fortement au changement climatique, car les ruminants émettent de grandes quantités de gaz à effet de serre. Les ruminants, et en particulier les bovins, ont également besoin de vastes surfaces, pour le pâturage ou la culture d'aliments pour animaux, avec une empreinte carbone élevée (Searchinger et al., 2018 ; Hayek et al., 2021).

Face à ces défis, il est crucial de concevoir un secteur de l'élevage durable, ce qui nécessite des évaluations de l'impact environnemental et économique des systèmes de production de ruminants. Pour réaliser ces évaluations, il est essentiel d'avoir une vision globale de la diversité des systèmes, i.e. les diverses techniques et pratiques d'élevage existantes dans le monde, car la production de ruminants est liée à de multiples aspects sur l'ensemble de la planète (Steinfeld, Wassenaar et Jutzi, 2006).

La diversité des systèmes d'élevage de ruminants est donc un élément majeur lorsqu'on parle de l'évolution de l'élevage de ruminants, car ils couvrent des gradients de conditions agroclimatiques

et géographiques ainsi qu'une diversité de fonctions, et des gradients d'intensification (allant des systèmes extensifs basés sur les prairies aux systèmes intensifs à grande échelle) (Dumont et al., 2013). Outre les facteurs liés à la demande, à la pression démographique et à l'environnement (McDermott et al., 2010), d'autres moteurs de l'intensification sont la recherche d'un intérêt économique privé, qui profite à l'agriculteur (ou à l'éleveur), ou la recherche d'un intérêt social, qui profite à l'ensemble d'une communauté ou d'une société. Ce dernier moteur conduit à un gradient d'intensification dont les limites sont deux objectifs d'intensification différents: un objectif purement privé d'une part (c'est-à-dire une intensification motivée par un avantage privé, notamment la génération de revenus, la production de fumier, la force de traction, etc.), et un objectif social de l'autre part (c'est-à-dire une intensification multifonctionnelle motivée par d'autres objectifs tels que la réduction des impacts environnementaux, la cohésion sociale, etc.).

L'objectif global de cette thèse est de développer des méthodes et des outils pour soutenir l'intensification durable des systèmes d'élevage de ruminants tout en capturant leur diversité et leur complexité, et de proposer un cadre conceptuel pour évaluer leurs impacts économiques (i.e., coûts, revenus, et production de viande et de lait), et environnementaux (principalement les émissions de GES et les pertes d'azote). Pour décomposer cet objectif global, cette thèse est divisée en quatre parties (voir Figure 1):

- Une revue des voies d'intensification des systèmes de production de ruminants, basée sur une revue de la littérature pour répondre aux questions suivantes: comment les systèmes d'élevage bovin sont-ils représentés dans la littérature? Comment les intensifications sont-elles définies et quelles sont les différentes voies d'intensification?
- Un cadre conceptuel et deux typologies des systèmes actuels d'élevage de bovins dans le monde pour l'évaluation des impacts afin de répondre aux questions suivantes: comment représenter au mieux les systèmes d'élevage de bovins dans le monde en tenant compte de leur multifonctionnalité, des liens entre les animaux apparentés et de leurs mouvements entre les systèmes? Comment les voies d'intensification sont-elles traitées dans ces cadres?
- Un modèle conceptuel et dynamique basé sur le cadre conceptuel présenté ci-dessus pour évaluer les impacts économiques et environnementaux des différents types de gestion, et pour répondre à la question suivante: comment construire un modèle qui pourrait prendre en compte la diversité et la complexité des systèmes et des voies d'intensification dans le monde entier?
- Une étude prospective sur les systèmes d'élevage laitier au Kenya et au Sénégal pour tester la pertinence du cadre conceptuel pour représenter la diversité des systèmes laitiers à

l'échelle infranationale, et prévoir des scénarios d'évolution de ces systèmes pour répondre aux questions suivantes: comment évoluent les systèmes d'élevage bovin? Comment adapter un cadre conçu à l'échelle mondiale à une échelle plus petite?

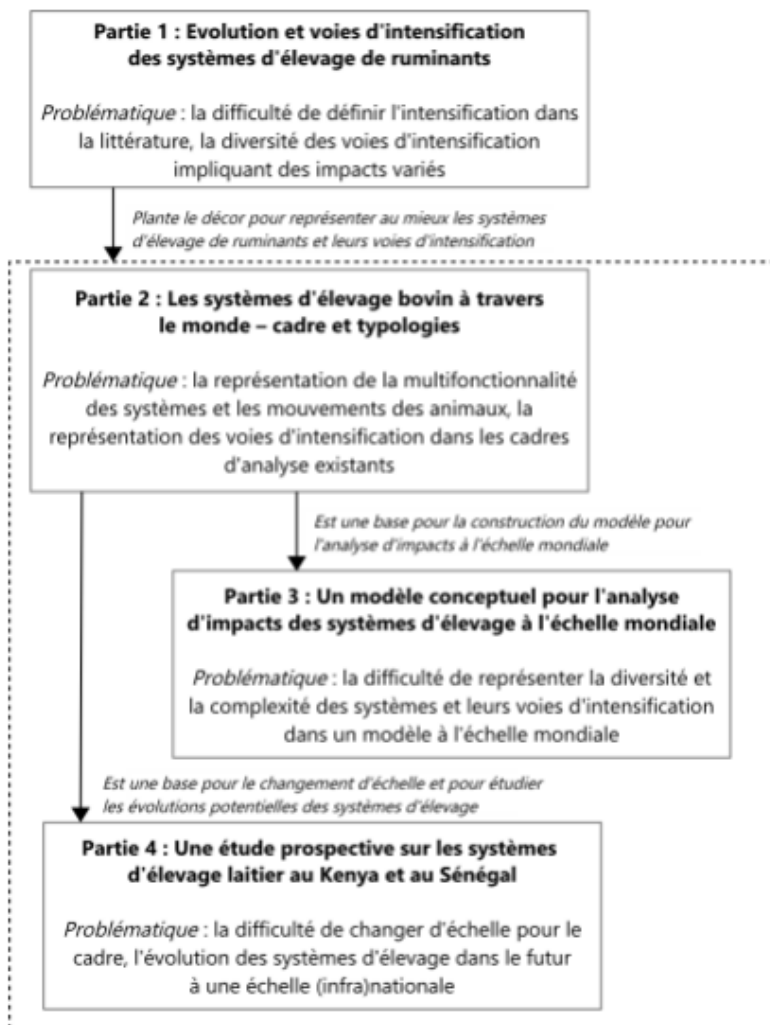


Illustration 1: Structure de la thèse et liens entre les quatre parties

Partie 1

Le mot intensification est souvent utilisé pour faire référence au changement, depuis les années 1950, qui a conduit à la concentration de la production sur des unités de production plus grandes mais en moins grand nombre (Fraser, 2005), et à l'utilisation fréquente d'intrants et de services externes. Mais lorsqu'on parle d'intensification dans les systèmes d'élevage, on peut faire référence à divers processus de changement tels que l'augmentation du taux de charge ou de la taille du troupeau, l'augmentation des terres ou de la main-d'œuvre, l'augmentation des aliments concentrés dans le régime alimentaire ou l'amélioration de la valeur génétique des races (Bava et al., 2014 ; Clay, Garnett et Lorimer, 2020). En outre, l'intensification des systèmes agricoles n'est pas nécessairement associée à cette définition (Robinson et al., 2011), car divers termes sont utilisés dans la littérature. Parmi les autres voies d'intensification, on peut citer l'intensification écologique,

l'intensification durable et l'intensification agroécologique (Delebecque, 2010), entre autres. Ces différentes voies d'intensification peuvent se placer sur un gradient d'objectifs d'intensification, allant d'une intensification avec un objectif uniquement économique pour générer des revenus, à une intensification avec des objectifs sociaux plus larges, contribuant à la préservation de l'environnement et de la société dans son ensemble.

Ces différentes voies d'intensification ne font pas l'unanimité et leurs définitions restent floues. Comme il semble difficile de caractériser précisément l'intensification, j'ai donc choisi de me concentrer sur les objectifs et les intentions qui la sous-tendent plutôt que sur les processus d'intensification proprement dits, comme développé dans la première partie de cette thèse. Dans ce travail, j'ai choisi d'étudier l'intensification d'un point de vue mondial, même si l'intensification peut être influencée par des nuances régionales et nationales.

Pour répondre à la demande croissante de produits d'origine animale, l'intensification des systèmes de production de ruminants, qu'il s'agisse d'intensification dominantes, écologiques, durables ou agro-écologiques, semble inévitable pour l'avenir (Derner et al., 2017), en particulier dans les régions où la valeur de la terre est élevée. Étant donné que de nombreuses communautés humaines dépendent largement de l'élevage pour leur subsistance (principalement des systèmes multifonctionnels), l'augmentation de la production animale et de la productivité des animaux et des terres, sans nuire à l'environnement et en s'adaptant aux défis actuels et futurs, semble être une priorité. Étant donné que ces défis semblent dépendre fortement des caractéristiques locales (par exemple, la disponibilité des aliments pour animaux et de l'eau, l'accès au marché et les caractéristiques socio-économiques), il semble nécessaire de réfléchir aux voies d'intensification et de prospecter les futurs systèmes agricoles à petite échelle (par exemple, au niveau national ou infranational) (Haenlein 2001 ; Laca et Demment 2009).

Partie 2

Le cadre conceptuel développé dans la thèse vise à représenter la diversité et la complexité des systèmes d'élevage bovin dans le monde afin d'évaluer au mieux leurs impacts. L'objectif de cette partie est de représenter la multifonctionnalité, la diversité et la complexité des systèmes dans le monde, de prendre en compte les mouvements des animaux et de regrouper les activités d'animaux apparentés, comme cela a été fait à plus petite échelle dans l'étude de Beauchemin et al. (2010). A ma connaissance, une telle étude n'existe pas à l'échelle mondiale. Il est donc nécessaire

d'élaborer une nouvelle méthode de représentation de l'élevage à l'échelle mondiale afin de répartir correctement les impacts sur les produits de l'élevage (lait, viande, fumier, animaux en tant qu'assurance et capital sur pied).

Comprendre la complexité des relations entre les systèmes d'élevage bovin à travers le monde afin de préparer le terrain pour d'autres études comparant leurs avantages ou inconvénients globaux (économiques, environnementaux, sociaux) à grande échelle est un défi majeur. Cela nécessite de décrire la diversité et la complexité des systèmes d'élevage, avec une délimitation claire de ces systèmes, tout en les regroupant et en les simplifiant [10,16,17]. Pour atteindre cet objectif, des typologies résultant d'une approche holistique basée sur trois niveaux principaux d'analyse sont développées dans la deuxième partie de cette thèse et testées sur les systèmes d'élevage bovin au Kenya. Le cadre est basé sur trois concepts liés:

- Le type de gestion, défini comme un ensemble de méthodes de production et de pratiques agricoles ;
- Les profils d'animaux, qui divisent la vie d'un animal en phases basées sur l'âge et le sexe;
- La matrilignée, qui regroupe les différents profils d'un animal de la naissance à la mort et permet d'aborder les contraintes de reproduction et de renouvellement du troupeau ainsi que la transition des animaux entre les types de gestion.

La première typologie présentée - la typologie des types de gestion - est basée sur les systèmes d'élevage bovin existants dans le monde. Seize types de gestion sont identifiés, tels que le type de gestion pastoral traditionnel avec un objectif multifonctionnel ou le type de gestion alimenté à l'herbe et complété en interne avec un objectif de production. La deuxième typologie - la typologie des matrilignées - a identifié six matrilignées différentes.

Ce cadre conceptuel a été contextualisé au Kenya. Cette contextualisation révèle que tous les systèmes bovins trouvés dans le pays peuvent être liés à un type de gestion de la typologie. Bien que les systèmes locaux soient plus spécifiques que la typologie développée dans cette thèse, la typologie permet d'englober une grande diversité de systèmes locaux, en accord avec les typologies détaillées proposées précédemment au Kenya [28-30]. La typologie proposée est donc le résultat d'une recherche exhaustive des systèmes bovins à l'échelle mondiale. Il est évident que tous les types de gestion ne sont pas censés être présents à des échelles plus petites (nationales ou infranationales).

Ce cadre conceptuel est destiné à servir de base aux études économiques et aux évaluations des impacts environnementaux des pratiques d'élevage bovin. Le premier niveau d'analyse, les types de gestion, permet une compréhension globale des pratiques et méthodes d'élevage bovin dans le monde. Grâce à la division de la vie des bovins en profils, les impacts environnementaux et les coûts économiques peuvent être évalués et attribués à tous les stades de la vie de l'animal. En outre, chaque animal est inclus dans une matrilignée, ce qui permet de prendre en compte les mouvements d'un profil à l'autre et d'un type de gestion à l'autre, le cas échéant. Ce cadre pourrait également être utilisé pour des études sociales et culturelles. Cependant, certains critères pertinents, tels que la taille du troupeau, la professionnalisation, l'égalité des droits, le nombre de travailleurs par animal ne sont pas présents dans ce cadre. Certains critères pourraient encore être liés à des éléments sociaux, religieux ou culturels, tels que l'intensité de l'utilisation des ressources.

Certains éléments, tels que le nomadisme, sont encore difficiles à prendre en compte avec précision dans une typologie en raison de leur dépendance à l'égard des conditions climatiques et locales. On peut également imaginer que certaines pratiques d'élevage adaptées à des conditions très locales et spécifiques, comme l'élevage oasien ou l'élevage de ruminants émergents, ou encore des pratiques adaptées au changement climatique et à l'évolution des habitudes de consommation, pourraient être absentes de ce travail. Malgré cette faiblesse potentielle, le cadre conceptuel conçu et les trois niveaux d'analyse devraient permettre une évaluation et une attribution précises des impacts environnementaux de la plupart des choix de gestion. Le test du cadre et des typologies dans le cas du Kenya a montré la pertinence du cadre à l'échelle du pays, mais aussi le manque de données sur les parts de systèmes.

Partie 3

La diversité des élevages de ruminants, leur évolution et leur intensification sont déjà au cœur de certains modèles intégrés étudiant les processus d'intensification et l'évaluation des impacts environnementaux. Malgré cela, ces systèmes souffrent de certaines limitations. Par exemple, ils sont caractérisés soit par leur climat (Robinson et al., 2011), soit par leur lien avec les cultures. Dans ce second cas, un système mixte avec des cultures se distingue d'un système pastoral plus indépendant (Seré et Steinfeld, 1996). La diversité des systèmes pris en compte dans ces modèles est donc limitée, ce qui est source de confusion, car des systèmes distincts ayant le même niveau d'intensification peuvent être regroupés (par exemple, les systèmes laitiers extensifs de montagne à base d'herbe avec l'élevage en ranch en Amérique du Nord). En outre, les transitions des systèmes

de production animale sont souvent définies par la modification de la part des animaux entre les systèmes de pâturage et les systèmes mixtes. Ces transitions peuvent être attribuées à des processus d'intensification ou d'extensification, ce qui rend difficile la différenciation des types et des processus d'intensification. Enfin, ces modèles globaux ne prennent pas en compte les liens entre les systèmes représentés par les matrilignées, comme développé dans le cadre conceptuel présenté précédemment.

Pour surmonter les limites de ces études (diversité des systèmes de production, type d'intensification et prise en compte des matrilignées) et évaluer les impacts économiques et environnementaux des systèmes d'élevage bovin à l'échelle mondiale, un modèle est proposé dans la troisième partie de cette thèse.

L'objectif de ce modèle est de comparer des systèmes de production représentés par leurs pratiques et processus sur la base de leurs performances (économiques et environnementales) en modélisant les profils d'animaux dans les types de gestion et en comparant les matrilignées. En particulier, deux objectifs d'intensification, situés aux limites du gradient d'intensification, sont comparés: (1) une intensification motivée par la maximisation d'un bénéfice économique privé, et (2) une intensification motivée par la maximisation d'un bénéfice social incluant des bénéfices socio-économiques.

Le modèle présenté est un modèle statique et déterministe avec optimisation. Le modèle est divisé en trois modules et est basé sur le cadre développé dans la partie 2, en utilisant des profils d'animaux et des matrilignées. Le premier module représente chaque profil d'animal de chaque type de gestion dans chaque cellule de la grille d'évaluation, ainsi que leurs coûts et leurs produits. Le deuxième module regroupe les profils d'animaux pour former la structure de la matrilignée, afin de déterminer le nombre de têtes pour chaque profil par le biais de la matrilignée et du modèle de troupeau. Le troisième module regroupe et évalue les impacts de chaque profil afin d'évaluer les bénéfices de la matrilignées. Enfin, une optimisation est réalisée pour spécifier trois variables nécessaires dans le premier module (à savoir le taux d'application de l'azote, le taux de charge et la part d'aliments produits sur l'exploitation). Les performances des matrilignées sont ensuite calculées dans ce modèle, ce qui permet de répartir correctement les impacts et de comparer les voies d'intensification.

Le dernier module de ce modèle consiste à analyser et à calculer les performances des

matrilignées, y compris les impacts environnementaux. Le bénéfice net est calculé pour chaque matrilignée afin de choisir la matrilignée ayant un bénéfice maximal. Les valeurs économiques des coproduits peuvent être évaluées indirectement en décomposant la valeur économique d'une matrilignée au niveau du profil et en répartissant les émissions de GES entre les différents produits de l'élevage en fonction de leur valeur économique (Weiler et al., 2014).

Partie 4

En travaillant sur les deuxième et troisième parties de la thèse, des questions ont été soulevées concernant l'évolution des systèmes d'élevage actuels et les mécanismes de cette évolution, ainsi que de savoir si le cadre conceptuel développé dans la partie 2 à l'échelle mondiale (et donc le modèle développé dans la partie 3) serait suffisamment flexible pour être adapté à une échelle plus petite (i.e., à une échelle nationale ou infranationale). Ainsi, à partir de la typologie des types de gestion, des questions et des intérêts ont été soulevés concernant l'évolution et les futurs impacts potentiels des systèmes de production dans une zone spécifique (Kenya et Sénégal), sur l'environnement, l'économie et la société, ce qui a conduit au développement de la partie 4.

Pour réaliser une étude qui puisse répondre à ces interrogations, l'accent est mis sur le continent africain et l'élevage bovin laitier. Ce choix a été fait en raison des défis actuels et futurs de l'élevage bovin laitier en Afrique, notamment en termes de changement climatique, de croissance de la population et de la demande, ainsi que d'insécurité et de conflits dans certaines régions. L'élevage laitier joue également un rôle crucial dans de nombreux pays d'Afrique, en particulier parmi les populations pastorales et agro-pastorales, générant une part importante des revenus de nombreux ménages (Diop et al., 2009). Le lait est en outre un élément central de nombreux régimes alimentaires locaux, contribuant fortement à la sécurité alimentaire et nutritionnelle (Kibogy, 2019). La demande en produits laitiers, y compris le lait, a augmenté en Afrique, atteignant récemment un taux de croissance de 4 % par an (ILRI, 2018 ; Kibogy, 2019).

Le travail de recherche présenté dans la quatrième partie a plusieurs objectifs, en particulier (i) d'identifier des scénarios potentiels pour les systèmes bovins futurs sur la base des systèmes actuels existant dans les deux pays, (ii) d'évaluer la résilience potentielle des systèmes futurs, c'est-à-dire leur capacité à s'adapter aux transformations (démographiques, climatiques, insécurité croissante), (iii) d'identifier les contraintes et les opportunités de ces transformations, et (iv) d'utiliser l'anticipation comme un processus de transformation du présent qui pourrait guider les

actions et les comportements futurs. Sur la base de la typologie des systèmes bovins de la partie 2, l'étude prospective visera à définir plusieurs trajectoires plausibles pour les systèmes d'élevage laitier ainsi que la résilience de ces systèmes dans le contexte des principaux enjeux de durabilité.

Cette étude prospective vise donc à valider le cadre conceptuel développé dans la partie 2 à une échelle plus petite (une échelle infranationale) et à l'utiliser d'une autre manière que celle représentée par le modèle développé dans la partie 3. Ce faisant, cette étude s'ouvre à d'autres indicateurs que ceux présentés dans la partie 3, tels que la durabilité, la résilience et l'évolution/adaptation, ce qui nous permet d'adopter un point de vue différent sur les voies d'intensification décrites dans la partie 1.

Sur la base de la méthode de la roue du futur, trois scénarios majeurs ont été identifiés et discutés par les experts et les parties prenantes dans les régions centrales du Kenya comme étant les changements se produisant actuellement ou qui ont le potentiel de dominer à l'avenir. Au Sénégal, en utilisant la même méthode, deux scénarios d'évolution ont émergé des discussions avec les experts et les parties prenantes. Selon eux, les scénarios d'évolution seront plus lents à se mettre en place au Sénégal qu'au Kenya à moyen et long terme (>20 ans). Ce rythme lent est attribué aux nombreux défis et incertitudes auxquels le secteur est confronté au Sénégal.

Les conséquences environnementales et socio-économiques directes et indirectes ont été identifiées pour les scénarios potentiels d'évolution de l'élevage laitier dans les deux pays. Les principaux impacts environnementaux positifs identifiés au Kenya par au moins quatre experts pour les trois scénarios sont les suivants: une dépendance minimale de la production d'aliments pour animaux à l'égard des événements climatiques, une diminution des émissions de méthane par animal, un potentiel accru de production de biogaz et une réduction du surpâturage et des dommages causés à la biodiversité. Certains impacts négatifs sont aussi identifiés tels que l'accumulation de déchets (fumier et déchets alimentaires), l'augmentation de la pollution par l'azote et le phosphore, et la détérioration de la santé des animaux due à l'augmentation du confinement. Des incidences socio-économiques sont aussi développées telles que l'amélioration de la nutrition et de la sécurité alimentaire grâce à une augmentation de la production laitière, et la stimulation de l'économie du pays. Bon nombre de ces impacts potentiels sont similaires à ceux signalés dans le nord du Sénégal: amélioration des moyens de subsistance, coûts de production élevés, pollution de l'air et de l'eau, réduction du surpâturage, augmentation de la charge de fumier, propagation des maladies, etc.

Cette étude met également en lumière des domaines d'intérêt pour la recherche et les politiques de développement tels que les impacts environnementaux de l'intensification laitière, l'accès au marché et l'organisation de la chaîne de valeur des produits laitiers, l'amélioration des moyens de subsistance des éleveurs grâce à l'augmentation de la productivité et de la production ou encore les coûts de production et d'investissement élevés des systèmes laitiers intensifs.

Discussion et conclusion

Suite à l'augmentation de la population, à la hausse des revenus et à l'urbanisation, les systèmes de production de ruminants sont confrontés au défi de répondre à la demande croissante de produits d'origine animale dans de nombreuses régions du monde. Les défis mondiaux tels que le changement climatique et l'augmentation des impacts négatifs sur l'environnement poussent les systèmes de production à subir des changements pour produire davantage tout en étant durables.

Pour atteindre l'objectif d'une production durable, une première étape pourrait consister à comprendre et à calculer les performances environnementales de chaque système de production ainsi que leurs performances économiques. Les typologies et le cadre conceptuel développés dans la partie 2 nous permettent de saisir la complexité de l'élevage bovin à l'échelle mondiale et de tenir compte des mouvements d'animaux entre les systèmes, grâce aux matrilignées.

Sur la base de ce cadre, l'évaluation des performances environnementales et économiques de chaque type de gestion est possible grâce à la modélisation. L'objectif du modèle théorique développé dans la partie 3 et basé sur le cadre développé dans la partie 2, est de comparer des matrilignées sur la base de leurs performances. En particulier, deux mesures de performance, correspondant aux limites d'un gradient d'objectifs d'intensification, sont comparées: (1) une performance économique privée basée sur la génération de revenus ou la maximisation multi-objectifs avec (2) une combinaison d'impacts socio-environnementaux et de performance économique privée. Cette dernière correspond à une combinaison de diverses activités d'élevage et de bénéfice économique avec une pénalisation des impacts négatifs sur l'environnement.

Etant donné que le secteur des ruminants subira des changements à l'avenir pour faire face à des défis tels que la croissance démographique, le changement climatique, l'insécurité et les conflits, il est nécessaire d'adopter une approche holistique et intégrée de la réflexion sur l'avenir. L'étude

prospective présentée dans la partie 4 vise à explorer les voies d'évolution des systèmes d'élevage laitier au Kenya et au Sénégal. Outre les voies d'évolution, les moteurs de l'évolution ainsi que les impacts environnementaux, économiques et sociaux potentiels sont examinés. Trouver un équilibre entre les systèmes de production et choisir le plus approprié en fonction du contexte agro-climatique, de la disponibilité des terres, du contexte socio-économique, des objectifs de production ainsi que des contraintes et des défis locaux semble essentiel pour maintenir la diversité et, par conséquent, la résilience.

L'étude et la classification de plusieurs pratiques d'élevage de ruminants dans le monde et la construction d'un modèle conceptuel ont permis d'établir un cadre pour les futures études d'évaluation d'impact. En effet, ce travail ouvre la voie à de futures études sur l'évaluation de l'impact environnemental et économique. L'objectif de ce cadre conceptuel est également de pouvoir réaliser des études d'évaluation d'impacts holistiques, en prenant en compte différents éléments environnementaux tels que les émissions de gaz à effet de serre, le bilan azoté, mais aussi des éléments économiques. Comme nous l'avons vu dans la partie précédente, les aspects sociaux et culturels des systèmes ne doivent pas être négligés. La prise en compte et la discussion des composantes d'un système d'élevage devraient également être une priorité, au même titre que les impacts environnementaux et économiques, afin d'obtenir une vision holistique des systèmes de production. La prise en compte de ces trois composantes de la durabilité devrait permettre d'identifier des voies de développement durable pour l'élevage de ruminants à l'avenir.

ACKNOWLEDGMENTS

I would like to particularly acknowledge Charles-Henri Moulin and Gilles Brunschwig for accepting to be the rapporteurs of this thesis, Anne Morret, and Philippe Lescoat for accepting to be the examiners, as well as Armelle Gac for playing a role in the PhD defence as a guest. Thank you very much for your availability and your interest in my work.

I would also like to particularly acknowledge Patrice Dumas, my director, and Mathieu Vigne, my co-supervisor for their precious pieces of advice, their time and availability, and for following my work and its evolution throughout the years.

I would also like to firstly acknowledge AgroParisTech, as well as CLAND for giving me the opportunity to carry on this thesis thanks to their support and funding, CIRED for welcoming me into their offices throughout this thesis, and ILRI for welcoming me as a graduate fellow in Nairobi (Kenya) giving me the opportunity to be on the field.

Finally, I would like to say a special thank you to some persons who helped me go through this journey and enlightened me with their knowledge and skills: Guillaume Duteurtre, Céline Dutilly, Pierre-Alain Jayet, Thierry Bonaudo, the ILRI team (especially Isabelle Baltenweck, Dolapo Enahoro, and Derek Chan), Prosper Houessionon, the CLAND team (especially Louise d'Armancourt, and John Bazire), the MISS team (especially Valérie Fortuna), and the Africa-milk researchers (especially Eric Vall, John Mburu, Asaah Ndambi, Mercy Mburu, Serena Ferrari, Christian Corniaux, and Jean-Daniel Cesaro), as well as all participants of the foresight study for their time and answers.

TABLE OF CONTENTS

Résumé de la thèse.....	5
Acknowledgments.....	16
Table of contents.....	17
Abbreviations.....	20
List of figures.....	21
List of tables.....	22
I - Introduction.....	24
I.1- Diversity of ruminant farming systems.....	24
I.2. The need for sustainable intensification.....	25
I.3. Objectives and structure of the thesis.....	26
I.4. Bibliography of the introduction.....	28
II- Part 1: Evolution and intensification of ruminant production systems.....	31
II.1. Diversity of intensification pathways.....	31
II.1.1. Dominant intensification.....	32
II.1.2. Sustainable and ecological intensifications.....	33
II.1.3. Agro-ecological intensification.....	34
II.1.4. Intensification pathways compared with intensification processes.....	39
II.2. Impacts of dominant livestock farming intensification.....	39
II.2.1. Environmental impacts.....	39
II.2.2. Livelihood and health impacts.....	42
II.3. Impacts of intensification on determinants and practices of ruminant farming	42
II.3.1. Crop-livestock integration in ruminant farming systems.....	42
II.3.2. The impacts of intensification on ruminant diets.....	43
II.3.3. The role of breeds in intensification.....	44
II.3.4. Various degree of intensification in pastures management.....	45
II.4. Conclusion.....	45
II.5. Bibliography of Part 1.....	48
Takeaway messages and presentation of Part 2.....	58
III- Part 2: Representing cattle farming around the world: a conceptual and holistic framework for environmental and economic impact assessment.....	60
III.1. Introduction.....	60
III.2. Materials and Methods.....	63
III.2.1. Conceptual framework.....	63

III.2.2. Methods for management type typology.....	66
III.2.3. Methods for lineage group typology.....	69
III.3. Results.....	71
III.3.1. Management type typology.....	72
III.3.2. Animal profiles.....	73
III.3.3. Lineage group typology.....	73
III.4. Contextualisation and comparison with existing typologies: case study of Kenya.....	74
III.4.1. Dairy production systems in Kenya	74
III.4.2. Beef cattle production systems in Kenya	79
III.4.3. Relevance of the typology in the context of Kenya.....	82
III.5. Discussion.....	85
III.5.1. Framework's use for various studies.....	85
III.5.2. Limits of previous methods and typologies.....	86
III.5.3. Strengths and weaknesses of the framework.....	87
III.6. Conclusion.....	89
III.7. Appendix A.....	90
III.8. References.....	94
Takeaway messages and presentation of Part 3.....	99
IV – Part 3 : A conceptual model for impact assessment of cattle systems at the world scale	
.....	100
IV.1. Limitations in global agricultural models for studying intensification and impact assessment	
.....	100
IV.2. Objectives of the model.....	102
IV.3. Module 1: representation of management types and located profiles modeling.....	104
IV.3.1. Determination of production areas and feed requirements: input and output	
quantification.....	105
IV.3.2. Financial and emission flows.....	118
IV.4. Module 2: lineage groups modeling.....	125
IV.5. Module 3: net benefits.....	131
IV.5. Performance calculations.....	133
IV.6. Discussion.....	135
IV.6. Bibliography of Part 3.....	138
Takeaway messages and presentation of Part 4.....	145
V- Part 4 : Foresight study on dairy cattle farming systems.....	147
V.1. Background and objectives.....	147

V.2. Anticipation versus foresight.....	148
V.3. A foresight method: the futures wheel.....	149
V.3.1. Strengths and weaknesses of the futures wheel.....	150
V.3.2. Detailed method.....	151
V.4. Article: Foresight study on dairy farming systems in central Kenya and north of Senegal.....	152
V.4.1. Introduction.....	152
V.4.2. Methods	156
V.4.3. Results.....	157
V.4.6. Discussion.....	174
V.4.7. Conclusion.....	178
V.4.8. Bibliography of Part 4.....	179
Takeaway messages.....	185
VI- General discusion	186
VI.1. Accounting for the multifunctionality of ruminant systems in the framework.....	186
VI.2. Designing a framework for ruminant systems at the global scale: strengths and risks.....	190
VI.3. Experiencing the framework at a smaller scale.....	191
VI.4. Limitations and next steps.....	193
VI.5. Bibliography of the discussion.....	195
VII- Conclusion.....	199
VIII- Annexes.....	201
Annexe 1: Expert consultations on typologies.....	201
1.1. Objectives.....	201
1.2. Questionnaire.....	202
1.3. Results.....	203
Annexe 2: Some data for the model.....	208
Annexe 3: Work plan and activity reports of the graduate fellowship at ILRI.....	211
Annexe 4: Material for the foresight study.....	220
Bibliography of the annexes.....	235

ABBREVIATIONS

CAP: Common Agricultural Policy

CIRAD: Centre de coopération Internationale en Recherche Agronomique pour le Développement;

FAO: Food and Agriculture Organization of the United Nations;

FIFAMANOR: Fiompiana Fambolena Malagasy NORveziana (Centre de Développement Rural et de Recherche Appliquée à Madagascar);

GHG: GreenHouse Gases;

IPCC: Intergovernmental Panel on Climate Change;

ILRI: International Livestock Research Institute;

INERA: Institut de l'Environnement et de Recherches Agricoles (Burkina Faso);

ISRA: Institut Sénégalais de Recherches Agricoles;

LG: Lineage Group;

MT: Management Type;

NPP: Net Primary Productivity;

NUE: Nitrogen Use Efficiency;

SDG: Sustainable Development Goal;

UoN: University of Nairobi;

WUR: Wageningen University & Research.

LIST OF FIGURES

Illustration 1: Structure de la thèse et liens entre les quatre parties.....	7
Figure 2: Description of management types, lineage groups, and animal profiles.....	65
Figure 3: Decision tree for the construction of cattle management types typology based on criteria (D: dairy breed, M: meat breed, P: production, M: multi-function, i: intensive pasture management, e: extensive pasture management).....	69
Figure 4: Cattle herd structure [26].....	70
Figure 5: Decision tree for the construction of the lineage group typology.....	72
Figure 6: Share of dairy production systems. Outer circle: dairy systems according to literature [28,29]. Inner circle: dairy systems according to the typology.....	84
Figure 7: Simplified framework of the model.....	105
Figure 8: Model system (feeds, herd management, herd mobility, relation to land, pasture management, manure management, GHG emissions, economic analysis and costs, climatic conditions).....	106
Figure 9: Simplified scheme of the use of ORCHIDEE-GM model for pasture management unit.....	111
Figure 10: Cattle herd structure (FAO, 2011).....	127
Figure 11: Number of interviewed experts and stakeholders in Kenya (outer circle) and Senegal (inner circle) according to their profession.....	159
Figure 12: Map of the main potential direct and indirect impacts of the three evolution scenarios for dairy farming systems in Central Kenya and central Rift Valley.....	168
Figure 13: Map of the main potential direct and indirect impacts of the two evolution scenarios for dairy farming systems in northern Senegal.....	170

LIST OF TABLES

Table 1: Comparison of dominant, ecological, sustainable, and agro-ecological intensification pathways.....	36
Table 2: Description of dairy production systems in Kenya [28,30,31,34,36], G = grazing; SZG = semi-zero-grazing, ZG = zero-grazing.....	77
Table 3: Description of beef production systems in Kenya [28].....	81
Table 4: Summary of some global agricultural models.....	102
Table 5: Examples of quantity of labour (hours) for some cattle farming activities (from Mosnier et al. 2017).....	121
Table 6: Variables and symbols used in the cost per head calculation.....	122
Table 7: Variables and symbols used in the lineage group modelling.....	128
Table 8: Variables and symbols used in the net benefits calculation.....	132
Table 9: Units used in the economic allocation.....	135
Table 10: Description of the dairy farming systems in Kenya.....	155
Table 11: Description of the dairy farming systems in Senegal.....	156
Table 12: Characteristics of interviewed farmers in Kenya.....	159
Table 13: Characteristics of interviewed farmers in Senegal.....	160
Table 14: Evolution scenarios for dairy farming systems in central Kenya.....	162
Table 15: Evolution scenarios for dairy farming systems in north of Senegal.....	163
Table 16: Correspondence of dairy farming systems in Kenya with the management type typology developed in Part 2.....	193
Table 17: Correspondence of dairy farming systems in Senegal with the management type typology developed in Part 2.....	194
Tableau 18: MTs identified by experts as present in region of specialization.....	205
Tableau 19: Parameters identified by experts for each MT.....	205
Tableau 20: Parameters identified by experts for each LG when present in their preferred region.....	207
Table 21: Various rates and data for dairy and meat cattle (Foray and Gac, 2018).....	209
Table 22: Parameters for cattle in mixed systems in sub-saharan Africa in various agro-ecological zones (Otte and Chilonda, 2002).....	209
Tableau 23: Parameters for sheep in pastoral systems in sub-saharan Africa in arid and semi-arid areas (Otte and Chilonda, 2002).....	210
Table 24: Parameters for sheep in mixed systems in sub-saharan Africa in various agro-ecological zones (Otte and Chilonda, 2002).....	210

Table 25: Parameters for goats in pastoral systems in sub-saharan Africa in arid and semi-arid areas (Otte and Chilonda, 2002).....	210
Table 26: Parameters for goats in mixed systems in sub-saharan Africa in various agro-ecological zones (Otte and Chilonda, 2002).....	210
Table 27: Parameters for non-traditional cattle systems in sub-saharan Africa (Otte and Chilonda, 2002).....	210
Table 28: Production parameters for various cattle breeds (Foray and Gac, 2018).....	211
Table 29: Milk yield for various dairy cattle breeds depending on the feeding strategy (Baumont et al., 2014).....	211
Table 30: References for useful data for the conceptual model.....	211

I - INTRODUCTION

I.1- DIVERSITY OF RUMINANT FARMING SYSTEMS

Since domestication, humans, and livestock have co-evolved (Laca and Demment, 2009), so livestock became a part of our societies and livelihoods. Nowadays, however, livestock production systems face significant challenges to meet the ever-increasing demand for animal protein (Derner et al., 2017). Indeed, demand for animal-based products is growing due to various factors: population growth, urbanization, higher income, and change in habits among others (Pfeifer, Morris and Mose, 2018). According to most recent predictions, animal production would need to increase by 70 percent by 2050 to accommodate nine billion humans and a rise in the global middle class, largely concentrated in South-East Asia, Africa, and Latin America (Derner et al., 2017). This high demand for animal-based products also appears in a world where our societies are challenging the place of meat in our diet, animal well-being, as well as the globalization of livestock production systems questioning the place of industrial and globalized systems.

Livestock systems are responsible for numerous impacts on the environment: water pollution, greenhouse gasses (GHG) emissions, biodiversity threats, soil degradation, as well as disruption of the natural nitrogen cycle (Pfeifer, Morris and Mose, 2018). To accommodate the growing demand for animal-based products globally without negatively impacting the environment, there is a strong need for designing sustainable livestock production systems. In addition to being key to sustainable agricultural transformation, livestock production can also improve livelihoods, nutrition, and food security (Herrero et al., 2009 ; FAO, 2018a), and participate in the global resilience of many communities.

Ruminant livestock – cattle, buffaloes, goats, sheep, camels – are vital in many parts of the world with populations relying on their products, such as milk, meat, and blood, for their income and self-consumption. By being able to transform cellulose into energy and protein suitable for human consumption, ruminants can valorise grasses and woody plants on rangelands and occupy lands that are not suited for crop production (Mottet et al., 2017). When feeding on crop residues, ruminants can also increase the efficiency of crop production by manure deposition (FAO, 2018b). They are, however, also a high contributor to climate change as ruminants emit large quantities of GHG. For instance, the low digestibility of forages and feeds is associated with high methane emissions from enteric fermentation (Cardoso et al., 2016). Ruminants, and especially cattle, also

require vast land areas, for grazing or feed cultivation, with a high carbon footprint (Searchinger et al., 2018; Hayek et al., 2021).

Faced with these challenges, it is crucial to design a sustainable livestock sector, which in turn requires environmental and economic impact assessments of ruminant production systems. To perform such assessments, having a global view of the diversity of systems is a major element, as ruminant production is linked to multiple aspects across the planet (Steinfeld, Wassenaar, and Jutzi, 2006). Many production systems have traditionally functioned without external inputs, existing in a sustainable equilibrium with the environment. For example, in many systems, ruminants and crops are closely interlinked like the rice/buffalo or cereal/cattle systems in Asia. In these systems, animal manure maintains soil fertility, which is one of the main reasons for keeping animals, in addition to draught power. In other systems, like pastoralism, the balance between human and animal populations as well as the vegetative biomass is the key to maintaining ruminant production (Steinfeld, Wassenaar, and Jutzi, 2006). Many of these systems are the result of a long evolution and are currently under pressure to adjust to rapidly evolving socioeconomic conditions (Steinfeld, Wassenaar, and Jutzi, 2006). To respond to the rapid growth demand for animal-based products, however, large intensive production systems, specifically in high-income countries, have quickly emerged (Steinfeld, Wassenaar, and Jutzi, 2006).

I.2. THE NEED FOR SUSTAINABLE INTENSIFICATION

The diversity of ruminant farming systems is therefore a major element when talking about the evolution of ruminant farming, as they cover gradients of agro-climatic and geographical conditions as well as a diversity of functions, and gradients of intensification (ranging from extensive grassland-based to large-scale intensive systems) (Dumont et al., 2013). Indeed, some ruminant farming systems are getting more and more intensified across the world driven by various factors impacting farming practices. In addition to demand factors, population pressure, and environmental factors (McDermott et al., 2010), other drivers of intensification are the wish for a private interest, benefiting solely the farmer (or herder), or the wish for a social interest, benefiting a whole community or society.

This last driver leads to a gradient of intensification which limits are two different objectives of intensification, a purely private objective on one side (i.e., intensification driven by a private benefit including income generation, the production of manure, draught power, etc), and a social

objective on the other side (i.e., a multi-functional intensification driven by other objectives such as reduced environmental impacts, social cohesion, etc). Opportunities for intensification pathways that are environmentally friendly, economically viable, and have positive social and livelihood impacts exist, although they require innovative and practical approaches (Tarawali et al., 2011). Many questions arise, however, on the future evolution of farming systems and their sustainable intensification paths, especially when confronted with challenges and changes such as land availability, climate change, and population growth.

I.3. OBJECTIVES AND STRUCTURE OF THE THESIS

The overall objective of this thesis is to develop methods and tools to support the sustainable intensification of ruminant farming systems by capturing their diversity and complexity, and to propose a conceptual framework for assessing their economic impacts (i.e., costs, income, and meat and milk production), and environmental impacts (mainly GHG emissions and nitrogen losses). To break down this overall objective, this thesis is divided into four parts (see Figure 1):

1. A review of ruminant production systems intensification pathways, based on a literature review to answer the following questions: *how are cattle farming systems represented in the literature? How are intensifications defined and what are the various intensification pathways?* By exploring various types of intensification, their definitions, and processes, as well as their drivers, impacts, and determinants, this first part sets intensification as a major driver of the diversity and the evolution of production systems, and thus, of their environmental and economic impacts;
2. A conceptual framework and two typologies of current cattle farming systems across the world for impact assessment to answer the following questions: *how to best represent cattle farming systems over the world while considering their multifunctionality, the links between related animals, and their movements between systems? How are intensification pathways treated in these frameworks?* This second part has been carried out based on a literature review and expert knowledge. After discovering some limitations in the current typologies of ruminant farming systems, a new framework is built based on three interlinked concepts: management types, animal profiles, and lineage groups;
3. A conceptual and dynamic model based on the above presented conceptual framework to assess the economic and environmental impacts of different management types, and to answer the following question: *how to build a model that could consider the diversity and complexity of systems and intensification pathways worldwide?* The goal is to model

various cattle production systems at the world scale to then compare intensification pathways;

4. A foresight study on dairy farming systems in Kenya and Senegal to test the relevance of the conceptual framework to represent the diversity of dairy systems at the subnational scale, and foresee evolution scenarios of these systems to answer the following questions: *how are cattle systems evolving? How to adapt a framework designed at the global scale, at a smaller scale?*. This case study, centered around a qualitative foresight study, allows putting into practice the management type typology developed in Part 2 and identifies future evolution paths for dairy farming. This work is implemented based on fieldwork interviews and farm visits.

Based on the above questions, the following research question was raised for this thesis: *"How to analyse the environmental and economic impacts of a diversity of ruminant farming systems, and their intensification paths at a world and subnational scales?"*.

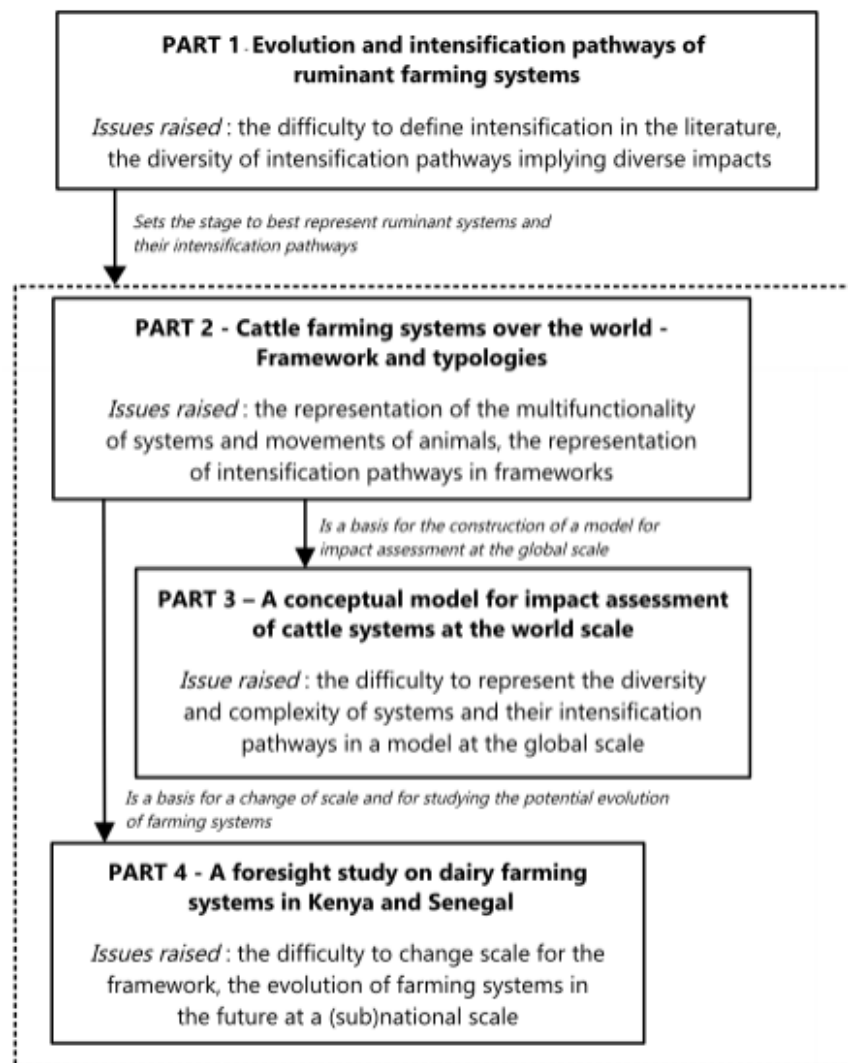


Figure 1: Structure of the thesis and links between the four parts

The results and research presented in each of the four parts of this work are discussed and put into perspective in a last part entitled "Discussion" followed by a small conclusion.

I.4. BIBLIOGRAPHY OF THE INTRODUCTION

Cardoso, A.S., Berndt, A., Leytem, A., Alves, B., de Carvalho, I., de Barros, S., Urquiaga, S., and Boddey, R.M, "Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use", *Agricultural Systems* 143 (March 2016): 86-96, 10.1016/j.agsy.2015.12.007.

Derner, J., Hunt, L., Filho, K.E., Ritten, J., Capper, J., Han, G., and Briske, D., "Livestock production systems", in *Rangeland systems: processes, management and challenges*, ed. Briske, David D. (Cham: Springer Nature, 2017), p347-372.

Dumont, B., Fortun-Lamothe, L., Jouven, M., Thomas, M., and Tichit, M., "Prospects from

Agroecology and Industrial Ecology for Animal Production in the 21st Century”, *Animal: An International Journal of Animal Bioscience* 7 (June 2013): 1-16, 10.1017/S1751731112002418.

FAO, *World Livestock Transforming the Livestock Sector through the Sustainable Development Goals* (Rome: Food and Agriculture Organisation of the United Nations, 2018a), 222p.

_____, *Livestock and Agroecology: How they can support the transition towards sustainable food and agriculture* (Rome: Food and Agriculture Organization of the United Nations, 2018b), 16p.

Hayek, M.N., Harwatt, H., Ripple, W.J., and Mueller, N.D., “The carbon opportunity cost of animal-sourced food production on land”, *Nature Sustainability* 4, no.1 (January 2021): 21-24, 10.1038/s41893-020-00603-4.

Herrero, M., Thornton, P.K., Gerber, P., and Reid, R., “Livestock, livelihoods and the environment: understanding the trade-offs”, *Current Opinion in Environmental Sustainability* 1, no. 2 (December 2009): 111-120, 10.1016/j.cosust.2009.10.003.

Laca, E.A., and Demment, M.W., “Livestock production systems”, in *Management of agricultural, forestry, and fisheries enterprises - Volume I*, (EOLSS Publications, 2009).

McDermott, J.J., Staal, S.J., Freeman, H.A., Herrero, M., and Van de Steeg, J.A., “Sustaining intensification of smallholder livestock systems in the tropics”, *Livestock Science* 130, no.1-3 (May 2010): 95-109, 10.1016/j.livsci.2010.02.014.

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., and Gerber, P., “Livestock: On our plates or eating at our table? A new analysis of the feed/food debate”, *Global Food Security* 14 (September 2017): 1-8, 10.1016/j.gfs.2017.01.001.

Pfeifer, C., Morris, J., and Mose, V., *CLEANED tool: Live spatial simulation to develop a shared vision for a sustainable livestock value chain transformation* (Dar es Salaam: Free and Open source software for geospatial (FOSS4G) Conference, 2018).

Searchinger, T., Wiersenius, S., Beringer, T., and Dumas, P., “Assessing the efficiency of changes in land use for mitigating climate change”, *Nature* 564, no.7735 (December 2018): 249-253, 10.1038/s41586-018-0757-z.

Steinfeld, H., Wassenaar, T., and Jutzi, S., "Livestock production systems in developing countries: status, drivers, trends", *Revue scientifique et technique* (International Office of Epizootics 25, no. 2 (2006): 12.

Tarawali, S., Herrero, M., Descheemaeker, K., Grings, E., and Blümmel, M., "Pathways for sustainable development of mixed crop livestock systems: Taking a livestock and pro-poor approach", *Livestock Science* 139, no.1 (July 2011): 11-21, 10.1016/j.livsci.2011.03.003.

II- PART 1: EVOLUTION AND INTENSIFICATION OF RUMINANT PRODUCTION SYSTEMS

Many authors disagree on the best way to identify future paths for ruminant farming. Steinfeld, Wassenaar and Jutzi (2006) argued that future expansion of the livestock sector will rely on intensive livestock systems, whereas Herrero et al. (2009) concluded that more extensive integrated crop–livestock systems could make a more significant contribution to food security (Dumont et al., 2013). The intensification of livestock farming can generally be seen as a process of transformation of systems in terms of animal production and productivity, land use, and/or socio-economic parameters (Domingues et al., 2019).

The word intensification is often used to refer to the historical change in agriculture, since the 1950s, towards the concentration of production on fewer and larger units (Fraser, 2005), and the frequent use of external inputs and services. But when talking about intensification in livestock systems, one can refer to various processes of change such as an increase in stocking rate or herd size, an increase in land or labour, an increase in concentrated feeds in the diet, or enhanced genetic merit of the breeds (Bava et al., 2014; Clay, Garnett, and Lorimer, 2020)). In addition, when discussing the intensification of farming systems, it is not necessarily associated with this definition (Robinson et al., 2011) as various terms are employed in the literature. Alternative modes of intensification include ecological intensification, sustainable intensification, and agro-ecological intensification (Delebecque, 2010), among others. These various pathways of intensification are not unanimously defined and their definitions stay blurry. As it seems difficult to precisely characterise the intensification, I, therefore, chose to focus on the objectives and the intentions behind it rather than the intensification processes per say.

In this work, I chose to study intensification from a worldwide perspective even though intensification can be influenced by regional and national nuances. Indeed, some motors of regional intensification, or regionalisation, depend on the specific constraints of the region such as climate, regional economy, historical events, development aid, etc, but will not be addressed in this work.

II.1. DIVERSITY OF INTENSIFICATION PATHWAYS

The term intensification pathway refers to the type of evolution from one production system, one

set of practices, to another. Four intensification pathways are described in this section (dominant, sustainable, ecological, and agro-ecological intensifications).

II.1.1. Dominant intensification

The term dominant intensification in animal husbandry refers to the intensification of the majority of systems worldwide. It often refers to the increase of an animal product's production and productivity per animal or per unit area through the increased use of production factors, other than labour, and external services (Udo et al, 2011; Udo & Steenstra, 2011; Smith et al., 2017; Wezel et al., 2015; Domingues et al., 2019), with a substitution of labour by financial capital or other inputs (e.g., mechanisation, fertilisation, improvement of pastures, increase of pasture areas, etc), and with the use of concentrated feed (Fraser, 2005) (see Table 1). The confinement of animals is often associated with dominant intensification, but is not mandatory (e.g., intensified systems of South America (Brazil, Argentina) or New Zealand with large grazing areas are included in this definition) (Basset-Mens et al., 2009; Bowman et al., 2012). Dominant intensification is also characterised by the high specialization of production units. By doing so, farmers and herders adopting dominant intensification concentrate solely on the increase in production and productivity, without considering other aspects of production systems (Wezel et al., 2015) (e.g., environmental aspects, social aspects, livelihoods, animal well-being, etc). As an example of consequences of dominant intensification, dairy herd size increased by 147 percent between 1997 and 2012 in New Zealand (Clay, Garnett, and Lorimer, 2020), and world milk production increased by 59 percent between 1988 to 2018 (FAO, 2023).

Dominant intensification and their associated processes of change are often considered as vulnerable to environmental changes and causes negative environmental impacts, such as pollution, soil degradation, reduced biodiversity, and GHG emissions. In addition, it is inaccessible to poor smallholder farmers because of its high cost of inputs and energy. Faced with these issues, other pathways are emerging to move away from the dominant intensification, based on the pillars of sustainability.

Dominant intensification of animal production systems has been widely driven primarily by market opportunities consequently to increased demand for animal products (McDermott et al., 2010; Udo and Steenstra, 2011; Enahoro et al., 2019). The increase in animal products demand around the world, in particular for low- to middle-income countries, is driven by:

- Population growth (Bouwman et al., 2005; Herrero et al., 2009; McDermott et al., 2010; Tedeschi et al., 2015);
- Urbanization (Herrero et al., 2009; McDermott et al., 2010);
- Increase in household income and prosperity. When household incomes exceed 2 dollars per day, the share of animal products in the diet increases (Herrero et al., 2009; McDermott et al., 2010; Williams et al., 1999);
- Changes in eating habits: leading to a greater proportion of animal products in the diet (Bouwman et al., 2005; McDermott et al., 2010).

Global consumption of animal-based products has increased by more than 40 kilograms per person per year in the last 25 years (Herrero et al., 2018), on average. Between 2000 and 2011, global milk and meat production increased by 28 percent and by 11 percent, respectively (Herrero et al., 2018). At the global level, these increases in consumption were covered by increases in animal numbers (dairy: +19 percent, meat: +10 percent), followed by increases in animal productivity (milk: +9 percent, meat: +1 percent) (Herrero et al., 2018). Disparities exist in the global increase in animal-based products consumption, depending on the type of products. Indeed, this increase is mainly due to enhanced poultry meat consumption (+8.1 percent worldwide between 1990 and 2015), pig meat consumption (+3.3 percent worldwide between 1990 and 2015), and milk consumption, excluding butter (+18.9 percent worldwide between 1990 and 2015) (Herrero et al., 2018). Large disparities also exist between countries. For example, poultry meat consumption increased by 28.1 percent in Brazil, whereas it increased by only 1.7 percent in India between 1990 and 2015 (Herrero et al., 2018).

According to recent projections by the FAO and under business-as-usual scenarios, demand for meat in low- and middle-income countries will increase by 80 percent by 2030 and by over 200 percent by 2050 (Salmon et al., 2018). It is expected that the increased demand for animal products will be met through the increased production of chicken and pork (Salmon et al., 2018). In Africa, however, ruminant populations are also expected to increase to meet the demand for meat and milk (Herrero et al., 2009). As consumption and production of animal products differ between regions, heterogeneity in the opportunities and threats associated with the expansion of the sector is greatly expected (Enahoro et al., 2019).

II.1.2. Sustainable and ecological intensifications

Sustainability is difficult to clearly define as it embodies multi-faceted concepts and a combination of variables that make a production system sustainable, which can be unique to each production situation (Tedeschi et al., 2015).

Many authors define sustainable intensification as the process designed to increase productivity per unit area while decreasing negative impacts on the environment, and building on and maintaining ecosystem functionality (Udo et Steenstra, 2011; Smith et al., 2017; Tedeschi et al., 2015; Paul et al., 2019; Dawson et al., 2019) (see Table 1). Although the term remains complicated to clearly define, sustainable intensification was embraced by several international organisations (e.g., FAO) as a potential answer to the increase in food demand for more animal proteins. In practice, this interpretation of sustainable intensification is primarily focused on production and has been criticized for lacking engagement with the social aspects of sustainability (Dumont, Groot and Tichit, 2018). Some authors, therefore, define sustainable intensification more holistically as a solution for our food system to reduce its environmental footprint and enhance human nutrition and animal welfare (Dumont, Groot and Tichit, 2018).

Some authors declare that sustainable intensification appears poorly positioned to address multidimensional issues associated with livestock systems such as animal welfare, human health, and social elements (Clay, Garnett and Lorimer, 2020) while still raising issues such as equity, access to food, and food distribution (Dumont, Groot and Tichit, 2018).

Other authors also use the term ecological intensification (Gomes et al., 2014; Wezel et al., 2015). A clear distinction between ecological and sustainable intensification is hard to make. Indeed, some authors define it as the aim to found innovative, productive, and sustainable production systems, by managing socio-agro-ecosystems and by valuing their environmental services, in an interactive way with the evolving socio-economic constraints of farms (Dugué et al., 2011). Ecological intensification is a possible solution to meet the challenges of reducing environmental impacts and increasing animal production on a global scale, while incorporating a local dimension, such as the use and exchange of resources among farmers at the local level, the sale and purchase of products on local markets, etc (Gomes et al., 2014). It is this latter component that distinguishes ecological from sustainable intensification.

II.1.3. Agro-ecological intensification

Finally, a third term is used to talk about another intensification pathway: agro-ecological intensification. Definitions and principles of the terms ecological, sustainable, and agro-ecological intensifications are sometimes confusing and overlapping and these terms can be easily used in exchangeable ways (Wezel et al., 2015), but some differences can be pinpointed. Firstly, agro-ecological intensification is primarily associated with a system re-conception and use of ecosystem services as well as higher resilience of agro-ecological systems (Dumont, Groot and Tichit, 2018) (see Table 1). In addition, the principles for agro-ecological intensification clearly show differences in practical implications. For example, a difference is the insertion of the social and cultural perspectives, which are of great importance as most of the solutions advocated in ecological and sustainable intensification mostly focus on the agronomic and environmental aspects and, to some extent, the economic ones. Agro-ecological intensification also distinguishes itself by emphasizing the importance of intensifying knowledge, not only for scientists and decision-makers but for smallholder farmers (Wezel et al., 2015).

To summarize, definitions of ecological and sustainable intensifications include the following two main key elements: "increased production to meet the needs of the growing population" and "minimized environmental impacts". Definitions of agro-ecological intensification re-use these key elements and add others such as "social and cultural perspective", "farmers' knowledge" and "system approach" (Wezel et al., 2015).

In addition, some regions of the world, such as Europe, experience a movement to de-intensify livestock farming (Duru and Hubert, 2009). Indeed, there is a growing awareness in high-income countries of the importance of sustainability and animal well-being, and the dominant intensification pathway is becoming controversial. The evolution to think towards systems that are more respectful of the environment and guarantee animal welfare calls into question these systems (Chambert et al., 2008). De-intensification of pasture systems may involve the decrease of fertilization or the increase of the contribution of pastures in an animal's diet by increasing grazing areas, early pastures during the year, or by practicing delayed grazing (Duru and Hubert, 2009). De-intensification of livestock systems must then be accompanied by changes in food habits and the reduction of animal herds to reach lower levels of consumption of animal-based products (Duru and Hubert, 2009).

Table 1: Comparison of dominant, ecological, sustainable, and agro-ecological intensification pathways

	Dominant intensification	Ecological intensification	Sustainable intensification	Agro-ecological intensification
Historical perspective	Used to describe the high specialisation of farms, mechanization (hardware and automation), use of chemical inputs to increase production and productivity since the 1950s (Fraser, 2005).	First used to describe a double approach which uses all possible measures favouring soil fertility maintenance and establishes the integration of crop and livestock production with forestry on the same parcel of land (Wezel et al., 2015).	First used in efforts aimed to increase the productivity of sub-Saharan agriculture in the 1990s (Dumont et al., 2013).	Used to denote a scientific discipline, a set of agricultural practices, and a social movement that promotes culturally sensitive, socially fair and economically viable farming systems (Dumont et al., 2013).
Quick definition	Increase of production and productivity through the increase of production factors used per unit area, and through the use of external services and inputs (Fraser, 2005).	Intensification of production systems to satisfy the anticipated increase in food demand while meeting acceptable standards of environmental quality and reducing the use of external input, by capitalizing on ecological processes and ecosystem services from plot to landscape scale (Wezel et al., 2015).	Increasing production from existing agricultural land in ways that lower environmental impacts and do not lead to further land conversion or loss of undisturbed natural ecosystems; Efficiency-oriented perspective (Dumont et al., 2013; Wezel et al., 2015).	The goal is to found innovative, productive, integrative and sustainable production systems on the new scientific foundations of agroecology into farm and system management, managing socio-agro-ecosystems, and enhancing their environmental services (Dugué et al., 2011; Wezel et al., 2015).

Livestock diet	Increase of cropland areas for livestock feed, intensification of grasslands for grazing animals.	Reasoned management of pasture areas. Use of grass and legume cultivars selected because of their higher biomass production (Dumont, Groot and Tichit, 2018).	Reasoned management of pasture areas. Increase in grassland area at the farm level. Crop rotations with temporary fodders, mixtures of crops and legumes (Dumont, Groot and Tichit, 2018). Has been criticized for using land inefficiently (Röös et al., 2022).
Land & grassland use evolution	Increase of cropland areas for livestock feed, intensification of grasslands for grazing animals.	Reasoned management of pasture areas. Use of grass and legume cultivars selected because of their higher biomass production (Dumont, Groot and Tichit, 2018).	Reasoned management of pasture areas. Increase in grassland area at the farm level. Crop rotations with temporary fodders, mixtures of crops and legumes (Dumont, Groot and Tichit, 2018). Has been criticized for using land inefficiently (Röös et al., 2022).
Genetic characteristic evolution of animals	Use of genetically improved breeds for increased production.	Use of productive livestock breeds (Dumont, Groot and Tichit, 2018).	Use of breed adapted to the environment and using a set of breeding practices that favour animal adaptations and strengthen their immune systems (Dumont et al., 2013).
Mechanisation and technology	Towards high specialisation and mechanisation.	Technology used to optimize the timing and quantity of inputs applied (Dumont, Groot and Tichit, 2018).	Diversification of draught power uses - reduction of the use of motorised transport. Technology must be accessible to smallholders and is used to monitor every

				component of the system (Dumont, Groot and Tichit, 2018).
Biodiversity	Little diversity, no use of biodiversity and ecosystems for production, linear economy. Often livestock manure discharges in the environment (FAO, 2018a), depending on the economic conditions.	Biodiversity conservation (Wezel et al., 2015). Use of residues and by-products in feed (circular economy) (Dumont, Groot and Tichit, 2018).		Use of diversity (biodiversity, ecosystems, breed), use of residues and by-products in feed (circular economy). Use of diversity to strengthen adaptive capacity and resilience (Dumont, Groot and Tichit, 2018).
Local dimensions	Not taken into account (Gomes et al., 2014).	Not taken into account (Gomes et al., 2014).	Taken into account (Gomes et al., 2014).	Incorporates local dimensions (Gomes et al., 2014).
Social and cultural considerations	Increase of revenues is the main social output considered. Difficulties for smallholders and pastoralists to participate in this intensification (FAO, 2018a).	Lack of key social principles of sustainability (Wezel et al., 2015).		Promotes food sovereignty, local autonomy, self-sufficiency and community control of land, water and genetic resources (Dumont, Groot and Tichit, 2018).

II.1.4. Intensification pathways compared with intensification processes

Intensification pathways have to be differentiated from intensification processes. Intensification pathways are described as an evolution of production systems, characterised by practices, concepts, and principles. Whereas intensification processes can be described as a substitution process where inputs or production factors are substituted by other inputs or production factors leading to intensified systems. Intensification pathways correspond to a higher-level concept that includes intensification processes. Diverse substitutions can happen within intensification pathways.

In this thesis, to study farming systems and their intensification, I chose to focus on intensification pathways. Indeed, intensification pathways allow defining conditions and drivers of change valid in many situations. Intensification pathways allow focusing on the practices and methods of production, which would enable us to assess the impacts of these practices and methods.

Various intensification pathways are presented above (dominant, sustainable, ecological, and agro-ecological), corresponding to a gradient of intensification objectives. This gradient would go from an intensification with a solely economic objective to generate revenues on one side, to an intensification with wider social objectives, contributing to the preservation of the environment and the society as a whole, on the other side.

II.2. IMPACTS OF DOMINANT LIVESTOCK FARMING INTENSIFICATION

The livestock sector is growing rapidly, leading to increased competition with other sectors for natural resources, as well as environmental impacts. It is therefore critical to assess the impacts of livestock on the environment and on the climate from broad socio-economic angles in order to identify environmentally sustainable interventions (McDermott et al., 2010).

II.2.1. Environmental impacts

The main impacts of the dominant intensification of livestock farming on the environment are the following (Bouwman et al., 2005; Herrero et al., 2009; McDermott et al., 2010; Tarawali et al., 2011; Tedeschi et al., 2015; Udo et al., 2016):

1. Air pollution: even if the dominant intensification is often associated with a decrease in GHG emissions per animal and per unit of product, livestock farming systems are still a source of large quantities of GHG: methane (from enteric fermentation), carbon dioxide (from deforestation), and nitrous oxide are the main ones. Overall, livestock constitutes 18 percent of anthropogenic GHG emissions, measured in CO₂ equivalent. Ruminant supply chains are responsible for 80 percent of GHG emissions from the livestock sector (5.7 GTeqCO₂ per year) (Opio et al., 2013). Air pollution is an impact of all intensification pathways;
2. Water pollution (groundwater and surface water) is caused by the poor management of manure, wastewater, and livestock-related waste as well as the concentration of farms on a territory, and the lack of regulations (FAO, 2017). This leads to eutrophication of surface water, leaching of nitrate and phosphorus, transfer of certain pathogens from the soil to groundwater, and the accumulation of high doses of nutrients in the soil affecting the fertility and highly impacting certain ecosystems (e.g., mangroves, wetlands);
3. Biodiversity threats reduce ecosystem functions and impact, directly or indirectly, food and feed production (Dawson et al., 2019). Biodiversity losses are, therefore, threatening agro-ecosystems. As discussed in Rigal et al. (2023), the dominant intensification, especially pesticide and fertilizer use, is the main pressure for the decrease in most bird populations in Europe. The diversity of animal breeds and feed crops can also contribute to increased production of crops (FAO, 2018a).

When measuring environmental impacts, many studies show different results when discussing the impacts of the dominant intensification of production systems. It is also important to know whether we are talking about impacts per product or per hectare of land as the conclusion can change greatly (Bava et al., 2014). Although many studies on South American countries show that dominant intensification, through pasture management and the replacement of grass by concentrated feeds, reduces GHG emissions per unit of product (Mazetto et al., 2015; Cardoso et al., 2016; Huerta et al., 2016), Basset-Mens et al. (2009) showed better environmental performance per unit of product for low input dairy systems in New Zealand, compared to more intensive systems from both a production and local perspective. Similar results were demonstrated by O'Brien et al. (2012) by comparing intensively grazed seasonal pasture-based farming and confinement dairy farming. Nevertheless, measuring the efficiency of land-use changes from the perspective of GHG emissions seems challenging, especially in the case of land-use conversion (Searchinger et al., 2018).

In addition to an important role in global environmental impacts – climate change – livestock systems are often responsible for equally significant negative local impacts such as the eutrophication of water. When considering the environmental burden from a local perspective, impacts are positively associated with the level of intensification (Bava et al., 2014). Bava et al. (2014) evaluated the environmental sustainability of dairy farms in the Alps and found that the best environmental performance was obtained by farms with low animal load rates, low production intensities, and large land availability. That study fails, however, to consider changes in land-use, which could bias results on some indicators.

Deforestation for livestock production, and specifically for pastures, is believed to be responsible for the emission of 2.4 million tonnes of CO₂ (Havlick et al., 2014). Gonçalves da Silva et al. (2017) estimate that a moderate intensification could lead to a decrease in the rate of deforestation (in Brazil), thus a decrease in GHG emissions, thanks to the reduction of land use.

The livestock sector also has a large impact on land-use. Animal feed is a critical constraint for intensification, especially in drier areas (McDermott et al., 2010). An increase in grazing areas and arable land to feed livestock, to the detriment of natural vegetation and arable land used for human food, is one of the main impacts of the increase in the livestock sector (Bouwman et al., 2005; Udo et al., 2016). Livestock farming indeed competes highly with agriculture for land mainly for feed production, resulting in food insecurity, especially in low-income countries in Africa (Mlambo and Mnisi, 2019), even though livestock, and especially ruminants, have the ability to use land that is unsuitable for human food production, through grazing, due to their low fertility or little rainfall (Mlambo and Mnisi, 2019). Dominant intensification is often seen as having positive impacts on land use, as it uses less land than extensive systems (e.g., ranching systems) or other types of intensification pathways (Gonçalves da Silva et al., 2017). But indirect impacts of dominant intensification on land-use also have to be taken into consideration such as the potential increase of animal numbers following the current high demand for animal-based products, and the stimulation of the global economy. One hypothesis that could be made is therefore that, to be sustainable in terms of land use in the future, intensified systems should be associated with a reduction of the demand of animal-based products (Duru and Hubert, 2009).

II.2.2. Livelihood and health impacts

The main impacts of livestock farming intensification on livelihoods and human health are the following (Herrero et al., 2009; McDermott et al., 2010; Tarawali et al., 2011; Havlik et al., 2014; Udo et al., 2016):

- Threats to human health (zoonoses) due to high concentrations of animals in intensive systems on small pieces of land, and the concentration of farms on a territory. These systems can also be the source of emerging diseases (e.g., Nipah, Bovine spongiform encephalopathy, avian influenza) with consequences for public health and food security. Intensive systems could also imply higher veterinary controls and services;
- Reduced micronutrient deficiency among the poorest, and improved child health and development in the case of smallholder intensification;
- Dominant intensification being linked to high demand and consumption of animal-based products, heavy consumption of animal products, and especially red meat and transformed meat, is cited as a cause of cancer, obesity, and heart problems in high-income countries;
- Scaling up and intensification of smallholder production will provide sufficient assets, skills, and income to adopt highly more diversified livelihood strategies and is a possible path to escape poverty;
- Small farms in rural areas provide many co-benefits to producers (e.g., labour force, mobile savings, fertility transfer, production of materials). As farms tend to be highly specialized when they intensify, this diversification might disappear.

II.3. IMPACTS OF INTENSIFICATION ON DETERMINANTS AND PRACTICES OF RUMINANT FARMING

II.3.1. Crop-livestock integration in ruminant farming systems

Mixed livestock-agriculture systems represent around 60 percent of world animal production systems (Dawson et al., 2019). Crop-livestock integration generally has a better level of performance at (Vall, Marre-Cast and Kamgang, 2017; Dawson et al., 2019):

- The economical level, as labour productivity is higher on mixed farms, and the association strengthens the autonomy of farms in inputs and energy while minimizing animal feed

costs;

- The environmental level, as mixed farms retain more carbon annually through the production of organic manure and the storage of fodder. Integrating livestock with agriculture can support adaptation to climate change and mitigation of its effects, in ways that crops or livestock alone are not able to do.

Another form of crop-livestock integration is the commercial exchange of biomass, between farms such as manure or fodder. Conventional intensification led to the specialisation of systems, either in livestock or in crops, as well as a geographical specialisation. The increase in crop-livestock integration constitutes a form of reconnection between agriculture and livestock farming, being economically and ecologically interesting (Martin et al., 2016; Vall, Marre-Cast and Kamgang, 2017), and could constitute a form of intensification (Bonaudo et al., 2014).

II.3.2. The impacts of intensification on ruminant diets

Ruminants consume mainly grass and cereals, and to a lesser extent, cereals and legumes in the form of concentrates (Poux and Aubert, 2018). One-quarter of the world's land surface is used as pasture, and one-third of croplands are used for animal feed production (Robinson et al., 2011). In view of the growing demand for animal products, the pressure on land for animal feeds is increasing, resulting in burdening impacts on natural resources, water, food production, and pastures. As an example, soybean production has increased by 7 percent per year between 1990 and 2010, largely for animal feeds (Robinson et al., 2011).

Dominant intensification is characterised by an increase in the proportion of grains and feeds concentrates (cereals and protein crops) in an animal's diet (Alvarez et al., 2008), implying a drastic decrease in the use of grass, and explaining the decrease in the surface area of permanent meadows in Europe (Poux and Aubert, 2018). Maize and barley are the most widely used cereals but this varies between regions, with maize being predominant in Brazil and the USA and wheat and barley in Europe and Canada (Steinfeld, Wassenaar and Jutzi, 2006).

Other paths of intensification (ecological, sustainable, and agro-ecological intensifications) promote the use of pastures and limit the use of feed concentrates for ruminants (Poux and

Aubert, 2018). The role of residues in feeding ruminants is also a basic supplement in fiber and calories and remains fundamental in mixed livestock-agriculture systems. In these systems, ruminants transform residues into valuable food and non-food goods and services (Steinfeld, Wassenaar and Jutzi, 2006; Mollier, 2019). Residues and by-products represent about one-third of feed consumption by livestock (Bélangier et al., 2019). Despite the importance of residues in mixed systems, their use is declining, caused by the genetic selection of cereals reducing residues and their quality, and more efficient harvesting machines. Intensive farming systems require feeds of very high nutritional quality, and the use of residues as a source of energy is decreasing (Steinfeld, Wassenaar and Jutzi, 2006).

The ruminant diet is one determinant of the production of methane by ruminants (Erb et al., 2017). Indeed, methane emissions depend on: the amounts of organic matter fermented in the rumen and the orientation of rumen fermentations. Methane emissions are therefore positively correlated with a diet rich in fodder. The proportion of metabolizable energy lost in the form of methane decreases significantly when the proportion of concentrates (or cereals) represents more than 40 percent of the ration (Jouany and Thivend, 2008).

II.3.3. The role of breeds in intensification

The use of highly productive breeds in dominant intensification, most often imported from developed countries, tends to replace or be crossed with local breeds (FAO, 2011). These improved breeds certainly have better feed conversion rates, positively affecting growth rates, yields, and reproductive efficiency but also leading to a decrease in genetic diversity (e.g., the Holstein-Friesian dairy breed is present in 164 countries) (FAO, 2011).

Local and well-adapted breeds mixed with productive breeds are favoured in other paths of intensification. The criteria sought are hardiness, adaptation to the environment, and the ability to use forage resources richer in lignin, and more spread over time (Poux and Aubert, 2018).

The proportion of local animal breeds at risk of extinction is increasing worldwide, despite the fact that a high degree of animal breed diversity contributes to increasing quantity, quality, and stability of production and to production efficiency by having mixed breeds (i.e., breeds suitable for co-

production of milk and meat) (Poux and Aubert, 2018; Bélanger et al., 2019). In addition to biophysical risks, species diversification can also reduce the risk associated with economic shocks such as loss of markets for particular products (Bélanger et al., 2019).

II.3.4. Various degree of intensification in pastures management

Grazing and mowing are the most common pasture management activities across the world, covering 28-56 Mkm² or 21-40 percent of the unfrozen land surface with vast differences in intensity. Less than 10 percent of grazed land is grazed with high intensity, around 65 percent with medium intensity, and around 25 percent with low intensity (Erb et al., 2017). The degree of intensification of pastures depends on fertilization and stocking rate and allows to differentiate various pasture types such as cultivated pastures, temporary, permanente, seminatural, rangelands, etc (Poux and Aubert, 2018).

Some intensification pathways tend to increase the use of pasture as well as reasoned pasture management practices with the use of grass and legumes to increase biomass production, such as rotating pastures, and multi-species cover (Delebecque, 2010; Rossi et al., 2014). Globally, animal manure makes up around 10-15 percent of nitrogen inputs to cropland (Smil, 1999; Zhang et al., 2021), and is the dominant source of nitrogen production in the southern hemisphere (Erb et al., 2017). Good pasture management practices are particularly interesting for increasing carbon storage capacity (Mosnier et al., 2013; Rossi et al., 2014), as they can store up to 0.4 to 0.6 CO₂eqGT of carbon (Gerber et al., 2014). In some contexts, grazed pastures can also decrease carbon stocks in the soil, when overgrazed (Erb et al., 2017).

Economically, grazed grass induces low production costs per unit of feed compared to the costs related to the production of corn and/or the purchase of concentrates, even if grass production also induces a cost (e.g., fertilization, management, etc). A meadow rich in legumes, therefore, makes farmers less dependent on fluctuations in market prices and allows better feed autonomy (Grignard, Stilmant and Kohnen, 2013).

II.4. CONCLUSION

The dominant intensification of production systems is a general and large term that can be used to define the concentration of production on fewer and larger units, and the frequent use of external inputs and services. I focused here on higher-level intensification pathways and not on the intensification processes, that describe the substitution of inputs by other inputs.

As seen previously, the different intensification pathways presented above imply various impacts, especially on the environment, and have consequences on production practices. These pathways are situated on a gradient of objective, either driven by a private objective, benefiting solely the farmer (or herder), or a social objective, benefiting the whole community or society. Both objectives coexist with different ratios. This driver leads to two opposed objectives of intensification, a purely private one on one side, and a social one on the other side. The latter is characterised by a choice from the farmer to include social/collective characteristics while intensifying his production. On the contrary, private objective derives from a wish to increase production or productivity to reach a solely private benefit. Intensification is not necessarily associated with an increase in yields but can be associated with an increase in animal numbers or land surface (e.g., Brazilian ranches), corresponding to an enlargement process rather than an intensification one. The private objective includes income generation, manure production, draught power, etc, and the social objective includes a combination of socio-environmental benefits (e.g., nitrogen cycling, decrease in GHG emissions and pollution, social elements) with a private benefit. These two objectives are the extremes of the gradient of intensification objectives.

Although these types of intensification seem interesting to differentiate based on their motors or objectives, it seems that many intensification pathways imply social benefits as well as solely private ones. For example, the long-term decrease of food prices with respect to input prices allowed by dominant intensification, would enable populations to reach food sovereignty, and improve food security and nutrition to some extent, implying a global interest for the populations as well as for the industry and suppliers. On the other hand, some environmental benefits such as nutrient cycling are not seen as a solely social outcome but also a private one (an efficient use implies economic benefits) (Tully and Ryals, 2017; Rütting, Aronsson and Delin, 2018).

To oppose private and social benefits seems therefore difficult as they do not seem mutually exclusive. Hence, the distribution of intensification pathways along a gradient. It seems also

important to specify from which angle these objectives are taken, either from herder, population, government, or industrial perspectives.

The types of intensification pathways presented above will induce contrasting practices in production systems, with differences in an animal's diet, breeds, pasture, and herd management and relation to land, i.e., crop-livestock integration. These practices appear to be well suited to compare production systems and their changes.

Crop-livestock integration is identified by many authors as a good option for improving food productivity and its sustainability (Sekaran et al., 2021) in comparison with specialized systems that would isolate agriculture from livestock herding. Integrated crop-livestock system practices can be seen as an answer to achieving environmental sustainability while enhancing food security and nutrition of populations (Baiyeri et al., 2019; Sekaran et al., 2021). This type of integration, however, is influenced by various regional nuances that could not be extended to larger scales. Indeed, specific conditions inherent to a country or a region are shaping livestock systems and therefore questioning their potential sustainability for the environment and for human populations. A study by Alary et al. (2019) carried out in the Mediterranean region shows that regional contexts imply various trends ranging from high specialization in favorable and harsher areas to diversification and crop-livestock integration in intermediate rain-fed areas. In other areas, regional nuance allows the reconnecting of crop and livestock farming taking advantage of the local context and adapting. Various examples of crop-livestock integration exist in France: small herds grazing in orchards, transhumance through the vines, transhumance between mountain areas and low-lying plains, etc (Napoleone et al., 2019).

The increasing demand for animal-based products might force ruminant farming systems to undergo changes and to intensify to supply this demand without harming the environment. Opportunities, therefore, arise to design and think about the future of ruminant production systems and intensification pathways. Several challenges await in the future, the main ones being climate change and global population growth. Some challenges that need to be addressed when systems intensify are forage availability (Derner et al. 2017) and storage capacities, infrastructure and market capacities, as well as genetic improvement (Derner et al. 2017). Fodder and forage availability are also closely linked to water availability, especially in an environment facing changes in rain patterns and higher temperatures.

To meet the growing demand for animal-based products, intensification of ruminant production systems, whether it is through dominant, ecological, sustainable, or agro-ecological intensifications, seems to be inevitable for the future (Derner et al., 2017), especially in regions where the value of the land is high. As many human communities depend largely on livestock for their livelihoods (mainly multi-functional systems), increasing animal-based production and the productivity of animals and land, without harming the environment, and adapting to the current and future challenges, seem to be a priority. As these challenges appear to depend highly on local characteristics (e.g., feed and water availability, market access, and socio-economic characteristics), thinking about intensification pathways and prospecting about future farming systems at small scales (e.g., national or subnational levels) appears necessary (Haenlein 2001; Laca and Demment 2009).

II.5. BIBLIOGRAPHY OF PART 1

Alary, V., Moulin, C.H., Lasseur, J., Aboui-Naga, A., and Sraïri, M.T., "The dynamic of crop-livestock systems in the Mediterranean and future prospective at local level: a comparative study for South and North Mediterranean systems", *Livestock Science*, 224 (2019): 40-49, 10.1016/j.livsci.2019.03.017.

Alvarez, A., del Corral, J., Solis, D., and Perez, J.A., "Does intensification improve the economic efficiency of dairy farms?", *Journal of Dairy Science* 91, no. 9 (September 2008): 3693-3698, 10.3168/jds.2008-1123.

Baiyeri, P.K., Foleng, H.N., Machebe, N.S., and Nwobodo, C.E., "Crop-livestock interaction for sustainable agriculture" in *Innovations in sustainable agriculture*, ed. Farooq, M., and Pisante, M. (2019), p557-582.

Basset-Mens, C., Ledgard, S., and Boyes, M., "Eco-efficiency of intensification scenarios for milk production in New Zealand", *Ecological Economics* 68, no. 6 (April 2009): 1615-1625, 10.1016/j.ecolecon.2007.11.017.

Bonaudo, T., Bendahan, A., Sabatier, R., Ryschawy, J., Bellon, S., Leger, F., Magda, D., and Tichit, M, "Agroecological principles for the redesign of integrated crop-livestock systems", *European Journal of Agronomy* 57 (2014): 43-51, 10.1016/j.eja.2013.09.010.

Bava, L., Sandrucci, A., Zucali, M., Guerci, M., and Tamburini, A, "How can farming intensification affect the environmental impact of milk production?", *Journal of Dairy Science* 97, no. 7 (July 2014): 4579-4593, 10.3168/jds.2013-7530.

Bélanger, J., and Pilling, D, *The state of the world's biodiversity for food and agriculture*, (Rome, Commission on Genetic Resources for Food and Agriculture, Food and Agriculture Organization of the United Nations: 2019).

Bouwman, A.F., Van der Hoek, K.W., Eickhout, B., and Soenario, I., "Exploring changes in world ruminant production systems", *Agricultural Systems* 84, no. 2 (May 2005): 121-153, 10.1016/j.agsy.2004.05.006.

Bowman, M.S., Soares-Filho, B.S., Merry, F.D., Nepstad, D.C., Rodrigues, H., and Almeida, O.T., "Persistence of cattle ranching in the Brazilian Amazon: A spatial analysis of the rationale for beef production", *Land Use Policy* 29, no. 3 (2012): 558-568, 10.1016/j.landusepol.2011.09.009.

Cardoso, A.S., Berndt, A., Leytem, A., Alves, B., de Carvalho, I., de Barros, S., Urquiaga, S., and Boddey, R.M, "Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use", *Agricultural Systems* 143 (March 2016): 86-96, 10.1016/j.agsy.2015.12.007.

Chambert, T., Defert, F., Galais, B., Peglion, M., and Tracol, C, *Etude d'un sujet de controverse: l'élevage intensif peut-il s'inscrire dans une agriculture durable?*. (Montpellier: Museum Agropolis. *Elevage intensif et agriculture durable*, 2008). 9p.

Clay, N., Garnett, T., and Lorimer, J., "Dairy intensification: Drivers, impacts, and alternatives", *Ambio* 49, no. 1 (January 2020): 35-48, 10.1007/s13280-019-01177-y.

Dawson, I., Park, S., Attwood, S., Jamnadass, R., Powell, W., Sunderland, T., and Carsan, S.,

"Contributions of biodiversity to the sustainable intensification of food production", *Global Food Security* 21 (June 2019): 23-37, 10.1016/j.gfs.2019.07.002.

Delebecque, D., *La nature comme modèle, pour une intensification écologique de l'agriculture* (Montpellier: Centre de coopération international en recherche agronomique pour le développement (CIRAD), 2010).

Derner, J., Hunt, L., Filho, K.E., Ritten, J., Capper, J., Han, G., and Briske, D., "Livestock production systems", in *Rangeland systems: processes, management and challenges*, ed. Briske, David D. (Cham: Springer Nature, 2017), p347-372.

Domingues, J.P., Bonaudo, T., Gabrielle, B., Perrot, C., Trégaro, Y., and Tichitt, M., "Les effets du processus d'intensification de l'élevage dans les territoires", *INRA Productions Animales* (June 2019): 159-170, 10.20870/productions-animales.2019.32.2.2506.

Dugué, P., Vayssières, J., Chia, E., Ouedraogo, S., Havard, M., Coulibaly, D., Nacro, H.B., Fagaye, D., Sangare, M., and Vall, E., *L'intensification écologique: réflexions pour la mise en pratique de ce concept dans les zones de savane d'Afrique de l'Ouest (Bobo-Dioulasso: Partenariat, modélisation, expérimentations: quelles leçons pour la conception de l'innovation et l'intensification écologique?*, 2011). 16p.

Dumont, B., Fortun-Lamothe, L., Jouven, M., Thomas, M., and Tichit, M., "Prospects from Agroecology and Industrial Ecology for Animal Production in the 21st Century", *Animal: An International Journal of Animal Bioscience* 7 (June 2013): 1-16, 10.1017/S1751731112002418.

———, Groot, J, and Tichit, M., "Review: Make ruminants green again – How can sustainable intensification and agroecology converge for a better future?", *Animal* 12 (December 2018): 210-219, 10.1017/S1751731118001350.

Duru, M., and Hubert, B., "Management of grazing systems from decision and biophysical models to principles for action", *Agronomie* 23, no. 8 (2009): 823-842.

Enahoro, D., Mason-D’Croz, D., Mul, M., Rich, K., Robinson, T., Thornton, P., and Staal, S., “Supporting sustainable expansion of livestock production in South Asia and Sub-saharan Africa: Scenario analysis of investment options”, *Global Food Security* 20 (March 2019): 114-121, 10.1016/j.gfs.2019.01.001.

Erb, K.H., Luysaert, S., Meyfroidt, P., Pongratz, J., Don, A., Kloster, S., Kuemmerle, T., Fetzel, T., Fuchs, R., Herold, M., Haberl, H., Jones, C., Marin-Spiotta, E., McCallum, I., Robertson, E., Seufert, V., Fritz, S., Valade, A., Wiltshire, A., and Dolman, A.J., “Land management: data availability and process understanding for global change studies”, *Global Change Biology* 23, no.2 (February 2017): 512-533, 10.1111/gcb.13443.

FAO, Dairy development in Kenya, by Muriuki, H.G. (Rome: Food and Agriculture Organization of the United Nations, 2011), 52p.

———, Water pollution from agriculture: a global review, by Mateo-Sagasta, J., Marjani Zadeh, S., and Turrall, H. (Colombo: Food and Agriculture Organization of the United Nations and the International Water Management Institute, 2017), 35p.

———, World Livestock Transforming the Livestock Sector through the Sustainable Development Goals (Rome: Food and Agriculture Organisation of the United Nations, 2018a), 222p.

———, “Milk production”, Food and Agriculture Organization of the United Nations, 2023, <https://www.fao.org/dairy-production-products/production/en/>.

Fraser, D., Animal Welfare and the Intensification of Animal Production: An Alternative Interpretation, editorial production and design group – publishing management service (Rome: Food and Agriculture Organisation of the United Nations, 2005).

Gerber, P., Steinfeld, H., Henderson, B., Mottet, A., Dijkman, Falcucci, A., Tempio, G., and Opio, C., Lutter contre le changement climatique grâce à l’élevage – Une évaluation des émissions et des opportunités d’atténuation au niveau mondial (Rome: Food and Agricultural Organization of the United Nations, 2014).

Gomes, L.C., Pailleux, J.Y., Dedieu, B., Regina, C., and Cournut, S., "An approach for assessing the ecological intensification of livestock systems", *Environmental Science* (April 2014): 1352-1363.

Gonçales da Silva, J., Ruviano, C., and Ferreira Filho, J., "Livestock intensification as a climate policy: Lessons from the Brazilian case", *Land Use Policy* 62 (March 2017): 232-245. 10.1016/j.landusepol.2016.12.025.

Grignard, A., Stilmant, D., and Kohnen, H., "La gestion intensive du pâturage", CRA-W: Centre wallon de Recherches agronomiques, March 15, 2013, <https://www.cra.wallonie.be/fr/la-gestion-intensive-du-paturage>.

Haenlein, G., "Past, present, and future perspectives of small ruminant dairy research", *Journal of Dairy Science* 84 (2001): 2097-2115, 10.3168/jds.S0022-0302(01)74655-3.

Havlik, P., Valin, H., Herrero, M., Oberstein, M., Schmid, E., Rufino, M., Mosnier, A., Thornton, P.K., Böttcher, H., Conant, R.T., Frank, S., Fritz, S., Fuss, S., Kraxner, F., Notenbaert, A., "Climate change mitigation through livestock system transitions", *Proceedings of the National Academy of Sciences* 111, no.10 (March 2014): 3709-3714, 10.1073/pnas.1308044111.

Herrero, M., Thornton, P.K., Gerber, P., and Reid, R., "Livestock, livelihoods and the environment: understanding the trade-offs", *Current Opinion in Environmental Sustainability* 1, no. 2 (December 2009): 111-120, 10.1016/j.cosust.2009.10.003.

———, Mason-D’Croz, D., Godde, C.M., Palmern J., Thornton, P.K., and Gill, M., *Livestock, land and the environmental limits of animal source-food consumption*, (Stellenbosch: Science Forum CGIAR, 2018).

Huerta, A.R., Guereca, L.P., and Lozano, M., "Environmental impact of beef production in Mexico through life cycle assessment", *Resources, Conservation and Recycling* 109 (May 2016): 44-53, 10.1016/j.resconrec.2016.01.020.

Jouany, J.P., and Thivend, P., "La production de méthane d'origine digestive chez les ruminants et son impact sur le réchauffement climatique", *Management & Avenir* 20, no.6 (2008), 10.3917/mav.020.0259.

Laca, E.A., and Demment, M.W., "Livestock production systems", in *Management of agricultural, forestry, and fisheries enterprises - Volume I*, (EOLSS Publications, 2009).

Martin, G., Moraine, M., Ryschawy, J., Magne, M. A., Asai, M., Sarthou, J. P., Duru, M., and Therond, O., "Crop–livestock integration beyond the farm level: a review". *Agronomy for Sustainable Development* 36, no.3 (September 2016): 1-21, 10.1007/s13593-016-0390-x.

Mazetto, A.M., Feigl, B.J., Schils, R., Cerri, C.E.P., Cerri, C.C., "Improved pasture and herd management to reduce greenhouse gaze emissions from a Brazilian beef production system", *Livestock Science* 175 (May 2015): 101-112, 10.1016/j.livsci.2015.02.014.

McDermott, J.J., Staal, S.J., Freeman, H.A., Herrero, M., and Van de Steeg, J.A., "Sustaining intensification of smallholder livestock systems in the tropics", *Livestock Science* 130, no.1-3 (May 2010): 95-109, 10.1016/j.livsci.2010.02.014.

Mlambo, V., and Mnisi, C.M., "Optimizing ruminant production systems for sustainable intensification, human health, food security and environmental stewardship", *Outlook on Agriculture* 48, no.2 (June 2019): 85-93, 10.1177/0030727019840758.

Mollier, P., "Quelques idées fausses sur la viande et l'élevage", INRAE, December 19, 2019, <https://www.inrae.fr/actualites/quelques-idees-fausses-viande-lelevage>.

Mosnier, C., Boutry, A., Lherm, M., and Devun, J., "Sensibilité des élevages bovins et ovins viande aux aléas selon la place des prairies dans les systèmes fourragers", *Fourrages* 213 (2013): 11-20.

Napoleone, M., Dufils, A., Moulin, C.H., and Lasseur, J., "Different forms of crop-livestock integration. Analysis in the South of France", in *Seminar FAO-CIHEAM of the Sub-Network on Production Systems & Sub-Network on Nutrition*, (eknes, Morocco, 2019), p309-313.

O'Brien, D., Shalloo, L., Patton, J., Buckley, F., Grainger, C., and Wallace, M., "A life cycle assessment of seasonal grass-based and confinement dairy farms", *Agricultural Systems* 107 (March 2012): 33-46, 10.1016/j.agsy.2011.11.004.

Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M., Vellinga, T., Henderson, B., and Steinfeld, H., *Greenhouse gas emissions from ruminant supply chain*, AGA/FAO (Rome: Food and Agricultural Organization of the United Nations, 2013).

Paul, C., Techen, A., Robinson J., and Helmning, K., "Rebound effects in agricultural land and soil management: Review and analytical framework", *Journal of Cleaner Production* 227 (August 2019): 1054-1067, 10.1016/j.jclepro.2019.04.115.

Poux, X, and Aubert, P.M., *Une Europe agroécologique en 2050: une agriculture multifonctionnelle pour une alimentation saine*, Study no. 9/18 (Paris: Iddri-AScA, 2018), 78p.

Rigal, S., Dakos, V., Alonso, H., Aunins, A., Benko, Z., Brotons, L., et al., "Farmland practices are driving bird population decline across Europe", *PNAS* 120 (21) (2023): 10.1073/pnas.2216573120.

Robinson, T., Thornton, P., Franceschini, G., Kruska, R., Chiozza, F., Notenbaert, A., Cecchi, G., Herrero, M., Epprecht, M., Fritz, S., You, L., Conchedda, G., and See, L., *Global livestock production systems* (Rome: Food and Agriculture Organization of the United Nations and International Livestock Research Institute, 2011).

Röös, E., Mayer, A., Muller, A., Kalt, G., Ferguson, S., Erb, K.H., et al., "Agroecological practices in combination with healthy diets can help meet EU food system policy targets", *Science of the Total Environment*, 847 (2022): 157612.

Rossi, A., Pottier, E., Defrance, P., Devun, J., and Granger, S., "Gestion extensive des surfaces fourragères: menaces et risques de disparition des pratiques bénéfiques pour l'environnement", Ministère de l'agriculture et de l'alimentation, 2014, <https://agriculture.gouv.fr/gestion-extensive-des-surfaces-fourrageres-menaces-et-risques-de-disparition-des-pratiques>.

Rütting, T., Aronsson, H., and Delin, S., "Efficient use of nitrogen in agriculture", *Nutrient Cycling in Agroecosystems*, 110 (2018): 1-5.

Salmon, G., Teufel, N., Baltenweck, I., van Wijk, M., Claessens, L., and Marshall, K., "Trade-offs in livestock development at farm level: Different actors with different objectives", *Global Food Security* 17 (June 2018): 103-112, 10.1016/j.gfs.2018.04.002.

Searchinger, T., Wirsenius, S., Beringer, T., and Dumas, P., "Assessing the efficiency of changes in land use for mitigating climate change", *Nature* 564, no.7735 (December 2018): 249-253, 10.1038/s41586-018-0757-z.

Sekaran, U., Lai, L., Ussiri, D., Kumar, S., and Clay, S., "Role of integrated crop-livestock systems in improving agriculture production and addressing food security - a review", *Journal of Agriculture and Food Research*, 5 (2021): 100190.

Smil, V., "Nitrogen in crop production: An account of global flows", *Global Biogeochemical Cycles* 13, no.2 (1999): 647-662, 10.1029/1999GB900015.

Smith, A., Snapp, S., Chikowo, R., Thorne, P., Bekunda, M., and Glover, J., "Measuring sustainable intensification in smallholder agroecosystems: A review", *Global Food Security* 12 (March 2017): 127-138, 10.1016/j.gfs.2016.11.002.

Steinfeld, H., Wassenaar, T., and Jutzi, S., "Livestock production systems in developing countries: status, drivers, trends", *Revue scientifique et technique (International Office of Epizootics)* 25, no. 2 (2006): 12.

Tarawali, S., Herrero, M., Descheemaeker, K., Grings, E., and Blümmel, M., "Pathways for sustainable development of mixed crop livestock systems: Taking a livestock and pro-poor approach", *Livestock Science* 139, no.1 (July 2011): 11-21, 10.1016/j.livsci.2011.03.003.

Tedeschi, L., Muir, J., Riley, D., and Fox, D., "The role of ruminant animals in sustainable livestock

intensification programs”, *The International Journal of Sustainable Development and World Ecology* 22, no.5 (August 2015): 1-14, 10.1080/13504509.2015.1075441.

Tully, K., and Ryals, R., “Nutrient cycling in agroecosystems: Balancing food and environmental objectives”, *Agroecology and Sustainable Food Systems* , 41, no. 7 (2017): 761-798, 10.1080/21683565.2017.1336149.

Udo, H., and Steenstra, F., *Intensification of smallholder livestock production, is it sustainable?*, (Yogyakarta: The 5th International Seminar on Tropical Animal Production, 2010).

Udo, H., Aklilu, H., Phong, L., Bosma, R., Budisatria, I., Patil, B., Samdup, T., and Bebe, B., “Impact of intensification of different types of livestock production in smallholder crop-livestock systems”, *Livestock Science* 139, no.1 (July 2011): 22-29, 10.1016/j.livsci.2011.03.020.

———, Weiler, V., Modupeore, O., Viets, T., and Oosting, S., “Intensification to reduce the carbon footprint of smallholder milk production: Fact or fiction?”, *Outlook on Agriculture* 45, no.1 (March 2016): 33-38, 10.5367/oa.2016.0229.

Vall, E., Marre-Cast, L., and Kamgang, H.J., “Chemins d’intensification et durabilité des exploitations de polyculture-élevage en Afrique subsaharienne: contribution de l’association agriculture-élevage”, *Cahiers Agricultures* 26, no.2 (March 2017): 25006, 10.1051/cagri/2017011.

Wezel, A., Soboksa, G., McClelland, S., Delespesse, F., and Boissau, A., “The blurred boundaries of ecological, sustainable, and agroecological intensification: a review”, *Agronomy for Sustainable Development* 35, no.4 (October 2015): 1283-1295, 10.1007/s13593-015-0333-y.

Williams, T., Hiernaux, P., Fernandez-Rivera, S., Maccarthy, N., Swallow, B., Kirk, M., and Hazell, P., “Crop-livestock systems in Sub-Saharan Africa: determinants and intensification pathways”, *Determinants and intensification pathways* (1999): 132-151.

Zhang, X., Zou, T., Lassaletta, L., Mueller, N., Tubiello, F., Lisk, M., Lu, C., Conant, R., Dorich, C., Gerber, J., Tian, H., Bruulsema, T., Maaz, T., Nishina, K., Bodirsky, B., Popp, A., Bouwman, L., Beusen,

A., Chang, J., Havlik, P., Leclère, D., Canadell, J., Jackson, R., Heffer, P., Wanner, N., Zhang, W., Davidson, E., "Quantification of global and national nitrogen budgets for crop production", *Nature Food* 2, no.7 (July 2021): 529-540, [10.1038/s43016-021-00318-5](https://doi.org/10.1038/s43016-021-00318-5).

TAKEAWAY MESSAGES AND PRESENTATION OF PART 2

Takeaway messages of Part 1

- 1. Intensification is driven by increased demand for animal-based products, caused by population growth, urbanisation, increase in income, and environmental pressure, among others;*
- 2. A private benefit maximization intensification objective is differentiated from a social benefit intensification objective;*
- 3. Understanding intensification pathways helps define contrasting determinants and practices of production systems, which are a good basis to compare production systems;*
- 4. Intensification is a major driver of the evolution of production systems.*

As Part 1 explores various intensification pathways of ruminant farming systems, it sets intensification as a major driver of the evolution of these systems, whereas it is through dominant, sustainable, ecological or agro-ecological intensification pathways, or whereas this intensification pathway is driven by a private objective or by a social/collective objective, or a mix between the two. Having the purpose of studying the intensification of systems and their determinants worldwide, some limitations were discovered in existing production system typologies during this work.

The representation of cattle farming systems' complexity worldwide in the existing literature suffers from several limitations. Firstly, often using the link with crops as an entry point makes the distinction between systems difficult. Systems of the same type can thus be very different from one region to another, some pastoral systems can correspond to very intensive ranching (e.g., in New Zealand) while others correspond to nomadic systems (e.g., in the Sahel region). Likewise, mixed systems cover both intensive European systems and significantly less intensive systems, such as some systems in Asia where crop residues are mostly used, leaving animals to roam the fields after harvest. Secondly, the link between systems (movement of animals) is ignored. For example, calves born and raised in a pastoral system can be sent to finishing feedlots. Ignoring the movements of cattle throughout their life could lead to mistakes in impact assessment, potentially allocating consequences to the wrong system.

Intensification pathways are defined as evolution processes, as seen in Part 1, where practices and determinants of production systems evolve. To study intensification pathways, it appears thus necessary to have a clear picture of the current production systems over the world, and their associated practices, to assess their environmental and socio-economic impacts worldwide. Therefore, to answer the questions: "How to best represent cattle farming systems over the world while considering their multifunctionality, the links between related animals, and their movements between systems? How are intensification pathways treated in existing frameworks?", the following part (Part 2) of the thesis presents an original and conceptual framework for building a typology of current cattle farming systems that can address these questions, overcoming the limitations outlined above, meaning the representation of the multifunctionality of systems and movements of animals, and the representation of intensification pathways in frameworks. This second part of the thesis is based on a literature review and expert knowledge. The conceptual framework is intended to serve as a basis for economic studies along with assessments of the environmental impacts of cattle farming systems at the world scale.

III- PART 2: REPRESENTING CATTLE FARMING AROUND THE WORLD: A CONCEPTUAL AND HOLISTIC FRAMEWORK FOR ENVIRONMENTAL AND ECONOMIC IMPACT ASSESSMENT

This part is based on an article published in *Ruminants* in 2022 under the following citation: Perin, L.; Dumas, P.; Vigne, M. Representing Cattle Farming around the World: A Conceptual and Holistic Framework for Environmental and Economic Impact Assessment. *Ruminants* **2022**, *2*, 360–381. <https://doi.org/10.3390/ruminants2040025>.

It aims at presenting a new framework for representing the diversity and complexity of cattle systems around the world in order to best assess their impacts. To test and evaluate this framework, typologies have been submitted to various experts for their approval thanks to discussions through a questionnaire (see Annexe 1).

The aim of this part is to represent the multifunctionality, diversity, and complexity of systems worldwide, take into account the movements of animals, and to group the activities of related animals together, as done at a smaller scale in the study from Beauchemin et al. (2010). No such study exists at the world scale to my knowledge. Therefore, a need arises for a new method of representation of ruminant farming worldwide to rightfully allocate impacts to their products (milk, meat, manure, animals as insurance and walking capital). With such a framework, all co-produced animals and their co-products can be taken into account.

From this part, I chose to focus on cattle systems and not on ruminants in general. This choice was made to simplify the study and as the large majority of cattle systems can be applied to other species of ruminants. Hence, the framework presented below lacks specific systems applying particularly to other ruminants such as sheep, goats, and camels.

III.1. INTRODUCTION

Cattle farming is a ubiquitous activity worldwide, characterized by strong heterogeneity in production methods and practices, with contrasting bio-physical characteristics and diverse production objectives [1]. Moreover, cattle movements within and between systems are common.

They involve seasonal and nomadic movements and/or geographical movements during the lives of animals; for example, dairy system grass-based weaned calves being sent to a grain-based meat production system to be fattened [2,3]. Such movements determine births, adult reproduction, and replacement of culled animals, as cattle production requires breeding, even when milk is the main product.

Cattle farming systems comprise multiple activities, produce diverse products, such as meat and milk, and generate diverse economic impacts depending on their use of land and inputs, farming intensity and fertility management [4]. In addition to direct financial income from the sale of products, some systems provide many co-benefits such as draught power, walking financial capital, and fertility transfer depending on farming practices and the availability of resources [5–8]. For instance, in many low to middle-income countries, cattle are kept as financial walking capital and insurance for smallholder herders [9]. While fulfilling diverse economic functions, cattle farming also produces various environmental services and disservices, locally and globally.

Cattle farming is associated with the extensive use of natural resources, mainly land, water, and nutrients [10]. In addition, cattle farming, and more globally ruminant farming, is criticized for contributing to greenhouse gas (GHG) emissions, which play a role in climate change. Ruminant supply chains are responsible for 80% of GHG emissions in the livestock sector, accounting for 5.7 GTeqCO₂/year [11], and livestock farming is responsible for 14% of GHG emissions associated with human activities in the world [2,10]; emission intensity differing according to species and product specification (milk or meat production) [2]. Alongside enteric fermentation, which accounts for 46% and 43% of the total emissions in the dairy and beef supply chains respectively, the efficiency by which feed is converted into product is a major driver of GHG emissions, and is determined by the availability and quality of feed and animal productivity [2]. GHG emissions thus depend on local climatic conditions, farming systems, and the associated feed diet [2].

Inadequate manure management in cattle farming, which leads to water pollution and especially eutrophication, is largely determined by variations in animal feed nitrogen richness, pasture management, and herd mobility and management [6,12]. However, in mixed crop-livestock systems, large ruminants often contribute to crop productivity, as manure is used to fertilize the soil and the integration of livestock and crops can enable efficient nutrient recycling [2]. Biodiversity can be impacted through the use of resources for feed rations, the intensity of

management, and the integration of livestock with other agricultural components. Livestock farming practices such as overgrazing, clearing, and ploughing can lead to soil compaction and ecosystem fragmentation [10]. However, most effects on biodiversity are indirect, such as deforestation, GHG emissions, water pollution, and increase of international trade. Positive impacts on biodiversity, such as maintenance of local grassland biodiversity, as well as maintenance of semi-natural vegetation agro-ecological infrastructures, can happen when cattle are not managed too intensively [13].

As cattle production systems have a significant environmental impact at both local and global levels, it would be interesting to be able to compare these systems. Given the difficulty of modeling the complexity of cattle production systems at a global scale, the most viable option would be to describe and classify them based on their production methods and practices. Furthermore, cattle production systems are not isolated, and interactions exist between them. Cattle frequently move across systems [14], for instance calves are born in dairy grass-based systems and are then fattened in feedlots. These movements, combined with the specific characteristics and constraints of animal production and co-production, pose challenges for environmental impact assessments, especially concerning GHG emissions. To assess these impacts, grouping activities related to cattle and their progeny as in [15], where cow-calf ranching and beef feedlot finishing are represented together, appears to be a relevant approach. The task is therefore to find the right boundaries, through lineage groups, while avoiding a level of complexity that makes modeling and assessment difficult. Environmental impacts targeted are GHG emissions, nitrogen pollution (N balance), and potentially biodiversity while economic impacts are returns, meaning the difference between costs and production.

Making sense of the complexity of relations between cattle systems across the world in order to set the stage for further studies comparing their overall benefits or downsides (economic, environmental, social) at a large scale is a major undertaking. It requires the diversity and complexity of cattle systems to be described, with a clear delimitation of these systems, while grouping and simplifying them [10,16,17]. To achieve this aim, typologies resulting from a holistic approach based on three main levels of analysis are developed in this paper and tested on cattle systems in Kenya. The framework is based on three linked concepts:

- Management type (MT), defined as a set of production methods and farming practices. The associated typology is partly based on existing typologies [18–21] used to describe and

classify the diversity of cattle production systems based on farming practices; animal profiles, which divide an animal's life into phases based on age and sex, to obtain homogeneous feed use and animal characteristics to simplify environmental impacts analysis and computation; information on location and climate is needed for the analyses performed on animal profiles;

- Lineage group (LG), which groups the different phases of an animal from birth to death and makes it possible to address breeding and herd renewal constraints as well as animals' transition between MTs. Lineage group is the functional unit used for the final assessment of economic returns and environmental impacts, which should be determined by aggregating values computed at the animal profiles.

III.2. MATERIALS AND METHODS

III.2.1. Conceptual framework

Highlighting the importance of the choice of farming practices and methods is at the core of this work. We therefore decided to introduce the notion of management type, which is characterized by specific criteria, including farming outcome, farming objective, general feed diet, herd management and mobility, pasture management intensity, crops and other agricultural component integration, and manure management (see Figure 2). These practices both influence GHG emissions and nitrogen use and impact landscapes, livelihoods, and costs. An animal could spend its entire life in the same MT, or could experience different MTs as it passes from one phase to another. The MT of reproductive cattle influences breeding choices, such as natural breeding or insemination. Finally, some animals are only present in particular MTs, such as oxen which are not produced in Mts specialized in dairy or meat production.

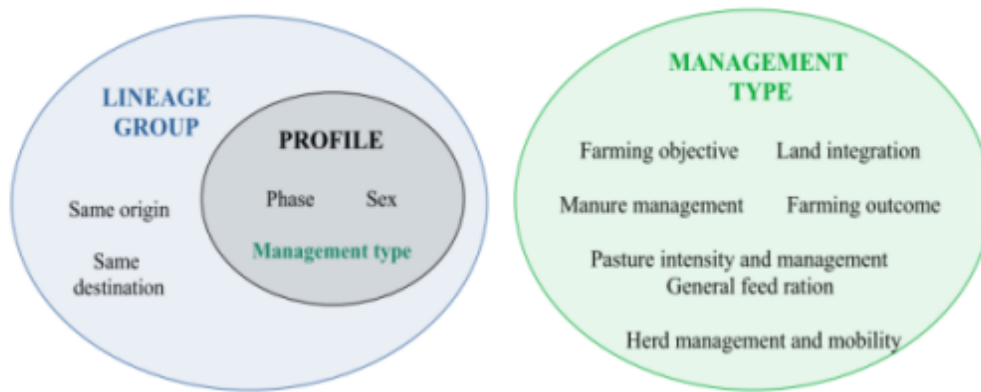


Figure 2: Description of management types, lineage groups, and animal profiles

MT is used here instead of systems to avoid using a word with multiple definitions. A livestock system, as described by [22], is defined by elements in interaction, including animal species, resources, techniques, and practices implemented by a community or by a livestock herder, to meet needs by developing natural resources through animals. Other authors use a typological approach to define systems based on their similarities [18]. Systems, in that case, are defined as groups of farms with similar structures and functions that are expected to fulfil similar production functions. To further simplify the assessment of resource use and environmental impacts within and across MTs, the life of an animal is subdivided into various profiles. Each animal profile is defined as a specific phase and sex (see Figure 2). An animal's life is therefore divided into phases depending on its age and reproductive status, distinguishing pre-weaning calves and young bovines after weaning, followed by young bulls and heifers having reached sexual maturity, and cows and bulls reared for reproduction and oxen, when relevant. Each MT is therefore composed of several animal profiles that are homogeneous in terms of practices, but concern different phases and sexes. In particular, a cattle's profile combined with its MT determines the diverse functions that it will fulfil, such as reproduction, milk or meat production, herd renewing, fattening purpose or draught power, as well as feed rations. This makes it possible to divide the life of an animal into homogeneous units and account for the environmental impacts at each stage of life, in particular through modeling.

The location of an animal profile and the associated climate, although it does not directly enter the MTs description, should be taken into account in the modelling of animal profiles. The animal profile is the unit at which the impacts are conveniently modeled and assessed, and MTs are

considered as major drivers of impacts. However, to assign impacts, all cattle profiles and their co-produced animals (animals from the same origin) are also regrouped in a lineage group, which is defined by a set of cattle profiles coming from the same mother and going through the same MTs. A lineage group is often seen as a linear relationship oriented from parents to children. In this case, an lineage group is a set of animal profiles of parents and children in a stationary state that are consistent with rates of offspring production and replacement of adults.

Notions of management types, animal profiles, and lineage groups differ from notions of herds and farms. Herds are groups of animals kept together that can be composed of diverse animal profiles, and can even group together animals of different species. A farm is an entity used for cultivation and livestock production. A farm can be composed of one or several herd(s). In general, farms are characterized by a homogenous management type, but this is not necessarily the case. It is possible, for example, to have both an intensive dairy management type, using high levels of concentrates, and a grass-based extensive management type for young bovines on the same farm and for the same herd but involving different animal profiles. It is also possible, though probably rare, to have different management types for a given animal profile within a farm. It should always be possible to decompose a farm or a herd into animal profiles, each associated with a management type. Lineage groups can spread over multiple farms, as is the case in the grass-based with finishing feedlot lineage groups in the USA and Europe. A lineage group also can be entirely contained within a single farm, as is usual in ranches specialized in meat based solely on grass, which are common in South America.

The division of the life of an animal into profiles allows one to better trace the movement of cattle between management types. As an example, a calf born and first raised on a pastoral dairy farm can then be transferred to a fattening feedlot to finish its life. A change of MT can potentially imply a change in geographical location. Lineage groups are considered as units at which impacts evaluated at the animal profile level should be aggregated, as it regroups co-produced animals from the same origin. In the framework we propose, the analysis and computation unit, the animal profile, is therefore distinguished from the final assessment functional unit, which is the lineage group.

We have introduced in this framework three levels of analysis: management types, animal profiles, and lineage groups. To analyze these levels, we organize each of them into typologies. A typology

of cattle farming captures its complexity by organizing farms into quite homogeneous groups to generate a simplified representation of its diversity [23]. Cattle farming management types may be classified according to multiple criteria and many possible combinations of criteria can be used [21,24]. Although typologies never capture the complete image of reality, they are regarded as a crucial factor in the description and analysis of various cattle farming systems, revealing productivity and future potential for growth [21] and intensification. Most of the time, typologies focus on the management type scale in addition to climatic conditions, but only treat the lineage group scale implicitly at large scales [16–18].

III.2.2. Methods for management type typology

Criteria used in the management types typology can be regrouped into seven main categories. Two of them do not appear explicitly in the decision tree (see Figure 3) as they are implied by other criteria:

1. Breed. Management types are characterized by specialized or multi-functional breeds. The latter includes breeds used for meat and milk production (without any type of specialization in one of these products), fertility transfer, draught power, etc. Cross-breeds (bos indicusXbos taurus) would also add value to production having higher outputs and lower impacts on resources use under certain conditions (e.g., cross-breeds in semi-arid areas have higher output than local or exotic breeds);
2. Farming objective. We differentiate management types with a multi-functional objective (e.g., meat/milk production, draught power, fertility transfer, generation of revenues, etc.,) and those with a production and revenue generation objectives. These objectives depend in particular on the availability of resources (water, feed, financial capital) and influence the age at which cattle are slaughtered;
3. Feed. Diet is an important criterion to take into account as it impacts animal production and is linked with pasture management, on-farm crop production, external feed purchases, and the use of waste and residues. Waste and residues use, as well as the use of the sides of roads and fields, are part of the typology as using these sources of feed renders it possible to spare natural resources. Feed rations depend on the animal profile and the management type. Diet impacts GHG emissions through digestibility, but also through crop feed production emissions and other environmental impacts and land use.
4. Relation to land:

- Intensity of pasture management, described as intensive (i) or extensive (e) in Figure 3. Pasture management covers fertilization, grazing practices (rotational, seasonal), and stocking rates. Grass resource management is closely linked with herd mobility and nomadism. Some management types are either extensive or intensive by definition, others are subdivided into extensive and intensive pasture management corresponding to high stocking rate, fertilization and a lower mobility for the latter;
 - Integration/relation to crops or other agricultural components (e.g., forests, pastures). This criterion has an impact on manure management and nutrient cycles, but also herd mobility and health, and diet composition. In the case of a multi-functional objective combined with crop integration, oxen may be present for draught power.
5. Herd management. Herd health and reproduction practices such as artificial and natural insemination are included in herd management. Cattle breeds are important to take into account due to their different impacts on farming objectives and production, as well as their environmental impacts. We consider herd management to be implicit to the breed, farming objectives and pasture management intensity considered, and therefore does not appear in the decision tree of Figure 3;
 6. Herd mobility. Herd mobility varies according to the management type considered, grazing management, resources availability (grasslands, forests), and carrying capacity, and differentiates mainly between nomad and sedentary management types, the latter reflecting a management based on grazing pastoralism along with a confinement of animals in barns when the weather dictates. It impacts grassland biodiversity, soil compaction, manure management, and nutrient and nitrogen cycles. Herd mobility also includes seasonal movement of animals such as nomadic pastoralism.
 7. Manure management. Nutrient and nitrogen cycles are closely linked to herd mobility as well as pasture management. Manure management ranges from direct and uncontrolled deposition on pastures by animals to manure collection and storage in various forms: solid, liquid or slurry. This criterion does not appear in the decision tree (see Figure 3) as it is considered to be implicit to herd management and mobility.

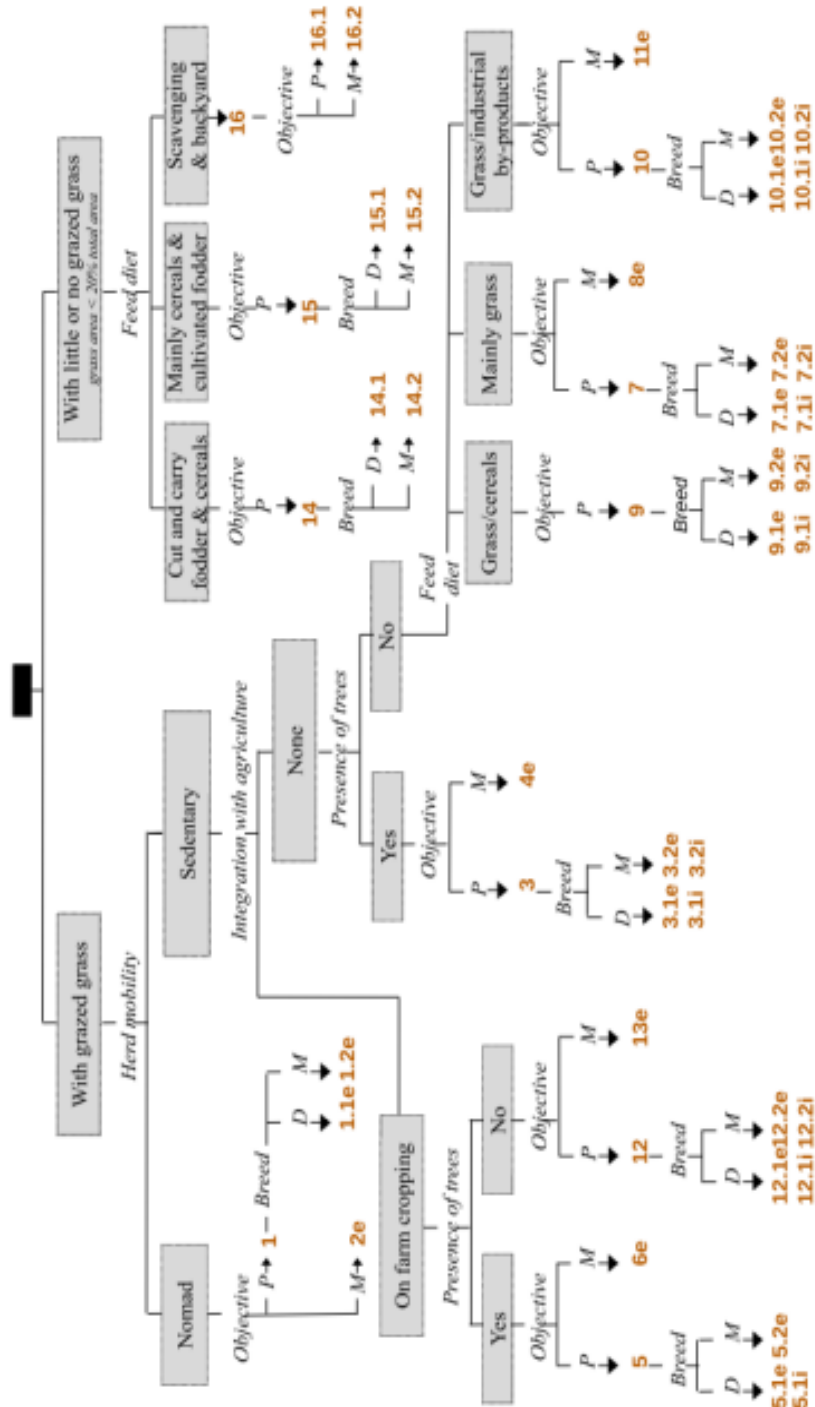


Figure 3: Decision tree for the construction of cattle management types typology based on criteria (D: dairy breed, M: meat breed, P: production, M: multi-function, i: intensive pasture management, e: extensive pasture management)

Geographical location and climate are considered as external factors, in contrast with other typologies based on the FAO agro-ecological zones (arid, humid, temperate) [25] which include climate as a criterion. Climate and location are taken into account in the framework, however, as they should be used for animal profile modelling. Climate is important because it influences the performance of each management type, in particular through net primary production (NPP) and on

farm feed yields. All management types could potentially and theoretically be based all over the world. In practice, environmental (temperature, NPP) and socio-economic (access to markets and credits) contexts favor one management type over another. Climate certainly influences the management type adopted and has consequences on some of the practices used through grass quality and yield, herd mobility and management (e.g., time spent indoors and outdoors), and pasture management (e.g., herd mobility through grazing patterns). It could even be that some management types cannot exist in certain regions of the world because of climatic constraints.

III.2.3. Methods for lineage group typology

Lineage groups regroup all co-produced animals, meaning all animals from the same origin, and going through the same management types. They allow one to characterize the trajectory of an animal over its life, including transitions between management types and geographical location. Understanding connections between animal profiles and the progression of animals from one management type to another are therefore needed to describe lineage groups. Relations between profiles are similar for all lineage groups as they have similar breeding constraints for calf production and replacement constraints for adults. A generic herd structure can therefore be used to link animal profiles together (see Figure 4).

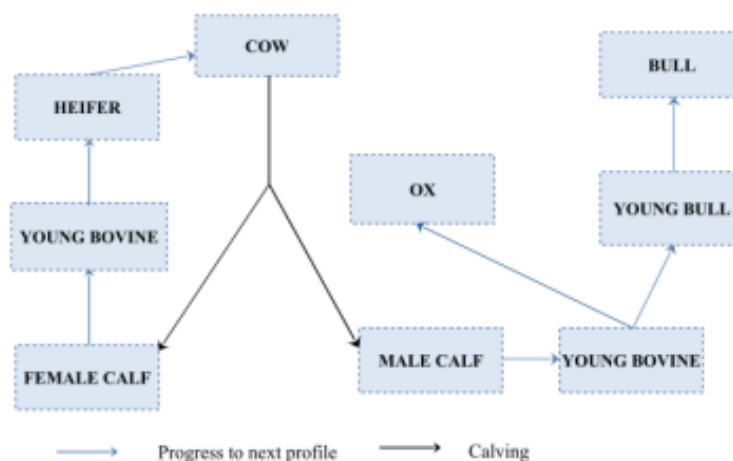


Figure 4: Cattle herd structure [26]

Lineage groups are classified using movements between management types. While evolving towards another profile (see Figure 4), cattle can progress towards another management type or stay in their management type of origin. When progressing toward other management types, possibilities are restricted by considering that cattle that are not destined for reproduction

preferentially move toward management types with more digestible feeds for fattening. Therefore, non-reproductive cattle born in feedlots and similar management types with a diet based on cereals and cultivated fodder stay in feedlots, while non-reproductive cattle originating from grass-based management types can move to specialized fattening feedlots or veal calf farming. In some cases, reproductive female cattle can also progress to other management types before returning to their origin, as it is common in New Zealand for example, where heifers from intensive dairy management type are reared in less productive areas before returning to their management type of origin [27].

Based on herd constraints and farming choices, six lineage groups were identified (see Figure 5) using criteria described below:

- The fate of non-reproductive cattle. This fate (culled or fattened) discriminates between lineage groups based on whether or not non-reproductive cattle (cattle that are not destined for reproduction) stay in their management type of origin.
- Location. For non-reproductive cattle progressing away from the management type of origin, there is a distinction between local and distant location from the management type of origin. A local management type is located at a close distance from the management type of origin while a distant management type is located at a long distance from the management type of origin. Local or distant location affects time and costs of cattle transport, contributing to environmental and economic impacts.
- In addition, each reproductive female cattle can pass through a specialized management type as heifers before returning to their management type of origin and participate in herd renewal/milk production as cows.

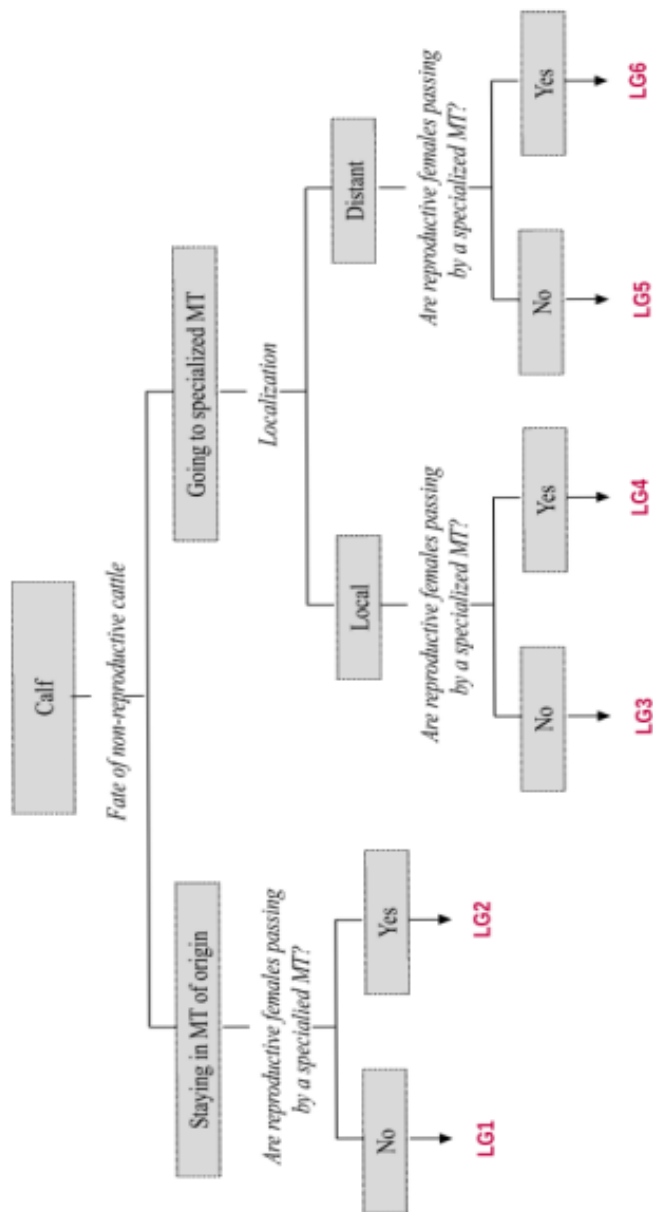


Figure 5: Decision tree for the construction of the lineage group typology

III.3. RESULTS

III.3.1. Management type typology

The typology presented is based on existing cattle farming systems from all over the world. Based on the decision tree in Figure 3, the 16 management types identified are presented below and are described in more detail in Table A1 in Appendix A:

- 1.1.e/1.2e—Traditional pastoral dairy/beef management type with a production objective;
- 2e—Traditional pastoral management type with a multi-functional objective;
- 3.1.e & 3.1.i/3.2.e & 3.2.i—Sylvo-pastoral dairy/beef management type with a production objective;
- 4e—Sylvo-pastoral management type with a multi-functional objective;
- 5.1.e & 5.1.i/5.2.e & 5.2.i—Agro-sylvo-pastoral dairy/beef management type with a production objective;
- 6e—Agro-sylvo-pastoral management type with a multi-functional objective;
- 7.1.e & 7.1.i/7.2.e & 7.2.i—Grass-fed dairy/beef management type with a production objective;
- 8e—Grass-fed management type with a multi-functional objective;
- 9.1.e & 9.1.i/9.2.e & 9.2.i—Externally complemented grass-fed dairy/beef management type with production objective;
- 10.1.e & 10.1.i/1.2.e & 10.2.i—Grass-fed dairy/beef management type, using industry by-products with a production objective;
- 11e—Grass-fed management type, using industry by-products with a multi-functional objective;
- 12.1.e & 12.1.i/12.2.e & 12.2.i—Internally complemented grass-fed dairy/beef management type with a production objective;
- 13e—Internally complemented grass-fed management type with a multi-functional objective;
- 14.1/14.2—Zero-grazing dairy/beef management type with grass, with a production objective;
- 15.1/15.2—Zero grazing dairy/beef management type without grass, with a production objective;
- 16.1/16.2—Scavenging & backyard management type with a production/multi-functional objective.

III.3.2. Animal profiles

Male and female calves first belong to the milk-fed pre-weaning phase. Cattle are born and raised with the mother until weaning, or separated from the mother and fed with milk powder in intensive management types. This phase is followed by a post-weaning phase called the young bovine phase. Female cattle leave that phase to become heifers as soon as they are ready to reproduce to then become a cow (after the first calving). Males able to reproduce become young bulls and then bulls if they are dedicated to breeding, or an ox if they are castrated. The age at which an animal belongs to a particular phase depends on the management type, in particular on the farming objective (specialized or multi-functional) as well as the specific diet, which influence animals' growth rates and sexual precocity. The animal profile together with the management type determines an animal's feed ration and function, and is a convenient unit for the analysis of feed use, environmental impacts, and costs. Typical ages for the different phases depending on the corresponding management type are shown in Table A2 in Appendix A.

III.3.3. Lineage group typology

From the LG decision tree (see Figure 5), we identified six lineage group categories:

- LG1—All cattle staying in their management type of origin

All reproductive and non-reproductive cattle are born and fully reared in their management type of origin.

- LG2—Cattle staying in their management type of origin with reproductive females going through another management type

Non-reproductive cattle stay in their management type of origin while reproductive female cattle go through another management type before returning to their management type of origin.

- LG3—Non-reproductive cattle progressing to a local management type

Non-reproductive cattle are born in one management type before progressing to a local management type to be reared until slaughter. Reproductive cattle stay in the management type of origin.

- LG4—Non-reproductive cattle progressing to a local management type with reproductive females going through a specific management type

Non-reproductive cattle progress to a local management type for fattening, while reproductive female cattle go through another management type, typically less intensive, before returning to the local management type.

- LG5—Non-reproductive cattle progressing to a distant management type

Non-reproductive cattle are born in one management type before progressing to a distant management type to be reared until slaughter. Reproductive cattle stay in the management type of origin.

- LG6—Non-reproductive cattle progressing to a distant management type with reproductive females going through a fattening management type

Non-reproductive cattle progress to a distant management type and reproductive female cattle go through another management type before returning to a local management type.

III.4. CONTEXTUALISATION AND COMPARISON WITH EXISTING TYPOLOGIES: CASE STUDY OF KENYA

Livestock production in Kenya contributes about 13.4 percent (USD 3.1 billion) to agricultural value added with cattle being the most important contributor [28]. Farmers raise cattle, both beef and dairy animals, in different production systems [29]. Dairy animals represent around 25% of all cattle population with an estimated population of 4.5 million cows in 2018 while beef animals represent around 75% of all cattle population with an estimated population of 14 million animals [29]. The herd structures in these different systems are not well described in publications, in particular the age of cattle in the different systems is not described.

III.4.1. Dairy production systems in Kenya

Kenyan dairy production systems are characterized either as sedentary or pastoralist [30]. They are divided into three general categories: grazing systems (GS), zero grazing systems (ZGS), and semi-zero grazing systems (SZGS), corresponding to different levels of external input uses by [30] (see Table 2) while [29] divide dairy production systems in intensive, semi-intensive and extensive systems. Even though both typologies are certainly similar to each other, they sometimes differ in inputting systems to categories. For example, systems classified as extensive “controlled” by [28], with cattle supplemented with high quality fodder and commercial concentrate correspond

better to the semi-intensive category in [30].

The three categories described by [30] are subdivided into mixed and solely livestock systems, as well as medium-to-large-scale (more than four cows) and small-scale systems (four or less cows) [31–33]. Low intensity middle-to-large scale mixed systems and solely livestock systems are described as grazing based, and are in the same regions. The difference between those systems seems to correspond to the level of specialization only, and not to differences in livestock management nor in integration with crops [30]. Similarly, low intensity small scale systems are based on grazing only and not easily differentiated.

Small-scale dairy farmers, also called smallholders farmers, are dominant in Kenya, owning over 80 percent of the dairy cattle national herd, and undertaking more than half of the country's milk production [30,34,35]. Large dairy farms represent the remaining 20 percent of the dairy cattle national herd, often from indigenous origin [34,36]. With the additional distinctions introduced by [30], mixed/solely livestock and small-scale/large-scale, the dairy farming system typology is more precise but is, however, lacking quantified shares for these distinctive systems.

In zero-grazing units, cattle are stall-milked and stall-fed [31], using cut- and carry fodder [34] as well as concentrates and alternative supplements [33]. Cattle are not grazing. ZGS are often associated with improved breeds for their higher yields, with high external input levels [30] and high level of management [28]. Small-scale zero-grazing units represent 34.5% of the dairy cattle population in Kenya whereas large-scale zero-grazing units represent 6.7% [28]. ZGS practices correspond to management types 14.1, 15.1, and 16.1 in the typology, depending on their association with agriculture and on the scale (see Table 2). Scavenging and backyard management type with a production objective (16.1) is mainly present in urban and peri-urban areas, close to large consumption centers, where animal breeding is not mixed with cropping mostly due to land unavailability. Zero grazing with grass dairy management type with a production objective (14.1) corresponds to ZGS mixed with fodder production, including cut and carry grass to stall-feed cattle. Zero grazing dairy systems without grass (15.1) are not common in Kenya and should correspond to large-scale dairy farms only. Cattle are kept indoors in those management types.

In semi-zero grazing systems, cattle are partly confined, mixing grazing during the day and confinement at night with feed supplementation [28]. They represent 47.6% of the dairy cattle

population in Kenya [28]. SZGS corresponds to various management types of the typology depending on the scale and on the association with crops. Mixed SZGS correspond to internally complemented grass-fed dairy management types with a production objective (12.1.e & 12.1.i) for medium-to-large scale farms and with a multifunctional objective (13e) for small-scale farms. Solely livestock SZGS correspond to externally complemented grass-fed dairy management type with a production objective (9.1.e & 9.1.i), a sedentary management type without integration with agriculture or trees where grazed or cut grass is the main feed for cattle. Other feed is produced off-farm. Share of extensive pasture management (e) and intensive pasture management (i) practices are difficult to characterize here as it depends on each farmer's own management decisions (grazing in paddocks, natural or managed pastures, fertilization, etc.). To our knowledge, the grazing intensities are not reported in any document, and the link between more detailed drivers of pasture management than the management types is not described either.

Table 2: Description of dairy production systems in Kenya [28,30,31,34,36], G = grazing; SZG = semi-zero-grazing, ZG = zero-grazing

		Small-scale - solely livestock	Small-scale - mixed	Medium- to large-scale - solely livestock	Medium- to large-scale - mixed
G	Corresponding MT	2.e	/	7.1 or 8	12.1.e or 7.1 or 8
	Controlled or uncontrolled (FAO typology)	Uncontrolled	/	Both controlled and uncontrolled	Controlled
	Farming objective	Multiobjective (dairy, meat, blood, manure, draft power, walking financial capital)	/	Multiobjective (self-consumption, manure, walking financial capital) and also market oriented, generation of income	
	Feed	Grass (natural)	/	Grass (natural)	Grass + crop residues, fodder, small amount

				concentrates [27]	
Average herd size	Less than 10 cows		Up to 50 cows (in controlled grazing systems [27])		
Breed	Local - Zebu purebred or crossbred				
Average milk production	Between 2 and 11 L/cow/day				
Market access	Poor market access, mainly for self-consumption or milk sells directly to consumers				
Land availability	High				
Intensification level	Low (extensive feed, mostly local breeds, no AI, large pieces of land)				
Location	Pastoralist areas	/	North Rift, South Rift	Rift Valley	
SZG	Corresponding MT	/	13.e	9.1.e & 9.1.i	12.1.e/i
	Farming objective	/	Multiobjective	Market oriented, generation of income	
	Feed	/	Grass (natural and improved pastures)+ fodder/silage + post-harvest grazing (on-farm)	Grass (natural and improved pastures) + supplements (off-farm)	Grass (natural and improved pastures) + supplements (on-farm)
	Average herd size	/	1-3 cows	More than 3-20 cows	
	Breed	/	Exotic - Fressian crossbred or Ayshire crossbred		
	Average milk production	/	Between 2 and 10 L/cow/day		
	Market access	/	Medium market access, milk sold directly to consumers or cooperatives		
	Land availability	/	Medium		
	Intensification	/	Medium (stall-fed and stall-milked, cross-breeds, little		

	level		use of AI, medium pieces of land)		
	Location	/	Central Rift, Western Region, Eastern Region	Central Rift	Central Rift, South Rift
ZG	Corresponding MT	16.1	14.1	16.1	15.1 or 14.1
	Farming objective	Market oriented, generation of income			
	Feed	High quality residues + concentrates	Cut and carry fodder, including grass + cereals + little concentrates	High quality residues + concentrates	Fodder + concentrates + cereals
	Average herd size	1-3 cows (rural) & 7-8 cows (urban)		More than 15 cows	
	Breed	Exotic - Fressian or Ayrshire mainly			
	Average milk production	15-30 L/cow/day			
	Market access	Market oriented, milk sells to traders or dairy cooperatives			
	Land availability	Scarce			
	Intensification level	High (intensive feed, small pieces of land, exotic breeds, AI)			
Location	(Peri)-urban	Central Region, Central Rift	(Peri)-urban	Central Region, Central Rift, South Rift	

Grazing systems are divided in two types in the FAO typology [28]:

- “Uncontrolled” GS, where local breeds are roaming on communal lands (e.g., Maasai lands in South Rift Valley), with unimproved pastures and limited supplementation. They represent 5.2% of the dairy cattle population in Kenya. This category corresponds to the grazing pasture based systems with low external input levels [30];
- “Controlled” GS on private lands, fenced and sometimes divided in paddocks, with improved or crossed breeds, use of artificial insemination (AI), improved grazing practices

supplemented with high quality fodder and commercial concentrates. They represent 5.9% of the dairy cattle population in Kenya. This category corresponds better to medium input level systems in [30];

GS also correspond to various management types of the typology depending on the scale, the external input used, and on the association with crops. Mixed controlled GS as described in the FAO typology correspond to internally complemented grass-fed dairy management types with a production objective (12.1.e) for medium-to-large scale farms. It is therefore difficult to differentiate mixed GS with mixed SZGS in the management types typology as the farming objective is the same and feed diet is similar. The main difference being that cattle are stall-fed and stall-milked at night in SZGS while cattle are kept outdoors constantly grazing in GS. Stall-feeding might help farmers to feed specific ration to each cattle, to meet the specific animal needs to reach the optimum milk production. Solely livestock GS correspond to traditional pastoral dairy management type with a production objective (1.1.e) or grass-fed dairy management type with a production objective (7.1) or a multi-functional objective (8) depending on the scale and the mobility type. The first one corresponds to "uncontrolled" GS, as they are nomad management types with high cattle mobility in search for feed resources, whereas the two latter can correspond to either "controlled" or "uncontrolled" GS as the distinction is not clear.

Few elements are available in the literature concerning movements of cattle. In Kiambu county, dairy farms are described as « flying herds » because of sourcing replacement heifers from the Rift Valley where infrastructure is better developed [30]. This situation corresponds to LG2 or LG4, with reproductive females going through a specific management type. Dairy calves can move to intensive production systems to be fattened for meat production, but without specific mention of their management types of origin [28]. It is not clear if beef cattle in other meat production oriented beef systems could come from dairy systems or not.

III.4.2. Beef cattle production systems in Kenya

The beef industry is the largest contributor to agricultural GDP in Kenya, at around 35 percent. Beef industry is especially valuable (income and employment) in the arid and semi-arid lands, where beef production from pasture is the main economic activity [28].

Beef production systems in Kenya are classified as [28] (see Table 3):

- Extensive grazing systems (both pastoralism and ranching) representing 56.4% and 5.3% of beef cattle population in Kenya respectively where cattle are born and reared in the same management type (LG1) or progressing to a local management type (LG3);
- Semi-intensive grazing systems (agropastoralism) representing 37.9% of beef cattle population where cattle are born and reared in the same management type (LG1) or progressing to a local management type (LG3);
- Intensive systems (feedlot) representing 0.3% of beef cattle population where cattle are either born and reared in the same management type (LG1) specialized in beef breed or often coming from another management type to be fattened for a few months before slaughter, either in a local management type (LG3) or a distant one (LG5).

Table 3: Description of beef production systems in Kenya [28]

Extensive	Pastoralism	Corresponding MT	1.2e
		Production objective	Income generation (meat or live animals) + manure
		Feed	Grass (natural)
		Average herd size	50 heads
		Breed	Indigenous - Zebu
		Average meat production	125 kg/head
		Market access	Meat sold directly to consumers or live animals in markets
		Land availability	High
	Ranching	Corresponding MT	7.2.e&7.2.i
		Production objective	Income generation
		Feed	Grass (natural and cultivated) + little supplements
		Average herd size	150 heads
		Breed	Crossbreeds
		Average meat production	240 kg/head
Market access	Local niche market and international market		

			(export)
		Land availability	High
Semi-intensive		Corresponding MT	6e
		Production objective	Income generation (+ manure)
		Feed	Grass + crop residues and by-products (on-farm)
		Average herd size	10-12 heads
		Breed	Mainly crossbreeds and pure exotic breeds
		Average meat production	240kg/head
		Market access	Medium – animals sold to middle-men in local markets
		Land availability	Medium
	Intensive		Corresponding MT
		Production objective	Income generation
		Feed	Highly nutritious fattening diet
		Average herd size	Few dozen for dairy breed and several hundreds for beef breeds
		Breed	Crossbreeds or exotic beef breeds
		Average meat production	/
		Market access	High – prime beef markets (urban areas or export)
		Land availability	High

Pastoralism extensive systems are subsistence systems with low inputs level. Pastoralism systems are nomadic, where cattle are moving in search for feed and water, often leading to conflicts over resources [28]. Pastoralism systems correspond to traditional pastoral beef management type with a production objective (1.2.e) in the typology. Ranching extensive systems are mainly turned toward commercialization and export markets [28]. Ranching systems correspond to grass-fed beef management type with a production objective (7.2.e & 7.2.i) where cattle are mainly grazing without association with agriculture, with potential partial confinement overnight or during some period of the year.

Semi-intensive systems are mixed systems with low inputs level and subsistence oriented, keeping livestock, and growing crops. Crop residues and by-products are used to feed cattle while animals produce manure and draught power. Cattle often graze on communal lands or in paddocks for agropastoralists with large pieces of land [28]. These systems correspond to agro-sylvo-pastoral beef management type with a multi-functional objective (6e) in the typology, where cattle are associated with rain-fed agriculture, including production of fodder.

In intensive systems, cattle are kept for a short period of time (3 months). Capital and labor intensive, some intensive systems focus on fattening dairy culls and dairy bull calves while others focus on fattening beef breeds [28]. Intensive beef systems correspond to feedlot fattening management type with a production objective (14.2) where cattle are fed with highly nutritious feed for fattening purpose and can be kept outdoors or indoors in dry climate.

III.4.3. Relevance of the typology in the context of Kenya

This contextualization to Kenya reveals that all cattle systems found in the country can be linked to a management type from the typology. Although local systems are more specific than the developed typology in this paper in a specific dimension, stall-fed and stall-milked at night versus outdoors constantly, the typology enables to encompass a large diversity of local systems, in line with detailed previously proposed typologies in Kenya [28–30]. However, by taking the FAO typology [28,29], large-scale GS with concentrated feed complement and SZGS are mixed in management type 12.1 (see Figure 6) [29]. Distinguishing them appears difficult based on grazing and feeding characteristics. This difficulty could have potential impacts on economic assessment but not much on the environmental assessment as the feeding practices appear to be similar. Low intensity systems in [30] are also difficult to segregate, same as in the typology developed in this paper.

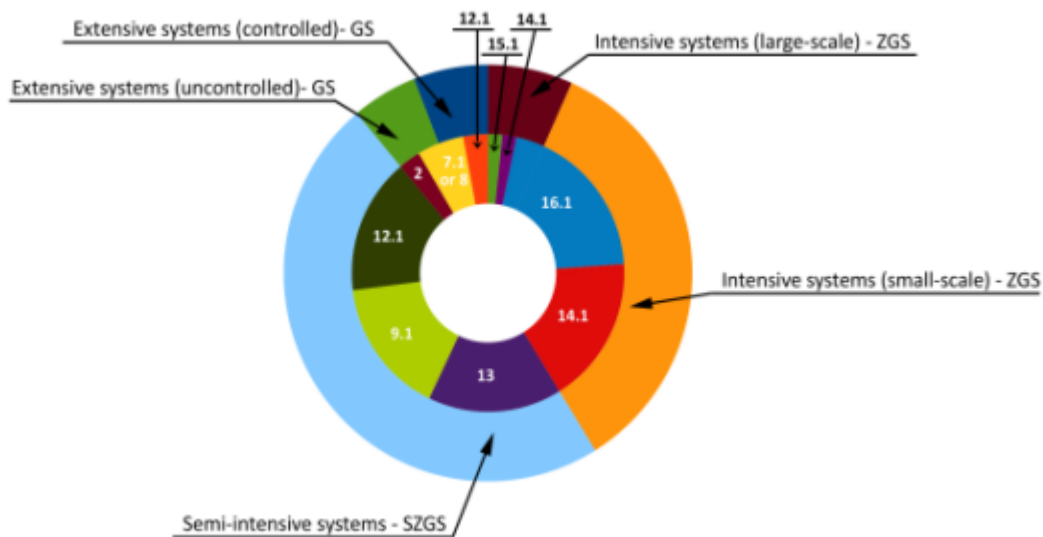


Figure 6: Share of dairy production systems. Outer circle: dairy systems according to literature [28,29]. Inner circle: dairy systems according to the typology

It is worth noting that the typologies made for Kenya did not take agro-ecological zones as an important criterion, which is in line with the management types typology developed in the article. However, this is not a generalization. In larger countries, such as Brazil, or in countries where the diversity of agro-climatic zones is the main constraint on practices, for example in Senegal, agro-ecological zones would have been part of the classifications. Farming practices would still have been present in the classification, sometimes confounded with the agro-ecological zone (e.g., the Ferlo sahelian zone being associated with nomadic extensive management types only) or sometimes co-existing in a given agro-ecological zone (in the South of Brazil, for instance).

The proposed typology is the result of a search for exhaustiveness on cattle systems on a global scale. Certainly not all management types are intended to be present on smaller scales (national or regional scales). In Kenya for example, some management types are not present or hardly present. Sylvo-pastoral management types (MTs 3 and 4) refer to the exclusive use of land for forest products and animal production (either grazing or fodder production). These management types are often planted forests (bocage form in Europe or orchards with trees used for fruit/nuts production and/or timber) with agroforestry practices or pastoralism in open shrub and tree savannah (e.g., Ferlo region in Senegal). From field observations, sylvo-pastoralism could have high potential interest in Kenya, particularly to reduce climate vulnerabilities of farmers and to restore degraded systems by deforestation [37].

Grass-fed management types using industry by-products (MTs 10 and 11) refer to the association

with the food industry whose waste is used for animal feed (e.g., sugarcane production, brewery waste, vegetable cakes, etc.) in addition to grazing. Feeding from industrial wastes or by-products might be present in Kenya. For example, management types based on spent grain in Western Kenya, a by-product of beer making process [38], or dairy management types in peri-urban areas in the Kiambu county [30], very localized and occasional, therefore not considered as a management type on its own. This feeding practice could allow smallholder farmers to access more easily intensive cattle systems, especially in arid and semi-arid areas, as wastes could be available at a lower price than off-farm commercial feed. Alongside valorizing industrial by-products and wastes, this feeding practice could allow the use of croplands for growing food instead of feed, especially in the context of growing population.

Environmental impacts assessment of the livestock sector is effective when it takes into account the multiple dimensions of livestock farming, including monetary and non-monetary benefits, such as income, food, draft power, manure, and insurance [28] as well as other sectors such as feeding practices including origin, nature and quality, but also grazing practices, breeds, etc. The management types typology developed in this paper appears to possess many dimensions necessary to assess environmental impacts [30] even if quantification of shares of management types at the country level is unknown; some shares are given by [29] but for a typology that is less specific than [30]. General characteristics of systems—feeding system, grazing management, breeds, production objectives—are given by [28–30] based on expert knowledge and fieldwork observations. But some grazing practices are still difficult to take into account as they appear to be related to the farmer's own choice rather than management types practices common to all units belonging to that management types. Nonetheless, the typology described here is relevant and can be operationalized to model detailed management type as in [30] even if absolute quantification appears difficult because of a lack of information on quantified shares of those systems.

There is a general lack of information on animal movements in the literature on Kenya livestock systems, although movements of calves exist from dairy systems to meat production systems [28], and within dairy systems across regions [30]. It could imply that these movements are not precisely taken into account in environmental analysis leading to a risk of incorrect allocation of environmental consequences of livestock rearing, such as greenhouse gas emissions. This is particularly problematic when determining emissions per unit of production. For example, the emissions associated with gestation and first years of calves rearing would be associated with dairy

systems, even if the calves end up in the feedlots system. A negative bias would be introduced in the evaluation of emissions per unit of meat, if the movements across systems are not taken into account, as in [29] (although emissions per unit of product are not shown in this document).

III.5. DISCUSSION

III.5.1. Framework's use for various studies

This conceptual framework is intended to serve as a basis for economic studies along with assessments of the environmental impacts of cattle farming practices. The first level of analysis, management types, enables a global understanding of cattle farming practices and methods across the world. Owing to the division of the life of cattle into profiles, environmental impacts and economic costs can be assessed and attributed at all life stages of the animal. Moreover, each animal is included in an lineage group, allowing one to take into account movements, from one profile to another and from one type of management to another, when relevant. In the framework, the analysis and computation unit, the animal profile, is distinguished from the final assessment functional unit, the lineage group. Such distinctions allow one to better attribute impacts and services to all phases of lineage groups and between management types. Targeting phases to which impacts can be attributed could help to find efficient solutions to decrease environmental impacts of the livestock sector. This framework and the system boundary used is similar to approaches used in life cycle assessment (LCA) studies [39]. Through lineage groups, products, costs, and impacts of an animal's ancestry can be assessed upstream and downstream. This allows one to account for all co-productions (animals and co-products included) in environmental impact assessments.

Along with environmental impact and economic studies at the country level [40] and at the global level [16,17], the typologies presented above could be used in any approach requiring clear specification and discrimination of the management farming practices and lineage groups. This framework also could be used for social and cultural studies. However, some relevant criteria, such as herd size, professionalization, rights equality, number of workers per animal centered on livestock farm structures and herder characteristics, are not present in this framework. Some criteria could still be linked with social, religious or cultural elements, such as intensity of resource use.

As the management types typology provides many details on practices, such classification can be useful when formulating new policy to support livelihoods of herders. Indeed, policymakers can focus on the specific needs and challenges faced by herders as the classification informs them in detail. The management types typology is somewhat exhaustive and detailed; such a level of detail may not be suitable for some studies and policy analysis. It is also possible to group together some management types, as some criteria described in the Section 2.2 could be irrelevant. For example, if the policy issue is about livestock and landscapes, criteria "Farming objective" and "Feed" could be disregarded and the corresponding management types aggregated. Similarly, if the issue is about economic incentives for specialization, criteria "Presence of trees" and "Feed" could be less relevant and corresponding management types aggregated.

Animal profiles and management types are relevant units to determine costs, although other elements could be added, for instance geographic elements on distance to markets or input transport costs, with effects of scale based on herd sizes. The split in lineage groups may not be the best solution for assessment of costs and profitability at the farm level, as farms are constituted around herds, and the price of animals bought or sold to other management types is generally considered as exogenous and known at that level. At higher scales, it is more relevant to split by activity (or representative farms) than by farm; the split in lineage groups and in phases within lineage groups thus is relevant to determine prices and costs that are different for animals moving across management types.

III.5.2. Limits of previous methods and typologies

Production management is at the core of the management type typology. Several typologies [18,19,21,26] use agro-ecological zones as criteria, meaning that production systems are determined by, among other elements, climatic conditions. Contrary to these studies, agro-ecological zones (arid, semi-arid, sub-humid, humid, highland) are not integrated in the management type typology developed in this paper. This choice makes it possible to distinguish management types solely on farming practices and methods and not on their geographical location, as management types could theoretically be established anywhere in the world. In the setup of the proposed framework, climate and agro-ecological zoning are nevertheless taken into account, as they should be integrated in the modeling of animal profiles. Climate influences the

performance of each management type through, for instance, NPP and on-farm crop yields.

Many typologies are also defined by the link with crops, such as [20], distinguishing between grazing, mixed, and industrial systems [21], criteria also used in the management type typology. However, when the link with crops is the sole entry point for management practices, various practices of farming are mixed, rendering it difficult to distinguish intensification levels. In particular, some pastoral systems can correspond to very intensive ranching (e.g., New Zealand), while others correspond to nomadic transhumance systems (e.g., Sahel). Likewise, mixed systems cover both intensive European systems and significantly less-intensive systems, such as some systems in Asia where crop residues are mostly used, leaving animals to roam the fields after harvest. Some studies [18,21] adopt a classification system based on several criteria, such as integration with crops, relation to land, irrigation, and agro-ecological zone. In these typologies, it may be easier to distinguish practices when they are closely tied to agro-ecological zones, but again, different practices and management intensities will still be confounded. The integration with crops (livestock only or mixed farming) is borrowed from those typologies, as well as the relation to land (landless or grassland-based). The application on Kenya shows that our typology is in line with detailed local typologies, which are based on intensification level, scale of farms, and integration with crops, and in that specific case, matches better with our approach centered on practices compared to other typologies based on agro-ecological zones. We think that, in other contexts, agro-ecological zoning could be used in existing typologies. In that case, practices should still be described, so that the management types typology can be used, and agro-ecological zones can be taken into account in the modelling of animal profiles.

As the management types typology provide many details on practices, such classification can be useful when formulating new policy to support livelihoods of herders. Indeed, policy-makers can focus on the specific needs and challenges faced by herders as the classification informs them in detail.

III.5.3. Strengths and weaknesses of the framework

To better distinguish intensification levels, we propose additional criteria based on management practices, such as herd mobility and management, and pasture management. Furthermore, the distinction is made between a productive objective and a multi-functional objective that integrates

milk/meat production, draught power, manure production, walking financial capital, and insurance possession, allowing many co-benefits of cattle farming to be considered in addition to meat and milk production. These additions allow different levels of intensification to be distinguished much more easily than any existing typology. Links with trees are ignored in existing typologies, although sylvopastoralism can be very different from pasture-based livestock farming [41]. We therefore added an explicit consideration of trees with sylvopastoralism to the integration with other agricultural practices. The contextualization of the management types typology applied to Kenya showed that the conceptual framework developed in this paper can be well applied to cattle systems in that context, with a good match with the detailed typology of [30]. Examining existing typologies for Kenya through the lens of our typology showed differences among those typologies, which could lead to confusion when describing dairy production systems. A criteria locally important for systems differentiation in Kenya, the practice of stall feeding at night is not explicit in our typology, however, systems differ on other characteristics in most cases. In one particular case, in the FAO typology, two systems correspond to the same management type, as similar feeding practices correspond to different systems ("controlled" GS and SZGS). Overall, the management types typology could describe systems with a relevant level of precision.

An advantage, but also a potential weakness of the typology is the level of detail. The management types typology is already detailed, and the analysis and computations on animal profiles should add location and/or climate as distinctive drivers. We could not find a way to simplify the typology while still accounting for all the criteria relevant for environmental impact and economic returns evaluation. As explained before, however, it is possible to simplify the management types typology by considering some criteria only and regrouping management types. The Kenyan case shows, however, that this level of detail may be relevant, and that some groupings done in livestock systems typologies for Kenya may be problematic.

A lack of data, especially in some regions such as sub-Saharan Africa, remains a major issue for future work using the framework developed here. Indeed, data for each management type, especially in low to middle-income countries, might be currently difficult to gather. Having a detailed typology of management types, however, should help to narrow down management parameters, such as herd management, pasture management and type of feed basket. Data on the share of each management type and lineage group may also be difficult to gather. In Kenya, the different management types are well described, however the share of management types is only

available for the FAO typology, which is less precise than our typology. Quantified information on cattle movements across management types, which could be used to determine shares of the lineage groups is also lacking. This issue, however, does not prevent the use of these typologies for only a specific country or region of the world where data are available. Added to an economic model, the data gap on management type shares could be overcome by making it possible to select management types that perform better in specific contexts.

When lineage groups are not clearly taken into account and defined [6,16,26], the full complexity of cattle farming risks is not considered. For instance, the link between grass-based management types for the pre-weaning and reproduction phases and feedlots for the finishing phases in the USA and Europe is ignored in studies at the global level. Even in Kenya studies, movements across management types are not precisely described, nor considered in assessments. The conceptual framework presented therefore makes it possible to capture and compare the multiple characteristics and functions of ruminant farming around the world in a more consistent way.

III.6. CONCLUSION

The management type typology might fail to capture the entire and complex diversity of cattle farming at a global scale. Some elements, such as nomadism or seasonal nomadism, are in effect still difficult to precisely take into account due to their dependence on climatic and local conditions. One can also only imagine that some breeding practices adapted to very local and specific conditions, such as oasis farming or emerging ruminant farming, or practices adapted to climate change and changes in consumption habits, could be missing in this work. Despite this potential weakness, the conceptual framework designed and the three levels of analysis should permit an accurate assessment and attribution of the environmental impacts of most management choices. Testing the framework and typologies in the case of Kenya showed the relevance of the framework at country scale, but also the lack of data on systems shares.

III.7. APPENDIX A

Table A1: management type typology classification (e: extensive pasture management, i: intensive pasture management)

Management type name	Description	Examples
---------------------------------	--------------------	-----------------

<p>1.1.e / 1.2e - Traditional pastoral dairy/beef MT with a production objective</p>	<p>Main outputs are milk and / or meat sold for income generation. High mobility. In case of low temperatures may cattle also be confined in barns. Extensive (e) pasture management with local breeds or locally adapted breeds. Possible feed complements, mainly cereals when grass is less or not available.</p>	<p>Mountainous dairy MTs (e.g., Europe).</p>
<p>2e - Traditional pastoral MT with a multi-functional objective</p>	<p>Main outputs are meat and milk for self-consumption, draught power, walking financial capital, and fertilizing. Based on the extensive movement of herds and flocks in search of forage, led by human family units with no permanent home base, sometimes following a cyclical grazing movement under the influence of rainfall [42]. Extensive (e) pasture management with local breeds or locally adapted breeds.</p>	<p>Traditional nomadic MTs from arid and semi-arid countries (e.g., the Sahel region, India).</p>
<p>3.1.e&3.1.i / 3.2.e&3.2.i – Sylvo-pastoral dairy/beef MT with a production objective</p>	<p>Refers to the exclusive use of land for forest products and animal production by browsing shrubs and trees and/or grazing co-existing forage crops [42]. Characterized by plantations of various tree species (e.g., walnut trees, cherry trees, oaks, etc.) associated with raising or leading the herd in a forest. Local, locally adapted or crossbreeds.</p>	<p>Bocage forms, pasture-orchards, meadows [36]; extensively managed pastures in dry climate (e.g., Ferlo region in Senegal); intensively managed pastures in humid climate (e.g., South America).</p>
<p>4e. Sylvo-pastoral MT with a multi-functional objective</p>	<p>Idem as MTs 3</p>	
<p>5.1.e&5.1.i / 5.2.e&5.2.i – Agro-sylvo-pastoral</p>	<p>Similar to sylvo-pastoralism MTs but associated with rain-fed agriculture (cultivation of livestock feed on site) [19]. Agro-sylvo-pastoralism</p>	<p>Not much represented in current practices</p>

dairy/beef MT with a production objective	incorporates agricultural crops, potentially including forage crops for livestock production, where trees may produce timber, pulp, fruits, rubber, and syrup or be browsed for grazing animals [42]. Local, locally adapted or crossbreeds.	
6e. Agro-sylvo-pastoral MT with a multi-functional objective	Idem as MTs 5	
7.1.e&7.1.i / 7.2.e&7.2.i – Grass-fed dairy/beef MT with a production objective	Pastoral dairy management types without association with agriculture. In semi-confinement, sometimes with only a few hours of grazing / day [43]. Animals are confined when weather conditions dictate. Local, locally adapted or crossbreeds.	Ranching MTs (e.g., New Zealand, USA, Brazil, Argentina, South Africa).
8e. Grass-fed MT with a multi-functional objective	Pastoral management types without association with agriculture, with a multi-functional objective including the possession of walking financial capital. Local, locally adapted or crossbreeds.	
9.1.e&9.1.i / 9.2.e&9.2.i – Externally complemented grass-fed dairy/beef MT with a production objective	MTs with grass in the cattle diet, associated with a high share of complements from external origin, without crop-livestock integration. Specialized management types and associated with an income generation objective. Animals are in semi-confinement, sometimes with only a few hours of grazing / day [43]. Local, locally adapted or crossbreeds.	Productive MTs typical of high-income countries (e.g., Europe).
10.1.e&10.1.i / 10.2.e&10.2.i – Grass-fed dairy/beef MT, using industry by-products with a	Associated with the food industry and whose waste is used for animal feed (e.g., beet pulp, whey, brewery waste, vegetable cake, fruit or vegetable waste). It is particularly interesting in countries with little capital [44,45]. Pastoral types	

production objective	without association with agriculture. Animals are kept in semi-confinement, sometimes with only a few hours of grazing / day [43]. Animals are also confined when weather conditions dictate. Local, locally adapted or crossbreeds.	
11e. Grass-fed MT, using industry by-products with a multi-functional objective	Idem as MTs 10	
12.1.e&12.1.i / 12.2.e&12.2.i – Internally complemented grass-fed dairy/beef MT with a production objective	Grass-fed management types with an agricultural component (e.g., cereals such as corn, wheat, or barley and/or soy) for animal feed, mainly produced on-farm. Local, locally adapted or crossbreeds [2].	
13e. - Internally complemented grass-fed MT with a multi-functional objective	Idem as MTs 12. These management types have a multi-functional objective where animals are present in small herds fed with grass and crop residues.	
14.1/14.2 – Zero-grazing dairy/beef MT, with grass, with a production objective	Cattle are housed and stall-fed with cut and carry fodder [33] complemented by cereals and little complements. Crossbreeds or genetically improved breeds/exotic breeds.	Countries where fodder from non-managed grasslands is available to cut (e.g. Kenya, Uganda, intensive family MTs in Vietnam)
15.1 – Zero grazing dairy MT without grass, with a production objective	Animals are contained mainly indoors, where cows eat and are milked on the spot [46]. Crossbreeds or genetically improved breeds/exotic breeds.	Middle and high-income countries MTs (e.g., USA and Brazil concentrated feedlots, Europe)

15.2 – Zero grazing beef MT without grass, with a production objective	Cattle are mainly kept in outdoor enclosures (sometimes indoors in dry climates) [46]. Crossbreeds or genetically improved breeds/exotic breeds.	Middle and high-income countries feedlot MTs (e.g., USA and Brazil concentrated feedlots, Europe)
16.1/16.2 – Scavenging & backyard MT with a production/multi-functional objective	Mainly sheep and goats (especially in high-income countries) but also sometimes cattle. Farming objectives are either production and generation of revenues, mainly in urban and peri-urban areas, or multi-objective, with, in particular, possession of walking financial capital (breeding at a family scale). Most often local or locally adapted breeds [47].	Mainly present in southern countries (e.g., India, urban and peri-urban areas of low-to-middle income countries) but little practiced in high-income countries today.

Table A2: Animal profile phase ages

Phase	Calf	Young bovine	Heifer	Cow	Young bull	Bull	Ox
Age	Generally less than 8 months or until weaning.	Generally 8 to 12 months. 8 months to 24 months from MT14 to MT16.	Generally more than 12 months (without calving). 1 to 4 years in MT1. 1 to 3 years from MT2.	Generally more than 24 months (+ first calving). 4 to 15 years in MT1. 3 to 8 years from MT2 to MT16.	Generally 12 to 20 months. 1 to 2.5 years from MT2 to MT13.	Generally more than 24 months (non-castrated). 1 to 15 years in MT1. 2.5 to 8 years from MT2 to MT13.	Generally more than 24 months (castrated). 2.5 to 8 years in MT4.2, MT5.2, MT12.2, MT13.2.

III.8. REFERENCES

1. Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M.C., Mosnier, A., Thornton, P.K., Böttcher, H., Conant, R.T., Franck, S., Fritz, S., Fuss, S., Kraxner, F., and Notenbaert, A., "Climate Change Mitigation through Livestock System Transitions", *Proceedings of the National Academy of Sciences* 111, no.10 (March 2014): 3709–3714, 10.1073/pnas.1308044111.
2. FAO, *Elevage & Changements Climatiques*, (Rome, Food and Agriculture Organization of the United Nations: 2016), <http://www.fao.org/3/a-i6345f.pdf>.
3. FAO, *Environmental Performance of Large Ruminant Supply Chains: Guidelines for Assessment*, Livestock Environmental Assessment and Performance Partnership (Rome, Food and Agriculture Organization of the United Nations: 2016).
4. Wint, G., and Robinson, T.P., *Gridded Livestock of the World*, (Rome, Food and Agriculture Organization of the United Nations: 2007).
5. Gerber, P., Chilonda, P., Franceschini, G., and Menzi, H., "Geographical Determinants and Environmental Implications of Livestock Production Intensification in Asia", *Bioresource Technology* 96, no.2 (January 2005): 263–276. doi.org/10.1016/j.biortech.2004.05.016.
6. Herrero, M., Thornton, P.K., Gerber, P., and Reid, R.S., "Livestock, Livelihoods and the Environment: Understanding the Trade-Offs", *Current Opinion in Environmental Sustainability* 1, no.2 (December 2009): 111–120, 10.1016/j.cosust.2009.10.003.
7. McDermott, J.J., Staal, S.J., Freeman, H.A., Herrero, M., and Van de Steeg, J.A., "Sustaining Intensification of Smallholder Livestock Systems in the Tropics", *Livestock Science* 130, no.1-3 (May 2010): 95–109, 10.1016/j.livsci.2010.02.014.
8. Tarawali, S., Herrero, M., Descheemaeker, K., Grings, E., and Blümmel, M., "Pathways for Sustainable Development of Mixed Crop Livestock Systems: Taking a Livestock and pro-Poor Approach", *Livestock Science Special Issue: Assessment for Sustainable Development of Animal Production Systems* 139, no.1, (July 2011): 11–21, 10.1016/j.livsci.2011.03.003.
9. Alary, V., Duteurtre, G., and Faye, B., "Élevages et sociétés: Les rôles multiples de l'élevage dans les pays tropicaux", *INRA Productions Animales* 24, no.1, (2011): 145–156.
10. Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., and Tempio, G., *Tackling Climate Change through Livestock—A Global Assessment of Emissions and Mitigation Opportunities* (Rome, Food and Agriculture Organization of the United Nations: 2014).

11. Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M., Vellinga, T., Henderson, B., and Steinfeld, H., *Greenhouse Gas Emission From Ruminant Supply Chains* (Rome, Food and Agriculture Organization of the United Nations: 2013), 191p.
12. Martinez, J., and Burton, C., "Manure Management and Treatment: An Overview of the European Situation", in *Proceedings of the 11th International Congress in Animal Hygiene*, (Mexico City: 2003), 23–27.
13. Eychenne, C., "Le pastoralisme entre mythes et réalités: Une nécessaire objectivation—l'exemple des Pyrénées", *Géocarrefour* 92 (February 2018): 9123987.
14. Styles, D., Gonzalez-Mejia, A., Moorby, J., Foskolos, A., and Gibbons, J., "Climate Mitigation by Dairy Intensification Depends on Intensive Use of Spared Grassland", *Global Change Biology* 24, no.2, (February 2018): 681–693, 10.1111/gcb.13868.
15. Beauchemin, K.A., Janzen, H., Little, S.M., McAllister, T.A., and McGinn, S.M., "Life Cycle Assessment of Greenhouse Gas Emissions from Beef Production in Western Canada: A Case Study", *Agricultural Systems* 103 (2010): 371–379, 10.1016/j.agry.2010.03.008.
16. Bouwman, A.F., Van der Hoek, K.W., Eickhout, B., and Soenario, I., "Exploring Changes in World Ruminant Production Systems", *Agricultural Systems* 84, no.2 (May 2005): 121–153, 10.1016/j.agry.2004.05.006.
17. Herrero, M., Havlik, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel, M., Weiss, F., Grace, D., and Obersteiner, M., "Biomass Use, Production, Feed Efficiencies, and Greenhouse Gas Emissions from Global Livestock Systems", *Proceedings of the National Academy of Sciences* 110, no.52 (December 2013): 20888–20893, 10.1073/pnas.1308149110.
18. Seré, C., and Steinfeld, H., *World Livestock Production Systems—Current Status, Issues and Trends*, (Rome, Food and Agriculture Organization of the United Nations: 1996).
19. Otte, M.J., and Chilonda, P., "Production parameters of ruminants in non-traditional systems", in *Cattle and Small Ruminant Systems in sub-Saharan Africa—A Systematic Review*, (Rome, Food and Agriculture Organization of the United Nations: 2002).
20. Laca, E.A., and Demment, M.W., "Livestock Production Systems", in *Management of Agricultural, Forestry, and Fisheries Enterprises*, Hudson, R.J., Ed. (Abu Dhabi: EOLSS Publications, 2009).
21. Teufel, N., Markemann, A., Kaufmann, B., Valle Zárate, A., and Otte, J., *Livestock Production Systems in South Asia and the Greater Mekong Sub-Region*, PPLPI Working Paper 48 (Rome, Food and Agriculture Organization of the United Nations: 2010).
22. Lhoste, P., *L'étude et le Diagnostic des Systèmes D'élevage*, (Montpellier, Atelier de

- Formation des agronomes SCV: 2001).
23. Alvarez, S., Timler, C.J., Michalscheck, M., Paas, W., Descheemaeker, K., Tiftonell, P., Andersson, J., and Groot, J.C.J., "Capturing Farm Diversity with Hypothesis-Based Typologies: An Innovative Methodological Framework for Farming System Typology Development", *PLoS ONE* 13, no.5 (May 2018): e0194757, 10.1371/journal.pone.0194757.
 24. Notenbaert, A., Herrero, M., Kruska, R., You, L., Wood, S., Thornton, P.K., and Omolo, A., *Classifying Livestock Production Systems for Targeting Agricultural Research and Development in a Rapidly Changing World*, ILRI Discussion Paper 19 (Nairobi, International Livestock Research Institute (ILRI): 2019).
 25. Robinson, T.P., Thornton, P., Franceschini, G., Kruska, R., Chiozza, F., Notenbaert, A., Cecchi, G., Herrero, M.T., Epprecht, M., Fritz, S., You, L., Conchedda, G., and See, L., *Global Livestock Production Systems*, (Rome, Food and Agriculture Organization of the United Nations: 2011).
 26. FAO, "Global Livestock Environmental Assessment Model", in *Version 2.1-Data Reference Year: 2010* (Rome, Food and Agriculture Organization of the United Nations: 2017).
 27. Dairy, N.Z., "Heifers", Dairy N.Z., accessed on December 6, 2021, <https://www.dairynz.co.nz/animal/heifers/rearing-options/>.
 28. FAO, "Livestock Production Systems Spotlight—Kenya—Cattle and Poultry Sectors", in *Africa Sustainable Livestock 2050* (Rome, Food and Agriculture Organization of the United Nations: 2018).
 29. FAO, "Integrated Snapshot—Kenya—Cattle and Poultry Sectors", in *Africa Sustainable Livestock 2050* (Rome, Food and Agriculture Organization of the United Nations: 2018).
 30. van der Lee, J., Bebe, B.O., and Oosting, S., "Sustainable Intensification Pathways for Dairy Farming in Kenya", in *A Case Study for PROIntensAfrica WP2, Deliverable 2.3997* (Wageningen, Wageningen Livestock Research: 2016).
 31. Bebe, B.O., Udo, H.M.J., Rowlands, G.J., and Thorpe, W., "Smallholder Dairy Systems in the Kenya Highlands: Breed Preferences and Breeding Practice", *Livestock Production Sciences* 82, no.2-3, (August 2003): 117–127, 10.1016/S0301-6226(03)00029-0.
 32. Ochungo, P., Lindahl, J., Kayano, T., and Sirma, A.J., "Mapping Aflatoxin Risk from Milk Consumption Using Biophysical and Socio-Economic Data: A Case Study of Kenya", *African Journal of Food* 16 (August 2016): 11066–11085, 10.18697/ajfand.75.ILRI08.
 33. ILRI, *USAID Kenya Crops and Dairy Market Systems Activity—Dairy Value Chain Assessment*, Technical Report (Nairobi, RTI International: 2018).

34. Odero-Waitituh, J.A., "Smallholder Dairy Production in Kenya; a Review", *Livestock Research for Rural Development* 29, no.7 (2017): 139.
35. Kibogy, M.R., "Kenya Dairy Industry: Status and Outlook", in *15th Esada Dairy Conference and Exhibition* (Nairobi, 2019).
36. Makoni, N., Mwai, R., Redda, T., van der Zijpp, A., and van der Lee, J., *White Gold: Opportunities for Dairy Sector Development Collaboration in East Africa*, CDI Report CDI-14-006 (Wageningen, Centre for Development Innovation: 2014).
37. AFAF, *Agroforesterie et Élevage Ovin—Produire et Protéger* (Auch, Association Française d'agroforesterie (AFAF): 2013).
38. Happy Feeds Limited, "Machicha - Brewery Spent Grain", Happy Feeds, accessed on May 12, 2022, <https://www.happyfeeds.co.ke/product/dried-machicha-cattle-feed/>.
39. Thévenot, A., Aubin, J., Tillard, E., and Vayssières, J., 'Accounting for farm diversity in life cycle assessment studies—the case of poultry production in a tropical island', *Journal of Cleaner Production* 57 (October 2013): 280–292, 10.1016/j.jclepro.2013.05.027.
40. Dutilly, C., Alary, V., Bonnet, P., Lesnoff, M., Fandamu, P., and de Haan, C., "Multi-Scale Assessment of the Livestock Sector for Policy Design in Zambia", *Journal of Policy Modeling* 42, no.2 (March 2020): 401–418, 10.1016/j.jpolmod.2019.07.004.
41. Murgueitio, E., Calle, Z., Uribe, F., Calle, A., and Solorio, B., "Native Trees and Shrubs for the Productive Rehabilitation of Tropical Cattle Ranching Lands", *Forest Ecology and Management* 261, no.10 (May 2011): 1654–1663, 10.1016/j.foreco.2010.09.027.
42. Allen, V.G., Batello, C., Berretta, E.J., Hodgson, J., Kothmann, M., Li, X., McIvor, J., Milne, J., Morris, C., Peeters, A., and Sanderson, M., "An International Terminology for Grazing Lands and Grazing Animals", *Grass and Forage Science* 66, no.1 (March 2011): 2–28, 10.1111/j.1365-2494.2010.00780.x.
43. Barbin, G., Chaumet, J.M., Chotteau, P., Le Gall, A., Lelyon, B., Monniot, A., Perrot, C., Mottet, A., Richard, M., Trossat, C., and You, G., "La filière laitière en Nouvelle-Zélande—Une furieuse volonté de croissance contrariée par l'environnement", in *Le dossier Economie de l'Élevage*, 404th ed. (France, Institut de l'Élevage: 2010).
44. FAO, *Résidus Agricoles et Sous-Produits Agro-Industriels en Afrique de L'ouest—Etat des Lieux et Perspectives Pour L'élevage*, (Ghana, Bureau régional pour l'Afrique de la FAO: 2014).
45. Chapoutot, P., Rouillé, B., Sauvart, D., and Renaud, B., "Les coproduits de l'industrie agro-alimentaire: Des ressources alimentaires de qualité à ne pas négliger", *INRAE Productions*

- Animales* 31, no.3 (2018): 201–220, 10.20870/productions-animales.2018.31.3.2353.
46. Endres, M.I., and Schwartzkopf-Genswein, K., "Overview of Cattle Production Systems", in *Advances in Cattle Welfare*; (Amsterdam, Elsevier: 2018).
47. Maman Lawal, A.A., Chaibou, M., Mani, M., Garba, M.M., and Gouro, A.S., "Pratiques d'éleveurs et résultats économiques d'élevage dans les exploitations urbaines et périurbaines de Niamey", *International Journal of Biological and Chemical Sciences* 12, no.1 (June 2018): 294, 10.4314/ijbcs.v12i1.24.

TAKEAWAY MESSAGES AND PRESENTATION OF PART 3

Takeaway messages of Part 2

- 1. The presented framework takes the complexity of farming systems into account to accurately attribute impacts;*
- 2. Management types describe the diversity of production systems over the world;*
- 3. Lineage groups regroup co-produced animals and account for movements of animals between management types;*
- 4. The framework is relevant at the global scale and to a lesser extent at a smaller scale, based on the case study of cattle production systems in Kenya;*
- 5. The lack of data is a major issue for using the framework, especially in low- and middle-income countries.*

To assess the economic and environmental impacts of cattle production systems worldwide, a conceptual model is built in the following part based on the framework developed in the previous part.

To answer the following question: "How to build a model that could consider the diversity and complexity of systems and intensification pathways worldwide?", the goal of Part 3 is to model various production systems at the world scale, based on Part 2, to then compare contrasted intensification pathways (a private objective compared to a social objective (e.g., respecting the environment, animal well-being, social objectives, etc)). The issue raised in the following part is the difficulty to represent the diversity and complexity of systems and their intensification pathways in a model at the world scale. This model is based on the intensity of input use (land, feed, grass) and the relations between livestock and other components of agriculture. It aims at analysing the environmental contributions of cattle farming systems to quantitatively evaluate greenhouse gas emissions and nitrogen pollution, and calculating their economic profitability.

IV – PART 3 : A CONCEPTUAL MODEL FOR IMPACT ASSESSMENT OF CATTLE SYSTEMS AT THE WORLD SCALE

IV.1. LIMITATIONS IN GLOBAL AGRICULTURAL MODELS FOR STUDYING INTENSIFICATION AND IMPACT ASSESSMENT

The diversity of ruminant farming as well as their evolution and intensification are already at the heart of some integrated models studying intensification processes and environmental impact assessment (see Table 4). While these models represent changes in practices, especially concerning feeds, they only represent intensification through the modification of shares of animals between systems. They do not distinguish the type of intensifications, nor do they consider links between systems as represented by lineage groups.

For example, the GLOBIOM model, for GLObal BIOsphere Management model, is a partial equilibrium model (Havlík et al., 2014) that studies GHG emissions and land use of ruminants. In this model, animals are divided between different climates and two main production systems, grazing or mixed, based on the typology developed by Seré and Steinfeld (1996), and takes also into account urban and other production systems that do not belong to grazing or mixed systems (Herrero et al., 2013; Havlik et al., 2014). The same approach is used in GLEAM, where cattle production systems are there divided into three categories: grazing, mixed, and feedlots (FAO, 2022), as well as in the NLU model (Souty et al., 2012), and the IMAGE model (Bouwman et al., 2005), for Integrated Model to Assess the Global Environment, where production systems are defined as “extensive” (grazing) or “intensive” (mixed or landless). GLEAM, for Global Livestock Environment Assessment Model, is a model allowing to estimate GHG emissions and intensity for main feed items, production systems, and regions of the world by taking the main elements of livestock supply chains (Gerber et al., 2014). The Nexus Land Use model, or NLU, represents agriculture intensification processes, by calculating crop and pasture yields and areas in order to minimize production costs for farmers (Souty et al., 2012). These four models are therefore based on two to three production systems based on practices, or two to eight systems in the case where climate types are also considered.

The systems considered in these global models are characterized either by their climate (Robinson

et al., 2011) or by their link with crops. In this second case, a mixed system with crops is distinguished from a more independent pastoral system (Seré and Steinfeld, 1996). Thus the diversity of systems considered in these models is limited leading to confusion as distinct systems having the same level of intensification could be regrouped (e.g., extensive mountainous grass-based dairy systems with ranching farming in North America). Given this difficulty, a viable option could be to classify systems based on their production methods and practices.

Moreover, livestock production system transitions are often defined by the modification of the share of animals between grazing and mixed systems, as done in NLU (Souty et al., 2012) and in GLOBIOM (Havlik et al., 2014). These transitions can be attributed to intensification or extensification processes, making it difficult to differentiate intensification types and processes. In the GLOBIOM model, these transitions are found to contribute to a reduction in GHG emissions when a larger proportion of animals shift from a grazing system to a mixed system. This corresponds to changes in practices, without being possible to differentiate the intensification pathways. When intensification with a social benefit is not considered, one can think of potential biases concerning the assessment of impacts as the multi-aspect characteristics of intensification are not taken into account.

Finally, these models do not consider links between systems represented by lineage groups, as developed in Part 2. It is possible that some system switches are not possible as intensified feedlot systems actually depend on grass-based systems. This limit could also imply potential biases in assessing GHG emissions attribution to systems (e.g., as done in GLOBIOM or GLEAM) by attributing them to a particular production system without considering how this system is linked to others.

Table 4: Summary of some global agricultural models

	GLOBIOM	GLEAM	NLU	IMAGE
Full name	GLObal BIOsphere Management model	Global Livestock Environment Assessment Model	Nexus Land Use model	Integrated Model to Assess the Global Environment
Small definition	Partial equilibrium model studying	Model estimating GHG emissions	Model representing	Model spatially distributing

	GHG emissions and land-use of ruminants	and intensity for feeds, production systems, and world regions	agriculture intensification processes	production systems and the use of feeds, manure and distribution
Representation of production systems	Grazing, mixed (and climate types)	Grazing, mixed, feedlots (and climate types)	Extensive (grazing), intensive (mixed or landless)	Extensive (grazing), intensive (mixed or landless)
Representation of system transitions in the model	Modification of the share of animals between grazing and mixed systems	/	Modification of the share of animals between grazing and mixed systems	/
References	Havlik et al., 2014	FAO, 2022	Souty et al., 2012	Bouwman et al., 2005

To overcome the limitations of those studies (i.e., diversity of production systems, intensification type, and lineage group consideration), and evaluate economic and environmental impacts of cattle systems at the world scale, we have proposed a framework (see Part 2) on which the model developed in this part is based.

IV.2. OBJECTIVES OF THE MODEL

The systems used in the global models presented above are characterized by their link with climate and/or their link with land. This represents a large diversity of herding practices but fails to take the links between systems and the multifunctionality of ruminant systems into account.

To counter this limitation, the choice was made to base the model on the conceptual framework developed in Part 2 – using the concepts of lineage groups, management types, and animal profiles. As presented before, such concepts have already been used in life cycle assessments in poultry farming (Thévenot et al., 2013) but have never been used before for cattle farming and at the world scale.

The objective of the model is to compare production systems represented by their practices and processes based on their performances (economic and environmental) by modeling animal profiles in management types and comparing lineage groups. In particular, two objectives of intensification, located on the limits of the gradient of intensification presented in Part 1, should be compared: (1) an intensification motivated by a private economic objective maximisation, and (2) an intensification motivated by a social objective maximisation including socio-economic benefits (e.g., nitrogen cycling, GHG emissions, landscape management, pollution reduction, community cohesion, etc). The latter corresponds to a combination of various livestock farming activities and economic profit with a penalization for negative impacts on the environment while maintaining the functionality of ecosystems and respecting the pillars of sustainability (Dawson et al., 2019; Smith et al., 2017; Tedeschi et al., 2015; Udo and Steenstra, 2010). In this case, we therefore also include externalities such as GHG emissions and local pollution. As some environmental impacts cannot easily be evaluated, it is also possible to use constraints on practices instead.

The model is divided into three modules and is based on the framework developed in Part 2, using animal profiles and lineage groups (see Figure 7). The first module of impact evaluation is done at the grid cell level, by representing each animal profile of each management type in each grid cell, as well as their costs and products. A second module groups animal profiles together to form the structure of the lineage group, to then determine the number of heads for each animal profile through the lineage group and the herd model. The third module aggregates and evaluates the impacts of each animal profile to then evaluate the benefits of the lineage group. Finally, an optimisation is done to specify three variables needed in the first module (namely the nitrogen application rate, the stocking rate, and the share of feed produced on-farm). Performances of lineage groups are then calculated in this model allowing to rightfully allocate impacts and compare intensification pathways. This model has been designed without being implemented.

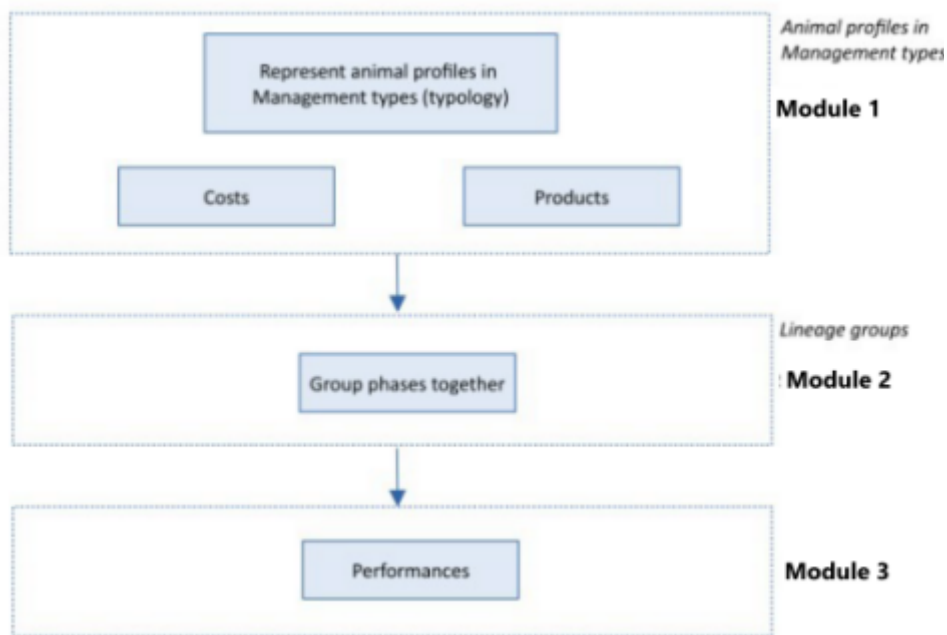


Figure 7: Simplified framework of the model

IV.3. MODULE 1: REPRESENTATION OF MANAGEMENT TYPES AND LOCATED PROFILES MODELING

For this module, the functional unit is an animal profile in a management type. The model represents management types from the typology based on criteria used to describe them: product outcome (dairy, meat), farming objective (production, multi-functional), feeds, pasture management, integration to land and other agricultural components, herd mobility, and manure management. We use “units” (see Figure 8; one color per unit) to model animal profiles in management types. Some units have spatially explicit elements, such as climate or distance to markets. Most of the model is, however, based on the non-spatial description of management types from the management types’ typology.

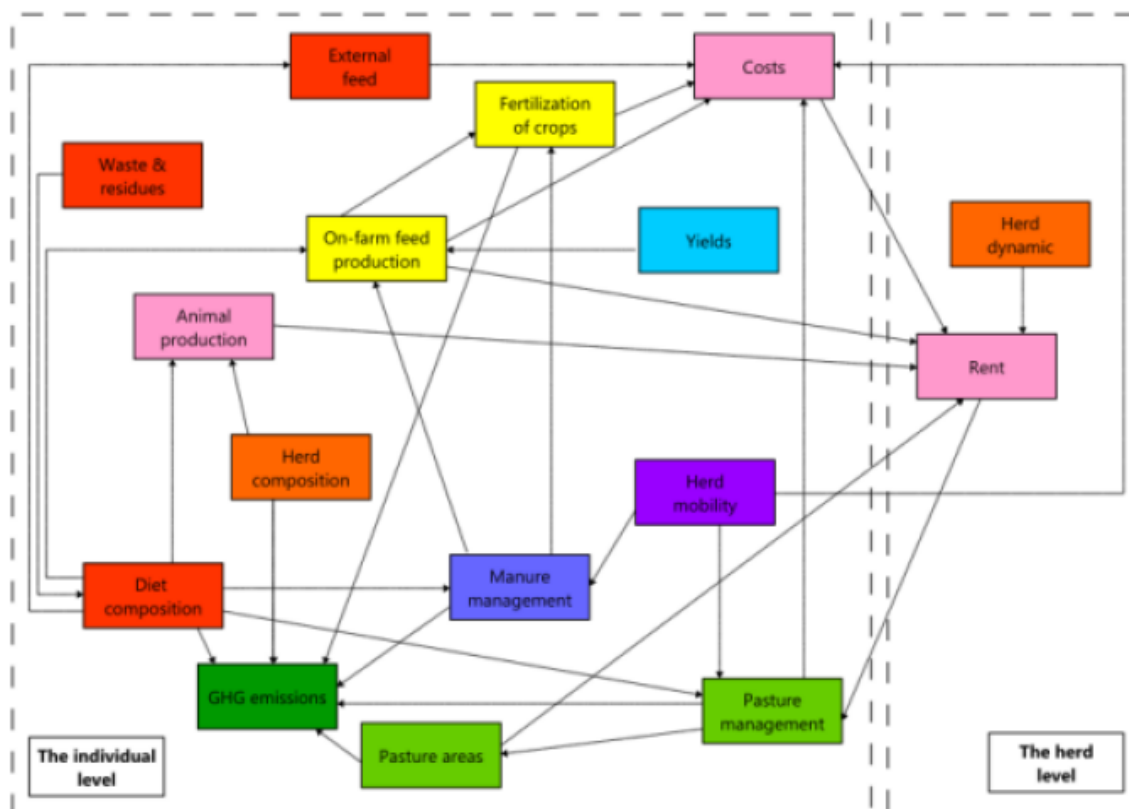


Figure 8: Model system (feeds, herd management, herd mobility, relation to land, pasture management, manure management, GHG emissions, economic analysis and costs, climatic conditions)

IV.3.1. Determination of production areas and feed requirements: input and output quantification

IV.3.1.1. Pasture management and herd mobility unit

In contrast with most other units for which well-established modelling approaches exist in the literature, pasture management, and pasture yields are not explicitly represented in global models. Pasture yields are, instead, represented by apparent yields obtained by dividing grass intake with pasture area. In addition, the distinction between grazing and harvesting grass is not explicit. There is also a lack of data on grass yield, pasture management practices, the share of grazing in grass intake, and actual stocking rates. To overcome the lack of data and represent pasture management, even in a simplified way, the method selected is the use of a pasture management model results as data. The ORCHIDEE-GM continental surface model (Chang et al., 2013) has been selected to provide modeled data on pasture yields and allows calculating the shares of grazed grass intake (see Figure 9).

ORCHIDEE-GM is an evolution of the ORCHIDEE land surface model. The latter is an ecosystem model based on processes to simulate carbon, water, and energy fluxes. ORCHIDEE-GM was developed to represent pasture management (Chang et al., 2015). There are two ways of solving the ORCHIDEE-GM model: (1) by finding the optimal animal stocking rate (number of livestock units per hectare) as done in the paper by Chang et al. (2015), or (2) by using the stocking rate as input and calculate time spent on pastures by animals before all biomass is eaten. The latter is the preferred option used in this model (see Figure 9).

Thanks to the use of the ORCHIDEE-GM model and additional computations in this pasture management and herd mobility unit, we wish to obtain the following parameters: grass biomass intake and harvested, grasslands carbon balance, grasslands nitrogen balance, and time spent in barns. To do so, inputs are used such as nitrogen application rate, livestock stocking rate, potential daily time spent on pastures, and constraints on climatic conditions (see Figure 9). The grass intake capacity per cattle is considered known and constant, with a maximum of 18 kilograms of dry matter per head and per day as used in the ORCHIDEE-GM model (Chang et al., 2013).

The desired outputs of this unit (i.e., grass biomass grazed and harvested, carbon balance, nitrogen balance, time in the year actually spent on pastures, and time spent in barns) cannot be obtained directly by running the ORCHIDEE-GM model. Therefore a simplified surrogate model is used to perform calculations on some desired outputs of ORCHIDEE-GM: yield of harvested biomass, carbon balance, and the time in the year actually spent on pastures (see Figure 9). By running the surrogate model, the desired outputs are obtained depending on stocking rates and nitrogen application rates.

Time spent on pastures

The time spent out on pastures determines the annual quantity of grazed grass and is both an input of the ORCHIDEE-GM model to give information on when cattle are housed in barns or are on pastures, and an output of the model when the grass needs to regrow. There are three mechanisms considered here to calculate the time spent on pastures: (1) the share of grass in the diet of the animals, meaning if they eat something else than grass, (2) the climate, and (3) the amount of grass available on pastures. These three mechanisms are explained hereafter.

Firstly, depending on the amount of grass in the diet of animals, which itself depends on the

management type, animals will spend more or less time grazing on pastures. This constraint is external to the ORCHIDEE-GM model. The amount of grass needed in the diet represents a threshold. When this threshold is reached, cattle are removed from the pastures to be housed. There, they are fed with other types of feed (e.g., cereals, concentrates, residues, forages, etc) depending on their diet. This constraint is indeed associated with the time spent in barns to eat other types of feed, but this constraint is surely satisfied as soon as animals do not graze more than they should. Therefore, various maximum times of grazing are given as inputs of the ORCHIDEE-GM model, ranging from 0 (e.g., in feedlots management types where animals are not grazing at all), up to 18 hours per day and per head (e.g., pastoralists management type where animals are grazing all day long minus the night time).

Secondly, the direct effect of climate on livestock is also a constraint, which is external to the ORCHIDEE-GM model. For example, in Europe, dairy cows spend four to six months indoors (Mosnier et al., 2017), while other ruminants are raised mainly indoors, spending three to five months in pastures on average. The upper critical temperature of cattle lies around 25-28°C in temperate countries (Van laer et al., 2014), and this same study found that long exposure to temperatures below 0°C has negative effects on cattle physiology. Even if the minimum temperature for cattle to be housed depends on many variables (e.g., the breed, the humidity), in this model, and to simplify, animals are housed when the minimum temperature of the day is below 5°C.

Thirdly, an internal constraint of the ORCHIDEE-GM model is determined when the grass biomass on pastures is not enough for animals to graze, and animals are then removed from pastures. In ORCHIDEE-GM, the threshold on biomass to trigger grazing is correlated to the total intake capacity per day. When the biomass is lower than $0.5 \times \text{threshold}$, grazing is stopped until the biomass regrows above the threshold. This assumption gives relatively sustainable grazing practices to avoid animals eating all biomass. The time spent on pastures depends on the stocking rate. Therefore the higher the stocking rate, the lower the time spent on pastures.

The days spent on pastures by animals given by ORCHIDEE-GM allow calculating the time not spent on pastures by the difference. This time is added to the time not spent on pastures constrained by the climate and the management type given in the input of the ORCHIDEE-GM model (see above). The total time spent on pastures can finally be determined as a difference

between the total time within a year and the time not spent on pastures. ORCHIDEE-GM determines the yield of harvested grass and the time spent on pastures for a set of values of nitrogen applied and stocking rates. The information given by the surrogate model, therefore, determines the time spent on pastures or in barns, as a function of the stocking rate (s), the nitrogen application rate (N_a), and the potential daily time spent on pastures (t^{pd}) (not always reached, when there is not enough grass available for example). This functional relationship is the output of the surrogate model.

The surrogate model can be obtained by fitting a curve linking the result points of interest from the ORCHIDEE-GM model, which could simply be a linear interpolation. ORCHIDEE-GM also computes the carbon balance and the carbon stored in the soils, which can be used for the GHG emissions computations but is not used further in this unit.

Harvested grass

For harvested grass areas, the ORCHIDEE-GM model gives the dry matter of harvested grass per unit of area, with a rule on the schedule of harvesting corresponding to an optimal or nearly optimal cutting. Harvested grass quantities are then summed for the year to obtain the yearly yield (Y_{har}).

Nitrogen fertilizer application

In ORCHIDEE-GM, the effect of nitrogen fertilizer application is modelled as net primary productivity (NPP) being a function of the nitrogen application rate on pastures, noted N_a . N_a corresponds to the sum of the synthetic nitrogen application rate, N_{synth} , and the organic nitrogen application rate, N_{spread} , obtained from the cattle manure. The synthetic fertilizer application rate is computed as: $N_{synth} = N_a - N_{spread}$.

Grazed grass

The information given by the surrogate model allows to determine the grazed grass intake from the time spent on pastures combined with the fixed grass intake capacity per head and per day, obtained through: $Q_{grazed} = grassintakecapacity \cdot t^p$ with t^p the time spent on pastures. From the quantity of grazed grass, the quantity of harvested grass is calculated as: $Q_{har} = Q_{totalgrass} - Q_{grazed}$.

The grazed area is obtained through: $A_{grazed} = \frac{1}{s}$ with s the stocking rate, and the harvested areas

is obtained as: $A_{har} = \frac{Q_{har}}{Y_{har}}$.

Constraints on the surrogate model

The constraints on optimal stocking rates and nitrogen application rates (see Figure 9) can also be pre-determined for some management types (e.g., a maximum nitrogen application rate or no synthetic application rate for extensively managed systems, noted e in the typology in Part 2, or a minimum stocking rate for intensively managed systems, noted i). The final quantity of synthetic nitrogen (N_{synth}), the final stocking rate (s), and the potential daily time spent on pastures (t^{pd}) are not determined in this unit. There are trade-offs embedded in the function linking areas, stocking rates, nitrogen input, and potential daily time spent on pastures obtained in the unit (e.g., the stocking rate and the potential daily time spent on pastures are putting pressure on resources), corresponding to different N_a and s , regarding the quantity of land used, the cost of nitrogen, and the cost of harvested grass which are solved when the rent is maximised (see IV.5). For example, if the stocking rate is low, then a larger proportion of animals can graze, and there is not much need for harvested grass. If the nitrogen application rate is low, animals have to stop grazing, and the harvested grass yield decreases too, leading to an increase in land-use.

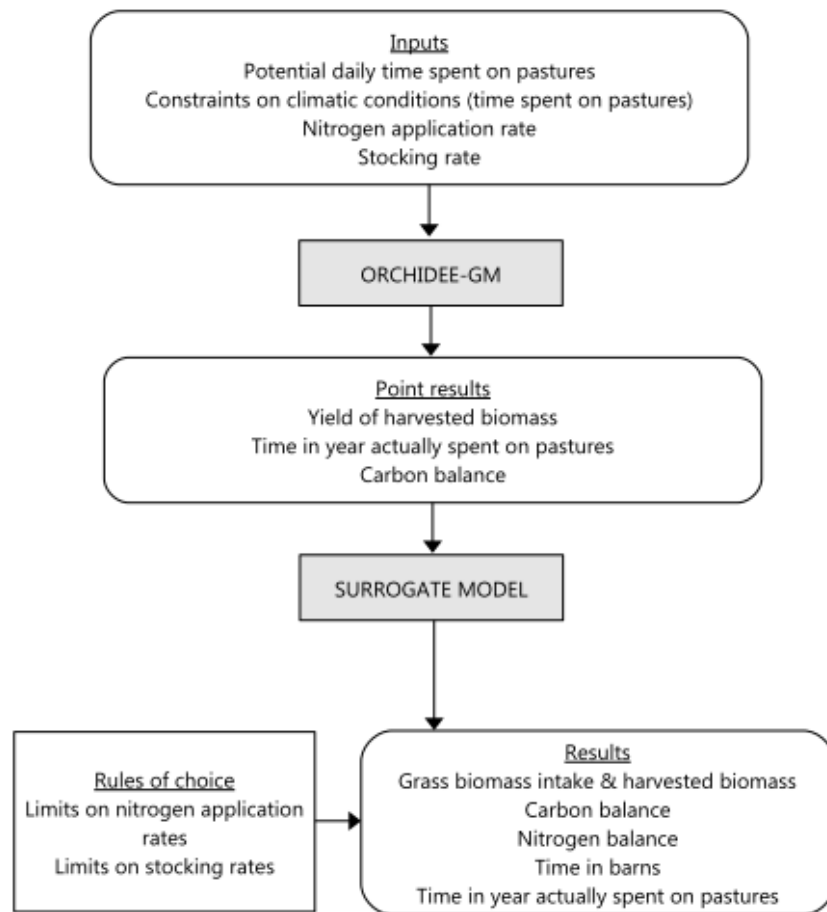


Figure 9: Simplified scheme of the use of ORCHIDEE-GM model for pasture management unit

Herd mobility

This pasture management unit also contains herd mobility parameters as it also takes into account the movements of animals on pastures. These movements are management-type specific, as they depend on the share of grass in the diet, and resource availability. Certain pasture practices, such as rotational grazing, are difficult to model and simulate. The ORCHIDEE-GM model can only simulate an average situation of biomass intake with the stocking rate and the time spent on pastures as inputs.

The ORCHIDEE-GM model is also not well suited to represent nomadism. A simpler method can be used based on the NPP from a land surface model, such as ORCHIDEE, with a rate of utilization. The NPP corresponds both to grass and trees in semi-arid locations (e.g., the Ferlo region in Senegal).

The effect of the canopy in intensive silvopastoralism could also be modeled here, simply as factors influencing the modeled processes, without explicitly modeling trees and their interactions with cattle and grass growth (Landholm et al., 2019).

Nitrogen balance of pastures

The organic nitrogen spread on pastures comes from the "Manure management" unit, considering the time spent in barns. Manure is considered spread in priority on on-farm crops for feed, and then on pastures. The nitrogen balance of pastures is also determined in the "Pasture management" unit. An average balance on total grassland area (i.e., harvested and grazed areas) is determined, assuming that there is a rotation among those two types of area. The nitrogen output includes nitrogen intake (in kgN per hectare per year) by cattle when grazing (N_{grazed}) and fed on harvested grass (N_{har}), based on the grass nitrogen content. Diverse sources of nitrogen for grass are accounted for to obtain N_{input} , including direct uncontrolled manure deposition (N_{manure}), which depends on the time spent on pastures and the stocking rate, synthetic fertilization from externally bought chemical fertilizer (N_{synth}), manure deposition (N_{spread}) as explained above, and fixation from pasture legumes (N_{fixated}): $N_{\text{input}} = N_{\text{manure}} + N_{\text{spread}} + N_{\text{synth}} + N_{\text{fixated}}$.

$$N_{\text{manure}} = \frac{d_N \cdot A_{\text{grazed}}}{A_{\text{grazed}} + A_{\text{har}}} \cdot s \cdot t^p$$
 with s the stocking rate, t^p the time spent on pastures, and d_N the rate

of nitrogen excreted remaining available for grass per animal and per day. Data could come from the application of the IPCC (2006) method, from Herrero et al. (2013), or from the GLEAM model (FAO, 2022).

$N_{\text{fixated}} = Y_{\text{legumes}} (A_{\text{grazed}} + A_{\text{har}}) \text{share}_{\text{legumes}}^p$ where $\text{share}_{\text{legumes}}^p$ is the percentage of legumes in the pasture (p), depending on the management type considered. Data comes from various literature such as Landholm et al., 2019 (e.g., the share of legumes in temperate climate pastures is approximately one-third). The yield of legumes (Y_{legumes}) can be estimated thanks to the difference of yield between pastures with legumes and pastures without (using for instance the difference of energy cost between legumes and non-legumes to overcome the lack of data (Vertregt and Penning De Vries, 1987)). To simplify, the model considers that the yield of legumes is the same for harvested grass and grazed grass.

$$N_{\text{output}} = N_{\text{grazed}} + N_{\text{har}} = Q^g \cdot s \cdot \frac{\text{share}_N^g}{(A_{\text{grazed}} + A_{\text{har}})}$$
 with share_N^g the percentage of nitrogen (N) in

grass (g) (data comes from Feedipedia), and Q^g is the grass biomass intake per head.

The total synthetic nitrogen needed for grasslands is obtained by:

$N_{synth}^{g,h} = N_a (A_{grazed} + A_{har}) - N_{spread}^{g,h}$ with $N_{spread}^{g,h}$ the spread of nitrogen on grasslands per head available after feed crop requirements for the same head have been met (see below in the « Relation to land » unit).

Nitrogen losses represent the difference between nitrogen inputs and outputs and are a proxy for the nitrogen pollution level (Zhang et al., 2015): $N_{losses} = N_{input} - N_{output}$.

Input parameters for unit 1: grass intake capacity, time spent in barns constrained by climate, minimum time spent in a barn by management type, limits on nitrogen application rates, and limits on stocking rates depending on the management type considered (if it is extensively (e) or intensively (i) managed).

Input variables for unit 1 (coming from other units): nitrogen spread by a unit of housed cattle head, and nitrogen needed for crops.

Output variables for unit 1: grass biomass intake and harvested biomass, carbon balance, time spent in barns, and nitrogen balance on pastures as a function of stocking rate and synthetic nitrogen applied on grasslands.

IV.3.1.2 Feed unit

The feed unit is based on the animal's diet, which depends on the animal profile and the management type in which the animal is situated. It depends on the presence/absence of pastures, presence/absence of crops grown on-farm, the availability of on-farm residues, and the need for external feed. Feed categories relevant at the global modeling scale could be crop residues, other residues (more digestible and richer in nitrogen, typically food residues or food processing by-products), scavenging, grass (grazed and harvested), concentrated feed rich in nitrogen, concentrated feed rich in energy (cereals), and cultivated fodders (e.g., silage corn, alfalfa). The quantity of each feed category in the diet per head is noted: $Q_f^h = \gamma \Phi^f$ where Φ^f is the share of each feed category in the diet, and γ is the input coefficient corresponding to the total quantity of feed per head. This coefficient depends on the total energy needed per animal, which itself depends on the profile and the species. Necessary energy per animal can be computed using the

equations in IPCC (2006).

The animal's diet is predetermined, and total gross biomass intake (grazed and harvested) (inputs of unit 1) is set here. Other feed categories are expressed as a percentage of the total feed input (either in digestible energy or in dry matter). All feeds are estimated to be cultivated on-farm except for concentrated feed. Feed digestibility is defined as digestible energy as a percentage of gross energy (FAO, 2020). Estimating feed digestibility requires information on diet composition and digestibility for each feed component and each animal profile. If oxen are used for work (see below), an additional energy requirement is added (Bouwman et al., 2005). Feed rations are expressed in terms of energy to correlate the energy needed to their feed intake – to neither be underestimated (underfed) nor be wasted (overfed).

Input data for animal feed ration composition, management-type specific, and average digestibility could be given by FAO (2017) or Herrero et al. (2013). Digestible energy (in MJ per kilogram of dry matter), and energy digestibility (%) for each feed category could be based on Feedipedia or IPCC (2006).

Input variables for unit 2: average digestibility for each feed category, animal's energy total requirement, and the share of each feed in total digestible energy or dry matter intake.

Output variables for unit 2: gross biomass intake, crop feed intake, residue intake, and estimated feed digestibility per animal profile.

IV.3.1.3. Herd management and production unit

Herd management inputs relevant at the animal profile level, such as live weight, (potential) weight gain, and (potential) milk production can come from the GLEAM model (FAO, 2017), and are discriminated by breed. Herd management input data relevant at the lineage group level are described below in the lineage group modeling section.

Animal production (milk and meat yields) depends on the feeding diet, constrained by the management type, and the breed. The correlation between the feeding diet and the production is, however, not explicitly implemented in the model, but can be taken from other modules (Bouwman

et al., 2005; Herrero et al., 2013; FAO, 2022). Here, milk and meat productions are used as inputs of the unit and some data on animal production can be found in Annexe 2.

Input variables for unit 3: live weights, weight gains, and milk and meat production.

Output variables for unit 3: production value.

IV.3.1.4. Relation to land unit

This fourth unit includes relationships between cattle breeding and agriculture. In the case of multi-functional objective management types combined with agriculture, oxen could potentially be present for draught power. In the first step, the need for oxen power per unit of cropland can be used. It could also be possible to determine the requirement of oxen power based on the relative cost of machinery and labour. The requirements of oxen power are used to determine the additional energy needed in the feed unit.

This unit also includes the nature and share of on-farm-produced crops in the cattle diet, depending on the management type considered. To avoid complicated modeling of crops, the economic trade-offs related to crop cultivation are not represented. Instead, fixed yields and a linear relation between yields and nitrogen inputs are used.

Crop yields for feed

Crop yields can be obtained from crop models, in particular, actual and potential yields of most crops used as feed can be obtained from the LPJmL model. LPJmL is a model that simulates the growth and productivity of natural vegetation and crops, linked through their water, carbon, and energy fluxes (Schaphoff et al., 2018). The actual crop yields, given in FAOSTAT, can be rescaled at the country level thanks to a coefficient corresponding to actual yields over potential ones, which is named here the relative yield gap coefficients. Potential yields are then rescaled by these same coefficients. Next, the relative yield gap coefficients per crop and per country can be computed. Lastly, those coefficients are applied to potential yields (given by the LPJmL model), to obtain actual yields for each grid cell. Crop categories, as described in the "Feed" unit, can then be aggregated.

Crop biomass yields can be used to compute above-ground cultivated fodder yields by using LPJmL yields multiplied by a coefficient (grain to grain plus residues) to take into account that the whole above-ground biomass is harvested for cultivated fodder.

On-farm produced feeds

The quantity of on-farm produced feeds per head ($Q_{crop,onfarm}$) is determined depending on the management type considered. In the typology, MTs 5, 6, 12, and 13 include on-farms cropping in addition to a share of grass in the diet, whereas management types 14, 15, and 16 do not include grass.

$Q_{crop,onfarm} = Q_{crop}^h \Phi_{onfarm}^{crop}$ with Q_{crop}^h the quantity of crop per head in the animal diet, and Φ_{onfarm}^{crop} the share of crops produced on-farm.

$A_{crop} = \frac{Q_{crop,onfarm}}{Y_{crop}}$ with A_{crop} the necessary area for crops per head (on-farm feed production), Y_{crop} the yield of each crop.

To define the share of on-farm produced feeds in the diet, a comparison between production costs and purchasing costs needs to be done. The result is then either producing everything or purchasing everything. If all feeds are chosen to be produced on-farm, then the fertilizer costs and the opportunity cost of land need to be taken into account. We assume that the choice of the farmer (producing or purchasing all) will always go towards the cheaper. The share of on-farm produced feeds, noted Φ_{onfarm}^{crop} , is not determined here as the opportunity of land is solved here after thanks to the rent maximisation equation.

To obtain a share of crops produced on-farm between 0 (all produced) and 100 (all purchased), risk could be considered (Shang and McEwan, 2021). In this study, a model is built on how a farmer maximises his expected utility by choosing the limit of his farm. This limit, in terms of feed production, is on a continuous spectrum from total purchase to total on-farm production. The share of on-farm-grown feed is an optimum level defined by Shang and McEwan (2021) as:

$\Phi_{onfarm}^{crop} = \frac{(\mu_b - \mu_m + \alpha Q_{crop,total} \sigma_b^2)}{\alpha Q_{crop,total} \sigma_b^2 + \alpha Q_{crop,total} \sigma_m^2}$ where $Q_{crop,total}$ the total required quantity of feed in the diet, μ_m and σ_m^2 the mean and variance, respectively, of C_m the average cost for on-farm

produced crop, μ_b and σ_b^2 the mean and variance, respectively, of C_b the average market price for the crop in question, and α a coefficient of risk aversion (>0) which increases as the farmer becomes more risk-averse.

Nitrogen input on crops

Total nitrogen input per crop depends on yields and can be based on a crop nitrogen balance using a nitrogen use efficiency (NUE) per crop and per country, and the balance from Zhang et al. (2015). The nitrogen input that is not already provided by biological fixation and deposition is first provided by nitrogen from manure collected in barns. If there is not enough nitrogen, synthetic nitrogen is used.

$$N_{need, cn(\Phi_{onfarm}^{crop})}^h = \left(\frac{Y_{cn} \alpha^N}{NUE_{cn} - N_{fixation, cn} - N_{deposition}} \right) A_{cn} = \left(\frac{\Phi_{onfarm}^{crop} Q_{total}^{crop} \alpha^N}{NUE_{cn} - N_{fixation, cn} - N_{deposition}} \right) A_{cn} \quad \text{with}$$

$N_{need, cn(\Phi_{onfarm}^{crop})}^h$ the nitrogen needed for one crop (cn meaning nth crop) used as feed per head (h), which will come from the manure spread from barns and the synthetic nitrogen, Y_{cn} the yield of one specific crop, NUE_{cn} the nitrogen-use efficiency of one specific crop, and α^N the proportion of nitrogen per unit of production. Only one equation is shown here, but there is actually an equation per representative crop type, and they are summed as needed, leading to $N_{need, crop(\Phi_{onfarm}^{crop})}^h$ the nitrogen needed for all on-farm crop production per head. The losses of nitrogen from croplands

are defined by: $N_{losses, crop} = Y_{cn} \alpha^N \left(\frac{1}{NUE_{cn}} - 1 \right) A_{cn}$.

If $N_{need, crop}^h < N_{spread, crop}^h$ then $N_{spread, g}^h = N_{spread, crop}^h - N_{need, crop}^h$ and $N_{synth, crop}^h = 0$

If $N_{need, crop}^h > N_{spread, crop}^h$ then $N_{spread, g}^h = 0$ and $N_{synth, crop}^h = N_{spread, crop}^h - N_{need, crop}^h$

If $N_{spread, crop}^h > N_{need, crop}^h + N_a (A_{grazed} (1/S) + A_{har} (s, N_a, t^{pd}))$ then the difference is $N_{manure surplus}^h$.

N_{spread}^h is the total nitrogen available from manure collected in barns for one head of livestock,

$N_{spread, g}^h$ is the total nitrogen from manure that can be spread on grasslands per livestock head,

and $N_{synth, crop(\Phi_{onfarm}^{crop})}^h$ is the synthetic nitrogen spread on on-farm crops produced per head.

Input parameters for unit 4: actual crop yields, type of cultivated crops, and nitrogen use efficiency per crop and per country.

Input variables for unit 4: animal's diet.

Output variables for unit 4: cultivated feed crop areas, manure nitrogen applied on crop areas and synthetic nitrogen applied on crop areas, and share of residues coming from the on-farm-cultivated feed.

IV.3.1.5. Manure management unit

Nutrients deposited on pastures and nitrogen intake from pastures are modeled in the pasture management unit.

Manure collection and storage in various forms – solid, liquid, slurry, compost, or methanization – should be represented in this unit, accounting for different fluxes (volatilization, methane, and N₂O emissions) as well as the nitrogen available for application on croplands or pastures. Data on nitrogen loss rates, management system data (e.g., differentiating between natural deposition of manure directly on fields, deposition in barns at night before applying it on fields or no application of manure on fields – depending on the management type), and leaching rates can be found in the GLEAM model (FAO, 2017), in Herrero et al. (2013) or in IPCC (2006, 2019).

$N_{spread}^h = e_N \cdot (1 - l_{barn}) \cdot t^b$ where t^b is the time spent in barns (in days), determined in the "Pasture management" unit, e_N is the nitrogen excretion rate per head and per day, and l_{barn} is the share of nitrogen lost in the environment, depending on the manure management system. Nitrogen losses from the barn is defined by: $N_{losses, barn}^h = l_{barn} e_N t^b$.

Input variables for unit 5: manure collection and use.

Output variables for unit 5: applied manure.

IV.3.1.6. Climatic conditions unit

Climatic conditions affect herd mobility (time spent in barns), animal production (i.e., weight gain and milk yield are negatively affected by extreme climatic conditions, especially high temperatures

(Das et al., 2016)), and GHG emissions. Yields used in the "Relation to land" unit and NPP used explicitly or implicitly in the "Pasture management" unit also depend on climate conditions. In those cases, the climate information is not used explicitly, but only through model results.

IV.3.2. Financial and emission flows

IV.3.2.1. Economic analysis and costs unit

Based on the study of Udo and Steenstra (2010), the economic analysis unit includes the added value of production, representing revenues from the sales as well as manure and draught power, and additional benefits. The latter represents the walking insurance and financial capital of the animals, corresponding to the money saved as a guarantee that future requirements can be met (equivalent to insurance), as well as the expenses avoided by selling an animal for urgent needs (Udo and Steenstra, 2010). The value of animals serving as insurance can be based on the animal's weight and the price of meat. This hypothesis can lead to an under-evaluation of young animals, but the error is considered small compared to the simplification of the modeling thanks to this hypothesis.

Transportation

A location close to urban centres allows direct access to demand with low transport costs, but there is always strong competition with other possible land uses (high land prices). On the contrary, when adequate infrastructure is present, proximity to food production has advantages in terms of reducing input costs (especially in intensive systems where external feed represents a large part of the diet). Location far from consumption centres is associated with low land and labour prices (Robinson, 2011).

To calculate transportation costs, one indicator can be used: accessibility to markets. The best conditions for intensification, especially for mixed farming/livestock systems, have been identified in areas close to large urban centres and markets. Good access to markets is defined as less than 8 hours of travel from an urban centre with more than 250,000 inhabitants (Robinson, 2011). To simplify, the hypothesis can be made that all transport is made by trucks, not taking into account any other transport means such as boat or plane. Total transport costs (\$/km) are a function of fixed costs added to variable costs. Fixed costs take into account fuel, oil, tires, and spares and

variable costs account for the driver's wage, other labour, depreciation, interest and overheads, and others (Kulovic, 2004).

Crop prices and costs

Average crop prices per country can be used for crops externally bought. For crops cultivated on-farm and used as feed, mostly cereals, and fodder, the hypothesis used is that labour and capital costs are fixed per unit of land and per representative crop (only crops used for feed), those costs being dominated by tillage, sowing, weeding, pesticides, and fertilizer application which do not depend on yields. In the second step, the cost of harvest could depend on yield. The crop costs can be obtained per country based on the GTAP database (Center for Global Trade Analysis, 2020). For pesticide use, a cost per country and per unit of area can be used based on the input from the sectors corresponding to chemistry, after removing the nitrogen cost.

The share of off-farm feeds is defined as management type specific and is explained in the "Relation to land" unit. Using the outputs of the "Feed" and "Relation to land" units, the quantity of off-farm feeds to be bought is then calculated as a difference from the quantity of on-farm produced feeds. The cost for off-farm feeds depends on the price of feeds (f).

Cost of synthetic fertilization

The total synthetic nitrogen per head needed for grasslands is determined in the "Pasture management" unit, while the total synthetic nitrogen per head needed for feed crop production is determined in the "Relation to land" unit.

Building costs

The costs of a building are proportional to the size of the building, and a minimum is set. The size of barns depends on the size of the animal and the potential regulatory limit imposed in each country. To simplify, the minimum size of a barn is equivalent to 3 square meters per head. For cost calculation, a minimum for livestock fencing associated with barns is set. According to Mayer and Olsen (2012), a barbed wire fence costs approximately 4.8\$ per meter (with a cost of labour of 16\$ per hour per person) and 16\$ per square meter for a barn. They are also associated with several equipment such as animal feed, clean stables, and transport of animals. Depreciation costs and labour requirements should be included (Mosnier et al., 2017). Buildings are only needed if animals are housed, as described in the "Pasture management" unit, depending on the climatic conditions,

and on the management type considered (animals are housed in management types 1, 3, 4, 5, 6, 7, 8, 12, and 13 in case of low temperatures, and management types 9, 10, 11, 14, 15, and 16 regardless of the climate). Therefore, the cost of a barn depends on the management type, and should be multiplied by an indicator function noted $\mathbf{1MT}(B) = [B \in MT]$ where B is a subset of all management types, in which the animals are housed. The elements of this subset are defined as one (management type with a barn), or zero (management type without a barn).

Herd management labour and capital costs

Labour and capital data (machinery costs such as tractors, but excluding grass harvesting machines costs) can come from large surveys on dairy and beef cattle farms such as Cournut and Chauvat (2010), or Fagon and Sabatté (2010) but also in studies specified on one country such as Grandin et al. (1991), Kreuter and Workman (1997), Mattos and Uhl (1994), Bowman et al. (2012). The quantity of labour includes times to monitor calvings and calves during their first days (Mosnier et al., 2017) (see Table 5). Time for milking is proportional to the number of dairy cows producing milk in a given month, and to the equipment but does not vary according to milk yield and cow breed (Mosnier et al., 2017).

Table 5: Examples of quantity of labour (hours) for some cattle farming activities (from Mosnier et al. 2017)

	Beef breeds	Dairy breeds
Time for monitoring calving and calves (h/calving)	2,28	3,34
Time for milking with a herringbone milking system (h/cow/month)	0	2,75
Time for milking with a milking robot (h/cow/month)	0	1
Time for cleaning and feeding (animals in barn) (h/LSU/month)	1	1

Feeding, cleaning time, and renewing litter are proportional to the number of animals present in a barn each month (1 hour per month per livestock unit) but depend on the type of barn and the level of equipment (Mosnier et al., 2017). To simplify the calculation of herd management costs, we propose to differentiate dairy from non-dairy breeds (as done in the typology) to calculate the time for monitoring calves and calving, as well as cleaning and feeding. For milking time, a distinction is just made between hand-maid milking and with a herringbone. Labour costs are fixed per country.

Additional time required to handle animals (vaccinations, seasonal, and various operations) is fixed per livestock unit (Mosnier et al., 2017).

For non-grazing or partially grazing animals, grass harvesting costs per unit of harvested grass can be obtained either directly if the information is available, or from the cost of harvested grass with a harvester, the quantity of labor needed for harvesting manually, and the share of mechanization. The share of mechanization could be endogenized if needed, using a functional form to represent substitution (for example a Cobb-Douglas), and a cost minimization to obtain the total cost as a function of agricultural sector salaries. Data on grass harvesting costs can be found in Rotz and Shinnars (2007) or Lépée (2011).

Cost per head

The cost per head c_p^{MT} depends on the stocking rate (s), the nitrogen application rate (N_a), and the potential daily time spent on pastures (t^{pd}). The cost per head is necessarily linked to a specific location as it is profile related, as well as to the management type considered (e.g., in feedlots, the cost per head does not depend on the stocking rate). The cost per head is therefore defined as (see Table 6):

$$c_p^{MT}(s, N_a, t^{pd}, \phi_{onfarm}^{crop}) = \sum \gamma_p^{MT} \left(\frac{cost_{onfarm}}{Y_{p, onfarm}^{MT}} \phi_{p, onfarm}^{MT} + \pi_{p, offfarm}^{MT} \phi_{p, offfarm}^{MT} \right) + A_{fd} cost_{fd} + (N_{synth, g}^h + N_{synth, crop(\phi_{onfarm}^{crop})}^h) \pi_{N_{synth}} + Y_{har}^{MT}(s, N_a; \phi_{p, g}^{MT} \gamma_p^{MT}) cost_{har} A_{har}(s, N_a, t^{pd}) + cost_{barn} 1_{MT}(B)$$

with $A_{fd} = \frac{\phi_{p, fd}^{MT} \gamma_p^{MT}}{Y_{fd}}$ the cultivated area for fodder.

Table 6: Variables and symbols used in the cost per head calculation

Symbols	Unit	Explanation
c_p^{MT}	\$	Cost per head of animal profile p over a year
$\phi_{p, y}^{MT}$	%	Share of a feed type in the diet per profile (p) in a management type (MT) (y corresponds to on-farm= on-farm produced feed, off-farm= externally bought feeds, g=harvested grass, or fd=fodder)
γ_p^{MT}	/	Input coefficient, the quantity of total feed energy or dry matter per head
$\pi_{p, z}^{MT}$	\$	Price (z corresponds to off-farm = externally bought feeds, N_{synth} = synthetic nitrogen)

$Y_{p,x}^{MT}$	kg/ha	Yield (x corresponds to on-farm= on-farm produced feed, har= harvested grass, fd= fodder)
$N_{synth,w}^h$	kg/ha	Synthetic nitrogen spread on crops per head (w corresponds to g= grasslands, crop = on-farm produced crops)
cost _{zx}	\$	Cost for various activities (x corresponds to fd = fodder, on-farm = on-farm produced crops, har = harvested grass, barn = housing)
A_x	ha	Necessary area per head (x corresponds to fd = fodder, har = harvested grass)

Input parameters for unit 7: access to market, labour and capital costs per unit of land and per representative feed crops, pesticide use cost per country and per unit of area, the minimum cost for a building, labour costs per country, capital costs, labour quantity per animal and per equipment, and grass harvesting costs per unit of harvested grass, concentrate feed crops prices, and synthetic nitrogen price.

Input variables for unit 7 (coming from other units): yield of representative feed crops per country, nitrogen use efficiency per crop and per country, synthetic nitrogen applied on feed crops and grasslands, the quantity of harvested grass, and presence or absence of barn.

Output variables for unit 7: costs for various activities (transportation, crop prices and costs, building costs, herd management costs, synthetic nitrogen cost).

IV.3.2.2. GHG emissions, nitrogen losses and carbon footprint unit

The main sources of global anthropogenic GHG emissions are the production of animal feed, the consumption of fossil energy for the transport and preservation of livestock products, enteric fermentation, and animal waste (Ickowicz et al., 2017). GHG emissions depend on diet composition, species and breeds, carrying capacity, land-use, and production.

Enteric fermentation is the digestive process of ruminants, one of the by-products of which is methane (CH₄). The amount of methane emitted depends on the species, and individual variables such as age, weight, and the quantity and quality of the feed intake. Ruminants, due to their

intestinal structure, are major methane emitters (ADEME, 2020). Below are some examples of amounts of methane produced by species (ADEME, 2020):

- Dairy cow: 121 kg CH₄/head/year;
- Other cattle: 51 kg CH₄/head/year;
- Goat: 11,7 kg CH₄/head/year;
- Sheep: 9,3 kg CH₄/head/year.

These figures are only orders of magnitude and not exact values since GHG emissions vary with input feed requirement and feed digestibility (IPCC, 2019), and also from one individual to another. Emission factors from enteric fermentation for cattle by production system and by region of the world can be found in GLEAM (FAO, 2017), or computed using the IPCC (2019) methodology.

Apart from being major GHG emissions contributors, ruminant systems can also help to stock carbon as grasslands are major carbon sinks. The soil carbon balance is computed in the ORCHIDEE-GM model. Below are some values on carbon stock in the soil per hectare, over the 0-30 centimeters horizon, depending on the type of land use (Gac et al. 2010):

- Arable lands: 43 t C/ha;
- Grasslands: 70 t C/ha;
- Long-term grasslands: 570 kg C/ha/year;
- Mixed forests: 70 t C/ha.

Nitrogen applied emissions

The nitrogen applied is determined based on nitrogen balances. Nitrogen balances, per unit of area, are described in the crop unit and pastures management units.

Soil and grassland managements produce GHG, N₂O from nitrogen application and soil management, and CO₂ from liming and urea application. Soil fertilization can be mineral (synthetic fertilizers) or organic (manure). The equations and emission factors used to calculate GHG emissions due to nitrogen fertilization are given in IPCC (2006).

For an average French farm, the nitrogen balance surplus is 81 kilograms N per hectare. The potential futures of this surplus (Foray and Gac, 2018) are:

- N stock in soil: 19 kg N/ha;
- Loss to water: 35 kg N/ha;
- Loss to air: 27 kg N/ha.

Mixed systems (crop/livestock) seem to have better results in terms of nitrogen balance and associated costs than specialized systems (Mischler, 2017):

- - 58% on the N/ha balance;
- -36% of phytosanitary products/ha on crops;
- -20% in fuel costs.

Other data needed for such a model can be gathered from GLEAM (FAO, 2017) such as emissions factors for feed processing and transport.

To account for the value of nitrogen losses (from on-farm production, off-farm production, pastures, and manure), an evaluation of water purification cost can be made through the price of water purification $\pi^{N_{water}}$. Although Singh and Craswell (2021) affirm that only 15 percent of nitrogen outflows are leaching, much of the unused nitrate in the soil, however, dissolves in rain and irrigation water, eventually leaching into aquifers or surface waters (Singh and Craswell, 2021). The study by Trepel (2010) estimates that water purification costs vary between 1€ and 50€ per retained kilogram of nitrogen. Nitrogen leaching leads to the eutrophication of water. The cost of eutrophication (c_e) is defined as:

$$c_e = \pi^{N_{water}} \cdot \sum N_{losses} \cdot \left(\frac{\lambda_{leach}}{\lambda_{vol} + \lambda_{leach}} \right) = \pi^{N_{water}} \cdot \sum N_{losses} \cdot \left(\frac{0,24}{0,16 + 0,24} \right), \text{ where } \lambda_{leach} \text{ is the fraction of}$$

nitrogen lost by leaching or runoff (Kg N)⁻¹ and λ_{vol} the average fraction of nitrogen that is volatilised from synthetic fertiliser and from all organic fertilisers applied and deposited (data comes from IPCC, 2019). N_{losses} are coming from on-farm and off-farm crops, pastures, and manure management. It could be relevant to not have the same fractions from the volatilisation of nitrogen from synthetic fertiliser and from organic fertiliser, but it allows for simplicity as a first approximation.

The value of GHG emissions per head is noted V_{GHG}^h . To account for the non-conventional intensification, where the private economic profit is not the only objective, a carbon price is added such as: $V_{GHG}^h = \pi^{cb} GHG^h$ with GHG^h the GHG emissions per head, and π^{cb} the price of

carbon. Carbon price trajectories could be taken from IPCC (2022), and GHG emissions per head are a sum of emissions coming from manure (see the “Manure management” unit and coefficients from IPCC) and emissions coming from enteric fermentation (IPCC, GLEAM (FAO, 2022)).

Input parameters for unit 8: enteric fermentation factors by production system and by region of the world, carbon stock value per hectare, emission factors for GHG emissions due to nitrogen, and emissions factors for feed processing and transport.

Input variables for unit 8 (coming from other units): feed requirement and feed digestibility, nitrogen balances per unit of area, areas, and carbon balance of grasslands.

Output variable for unit 8: GHG emissions and carbon balance, nitrogen balance.

IV.4. MODULE 2: LINEAGE GROUPS MODELING

The functional unit for the lineage group is one cow head per lineage group.

The link between animal profiles is represented by the cattle herd structure (see Figure 10), which is a linear and stationary system model with the year as the temporal factor. Lineage groups are classified using movements between management types. While evolving towards another profile, cattle can progress towards another management type or stay in their management type of origin. In the lineage groups classification (see Part 2), the possibility of reproductive cattle going through specialized systems is considered. For the global modeling, however, this possibility is not considered, as this increases importantly the number of possible lineage groups and it has been described as a rare case by experts (see Annexe 1) that should not bring in many variations to the model.

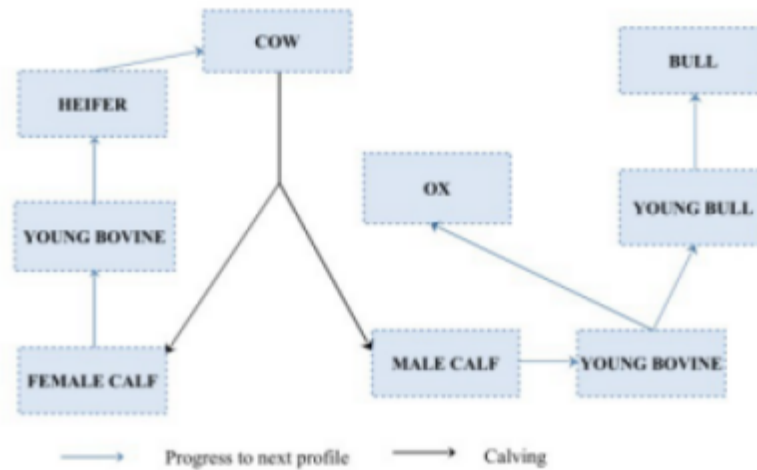


Figure 10: Cattle herd structure (FAO, 2011)

To obtain the number of heads per mother for each animal profile of each lineage group, some values and data are needed. These values depend on management types, in particular on the management type of origin, but also on market conditions. Therefore lineage group structures are closely interlinked to management types that compose them, in terms of cattle breeds and herd management as they distinguish between multi-functional objectives and meat or dairy production. The relevant parameters for lineage group structure depending on management types are the following:

- herd parameters: mortality rates, birth rates, replacement rates, age at first calving, including slaughtering at birth (multifunctionality is considered to be the main driver here, also possibly the breed in case of specialized systems, meat or dairy);
- number of bulls used for natural reproduction, or use of artificial insemination, depending in particular on breed and whether the management type is multi-functional or specialized, specialized management types with dairy breeds being often associated with artificial insemination, more rarely other management types;
- numbers of oxen, if any, only present in case of integration with cropping and with multi-functional objectives. The management type is not necessarily the only driver of oxen presence, the relative price of other draught sources, in particular, labour and machinery can also influence the presence and use of oxen for draught power;
- numbers of animals slaughtered per profile (off-take rates).

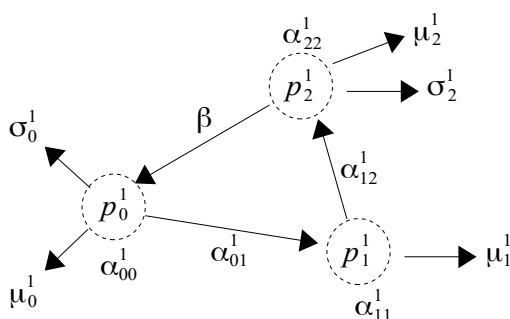
The use of veterinary services could also be considered here, based on the management type. Herd management input data relevant at the lineage group level such as death rates, fertility rates, replacement rates, age at first calving, and bull-to-cow ratio could be coming from GLEAM (FAO,

2017).

As a first example (**example n°1**), a flow system model can be built with one management type (MT1) and three animal profiles (p_0 , p_1 , and p_2), belonging to the same lineage group (LG1). We are below building a system with the year as our temporal factor (see Table 7).

Table 7: Variables and symbols used in the lineage group modelling

Symbols	Unit	Explanation
p_x^y	/	Animal profile x in management type y
$Nb_{x,t}^y$	#	Number of animals per animal profile x in management type y at time t
α_{kp}	%	Rate of animals going from animal profile k to animal profile p within a year
β_p	%	Birth rate in animal profile p
σ_p	%	Slaughter rate in animal profile p
μ_p	%	Annual mortality rate of animal profile p
$A_{LG}(s, N_a)$	ha	Necessary area for one lineage group (copping land and pastures) depending on the stocking rate (s) and the nitrogen application rate (N_a)
$A_p^{MT}(s, N_a)$	ha	Necessary area for one profile p in one management type MT depending on the stocking rate (s) and the nitrogen application rate (N_a)



p_0^1 → profile 0 of MT1, calf fed with grass
 p_1^1 → profile 1 of MT1, heifer fed with grass
 p_2^1 → profile 2 of MT1, dairy cow fed with a mix of grass and cereals

The factors to go from one profile to another are determined by the rates of animals going from one profile to another (α), while taking the mortality rate (μ) and the slaughter rate (σ) of each profile into account, as described in the above flow model. α_{pp}^1 Here refers to the

rate/probability at which an animal of profile p remains in profile p after one year, which is inversely proportional to the amount of time that an animal stays in that profile, on average. By definition of rates adding up to 100 percent, it follows that:

$$\alpha_{01}^1 + \mu_0^1 + \sigma_0^1 + \alpha_{00}^1 = 1 \quad \Leftrightarrow \quad \alpha_{00}^1 = 1 - \mu_0^1 - \sigma_0^1 - \alpha_{01}^1$$

$$\alpha_{12}^1 + \mu_1^1 + \alpha_{11}^1 = 1 \quad \Leftrightarrow \quad \alpha_{11}^1 = 1 - \mu_1^1 - \alpha_{12}^1$$

$$\alpha_{22}^1 + \mu_2^1 + \sigma_2^1 = 1 \quad \Leftrightarrow \quad \alpha_{22}^1 = 1 - \mu_2^1 - \sigma_2^1$$

For this example, I consider that, at birth, the proportion of male and female calves is half-half. In the case of a female, the animal moves to the heifer profile, whereas in the case of a male, the animal is slaughtered. After first calving, heifers are moving to the dairy cow profile. For all profiles, mortality rates are accounted for.

The number of heads for each profile of the lineage group is used to describe the lineage group. Therefore, for animal profiles, p_1^1 , p_2^1 and p_0^1 , the variation of the number of animals (Nb) across time (t) are:

$$Nb_{0,t+1}^1 = Nb_{0,t}^1 - \alpha_{01}^1 Nb_{0,t}^1 - \sigma_0^1 Nb_{0,t}^1 - \mu_0^1 Nb_{0,t}^1 + \beta Nb_{2,t}^1 = \alpha_{00}^1 Nb_{0,t}^1 + \beta Nb_{2,t}^1$$

$$Nb_{1,t+1}^1 = Nb_{1,t}^1 - \alpha_{12}^1 Nb_{1,t}^1 - \mu_1^1 Nb_{1,t}^1 + \alpha_{01}^1 Nb_{0,t}^1 = \alpha_{11}^1 Nb_{1,t}^1 + \alpha_{01}^1 Nb_{0,t}^1$$

$$Nb_{2,t+1}^1 = Nb_{2,t}^1 - \sigma_2^1 Nb_{2,t}^1 - \mu_2^1 Nb_{2,t}^1 + \alpha_{12}^1 Nb_{1,t}^1 = \alpha_{22}^1 Nb_{2,t}^1 + \alpha_{12}^1 Nb_{1,t}^1, \text{ where the second equation follows from the set of equation directly above (definition of rates summing to one).}$$

At the stationary state, we have $Nb_{0,t+1}^1 - Nb_{0,t}^1 = 0$, $Nb_{1,t+1}^1 - Nb_{1,t}^1 = 0$, and

$$Nb_{2,t+1}^1 - Nb_{2,t}^1 = 0.$$

$$Nb_0^1 = \alpha_{00}^1 Nb_0^1 + \beta Nb_2^1 \quad \Leftrightarrow \quad (1 - \alpha_{00}^1) Nb_0^1 = \beta Nb_2^1 \quad \Leftrightarrow \quad (\alpha_{01}^1 + \mu_0^1 + \sigma_0^1) Nb_0^1 = \beta Nb_2^1$$

$$Nb_1^1 = \alpha_{11}^1 Nb_1^1 + \alpha_{01}^1 Nb_0^1 \quad \Leftrightarrow \quad (1 - \alpha_{11}^1) Nb_1^1 = \alpha_{01}^1 Nb_0^1 \quad \Leftrightarrow \quad (\alpha_{12}^1 + \mu_1^1) Nb_1^1 = \alpha_{01}^1 Nb_0^1$$

$$Nb_2^1 = \alpha_{22}^1 Nb_2^1 + \alpha_{12}^1 Nb_1^1 \quad \Leftrightarrow \quad (1 - \alpha_{22}^1) Nb_2^1 = \alpha_{12}^1 Nb_1^1 \quad \Leftrightarrow \quad (\sigma_2^1 + \mu_2^1) Nb_2^1 = \alpha_{12}^1 Nb_1^1$$

Because of the colinearity of the three equations above, we have

$$\beta Nb_2^1 = (\alpha_{01}^1 + \mu_0^1 + \sigma_0^1) Nb_0^1$$

$$Nb_0^1 = \frac{(\alpha_{12}^1 + \mu_1^1)}{\alpha_{01}^1} Nb_1^1$$

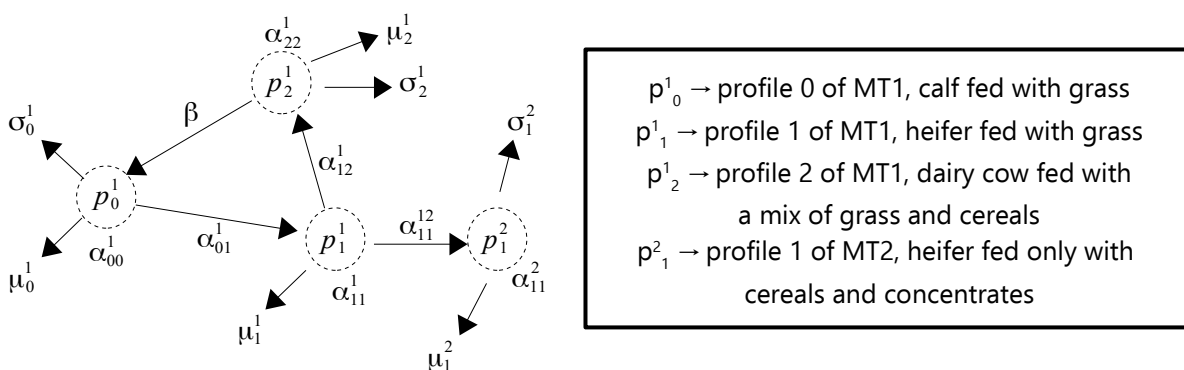
$$Nb_1^1 = \frac{(\mu_2^1 + \sigma_2^1)}{\alpha_{12}^1} Nb_2^1$$

$$\beta Nb_1^1 = \left(\frac{\mu_2^1 + \sigma_2^1}{\alpha_{12}^1} \right) (\mu_0^1 + \sigma_0^1 + \alpha_{01}^1) \left(\frac{\mu_1^1 + \alpha_{12}^1}{\alpha_{01}^1} \right) Nb_1^1 \Leftrightarrow \beta = (\mu_2^1 + \sigma_2^1) \left(1 + \frac{\mu_0^1 + \sigma_0^1}{\alpha_{01}^1} \right) \left(1 + \frac{\mu_1^1}{\alpha_{12}^1} \right)$$

From the above equations, the birth rate is correlated to all other parameters of the flow model. Therefore, at the stationary state, the birth rate increases when the mortality rates and slaughter rates increase. The birth rate, however, decreases when the rates to go from one profile to another increase.

By the definition of the functional unit, $Nb_2^1 = 1$. The necessary area for the lineage group (LG1) is defined by: $A_{LG1}(s, N_a) = \sum Nb_p^{MT1} \cdot A_p^{MT1}(s, N_a)$.

As a second example (**example n°2**), another flow system is built with two management types (MT1 and MT2) and four animal profiles ($p_0^1, p_1^1, p_2^1, p_1^2$), all belonging to the same lineage group (LG1). Compared with example n°1, this example adds a possibility to leave MT1 at the heifer profile to be fattened in another management type (MT2).



The factors to go from one profile to another are determined by the rates of animals going from one profile to another (α), while taking the mortality rate (μ) and the slaughter rate (σ) of each profile into account, as described in the above flow model. α_{pp}^1 Here refers to the rate/probability at which an animal of profile p remains in profile p after one year, which is inversely proportional to the amount of time that an animal stays in that profile, on average. By definition of rates adding up to 100 percent, it follows that:

$$\begin{aligned} \alpha_{01}^1 + \mu_0^1 + \sigma_0^1 + \alpha_{00}^1 &= 1 \Leftrightarrow \alpha_{00}^1 = 1 - \mu_0^1 - \sigma_0^1 - \alpha_{01}^1 \\ \alpha_{12}^1 + \mu_1^1 + \alpha_{11}^1 + \alpha_{11}^{12} &= 1 \Leftrightarrow \alpha_{11}^1 = 1 - \mu_1^1 - \alpha_{12}^1 - \alpha_{11}^{12} \\ \alpha_{11}^2 + \mu_1^2 + \sigma_1^2 &= 1 \Leftrightarrow \alpha_{11}^2 = 1 - \mu_1^2 - \sigma_1^2 \end{aligned}$$

$$\alpha_{22}^1 + \mu_2^1 + \sigma_2^1 = 1 \quad \Leftrightarrow \quad \alpha_{22}^1 = 1 - \mu_2^1 - \sigma_2^1$$

The number of heads for each profile of the lineage group is used to describe the lineage group. Therefore, for animal profiles, p_0^1 , p_1^1 , p_2^1 , and p_1^2 , the variation of the number of animals (Nb) across time (t) are:

$$Nb_{0,t+1}^1 = Nb_{0,t}^1 - \alpha_{01}^1 Nb_{0,t}^1 - \sigma_0^1 Nb_{0,t}^1 - \mu_0^1 Nb_{0,t}^1 + \beta Nb_{2,t}^1 = \alpha_{00}^1 Nb_{0,t}^1 + \beta Nb_{2,t}^1$$

$$Nb_{1,t+1}^1 = Nb_{1,t}^1 - \alpha_{12}^1 Nb_{1,t}^1 - \alpha_{11}^{12} Nb_{1,t}^1 - \mu_1^1 Nb_{1,t}^1 + \alpha_{01}^1 Nb_{0,t}^1 = \alpha_{11}^1 Nb_{1,t}^1 + \alpha_{01}^1 Nb_{0,t}^1$$

$$Nb_{1,t+1}^2 = Nb_{1,t}^1 - \sigma_1^2 Nb_{1,t}^1 - \mu_1^2 Nb_{1,t}^1 + \alpha_{11}^{12} Nb_{1,t}^1 = \alpha_{11}^2 Nb_{1,t}^2 + \alpha_{11}^{12} Nb_{1,t}^1$$

$Nb_{2,t+1}^1 = Nb_{2,t}^1 - \sigma_2^1 Nb_{2,t}^1 - \mu_2^1 Nb_{2,t}^1 + \alpha_{12}^1 Nb_{1,t}^1 = \alpha_{22}^1 Nb_{2,t}^1 + \alpha_{12}^1 Nb_{1,t}^1$, where the second equation follows from the set of equation directly above (definition of rates summing to one).

At the stationary state, we have $Nb_{0,t+1}^1 - Nb_{0,t}^1 = 0$, $Nb_{1,t+1}^1 - Nb_{1,t}^1 = 0$, $Nb_{2,t+1}^1 - Nb_{2,t}^1 = 0$, and $Nb_{1,t+1}^2 - Nb_{1,t}^2 = 0$.

$$Nb_0^1 = \alpha_{00}^1 Nb_0^1 + \beta Nb_2^1 \quad \Leftrightarrow \quad (1 - \alpha_{00}^1) Nb_0^1 = \beta Nb_2^1 \quad \Leftrightarrow \quad (\alpha_{01}^1 + \mu_0^1 + \sigma_0^1) Nb_0^1 = \beta Nb_2^1$$

$$Nb_1^1 = \alpha_{11}^1 Nb_1^1 + \alpha_{01}^1 Nb_0^1 \quad \Leftrightarrow \quad (1 - \alpha_{11}^1) Nb_1^1 = \alpha_{01}^1 Nb_0^1 \quad \Leftrightarrow \quad (\alpha_{12}^1 + \mu_1^1 + \alpha_{11}^{12}) Nb_1^1 = \alpha_{01}^1 Nb_0^1$$

$$Nb_1^2 = \alpha_{11}^2 Nb_1^2 + \alpha_{11}^{12} Nb_1^1 \quad \Leftrightarrow \quad (1 - \alpha_{11}^2) Nb_1^2 = \alpha_{11}^{12} Nb_1^1 \quad \Leftrightarrow \quad (\mu_1^2 + \sigma_1^2) Nb_1^2 = \alpha_{11}^{12} Nb_1^1$$

$$Nb_2^1 = \alpha_{22}^1 Nb_2^1 + \alpha_{12}^1 Nb_1^1 \quad \Leftrightarrow \quad (1 - \alpha_{22}^1) Nb_2^1 = \alpha_{12}^1 Nb_1^1 \quad \Leftrightarrow \quad (\mu_2^1 + \sigma_2^1) Nb_2^1 = \alpha_{12}^1 Nb_1^1$$

Because of the colinearity of the equations above, we have

$$\beta Nb_2^1 = (\alpha_{01}^1 + \mu_0^1 + \sigma_0^1) Nb_0^1$$

$$Nb_0^1 = \frac{(\alpha_{12}^1 + \mu_1^1 + \alpha_{11}^{12})}{\alpha_{01}^1} Nb_1^1$$

$$Nb_1^1 = \frac{(\mu_2^1 + \sigma_2^1)}{\alpha_{12}^1} Nb_2^1$$

$$\beta Nb_2^1 = \left(\frac{\mu_2^1 + \sigma_2^1}{\alpha_{12}^1} \right) (\mu_0^1 + \sigma_0^1 + \alpha_{01}^1) \left(\frac{\mu_1^1 + \alpha_{12}^1 + \alpha_{11}^{12}}{\alpha_{01}^1} \right) Nb_2^1 \quad \Leftrightarrow \quad \beta = (\mu_2^1 + \sigma_2^1) \left(1 + \frac{\mu_0^1 + \sigma_0^1}{\alpha_{01}^1} \right) \left(1 + \frac{\mu_1^1 + \alpha_{12}^1}{\alpha_{12}^1} \right)$$

The conclusions from the example n°1 holds in this example. If the rate to go from profile 1 of MT1 to profile 1 of MT2 increases, then the birth rate also increases.

For the lineage group (LG1):

$$A_{LG1}(s, N_a) = \sum (Nb_p^{MT1} + Nb_p^{MT2}) \cdot (A_p^{MT1}(s, N_a) + A_p^{MT2}(s, N_a))$$

IV.5. MODULE 3: NET BENEFITS

Meat production is defined as the difference in weight between the beginning of the animal profile and the end of it.

The cost per head is c_p^{MT} and is described in the "Economic analysis and costs" unit. When a lactating cow has a calf (until weaning), the cost of the calf is added to the mother's cost. The total cost of an animal profile is obtained by multiplying the number of animals in each profile by the cost per head (see Table 8).

Table 8: Variables and symbols used in the net benefits calculation

Symbols	Unit	Explanation
p_x^y	/	Animal profile
Nb_p^{MT}	#	Number of animals per animal profile p in MT
α_{kp}^{MT}	/	Rate of animals going from animal profile k to animal profile p in management type MT within a year
S_p^{MT}	#	Number of animal slaughtered per profile
Q_p^x	kg	Quantity per profile (x corresponds to m=meat, f=feed, or mi=milk)
ρ_p^m	kg	Average weight of a carcass per profile
ρ_p^{mi}	L/year	Average milk production per profile
$c_p^{MT}(s, N_a, t^{pd}, \phi_{onfarm}^{crop})$	\$	Cost per head of animal profile p in management type MT depending on the stocking rate (s), the nitrogen application rate (N_a), the potential daily time spent on pastures (t^{pd}), and the share of on-farm crops (ϕ_{onfarm}^{crop})
π^z	\$	Price (z corresponds to f=feed, c=crop, g=grass, m=meat, cb=carbon, r=residues, mi=milk, N_{synth} = synthetic nitrogen, ec=external feeds, t=transport costs)
C_{LG}	\$	Total cost of the lineage group
$N_{synth}^{g,T}$	kg/ha	Synthetic nitrogen spread on crops for all livestock head

A_x	ha	Necessary area (x corresponds to grazed= grazed grass, har=harvested grass, crops = on-farm crops for feed)
$\hat{V}_{f,i}$	€	Value of the use of animals as walking financial capital (f) and insurance (i)
$\hat{V}_{ma\ surplus}$	€	Value of the surplus of manure (ma)
τ	/	The gain per unit of value taking into account the gain as walking financial capital and insurance
$N_{masurplus}^h$	kgN/h a	Nitrogen application rate of surplus of manure per head
$\Phi_{crop, onfarm}$	/	Share of on-farm crops in the diet of animals

The costs of animal profile p in management type MT are defined as:

$$Nb_p^{MT} c_p^{MT}(s, N_a, t^{pd}, \Phi_{onfarm}^{crop}) .$$

The total cost of the lineage group is obtained by adding all costs per head :

$C_{LG} = \sum Nb_p^{MT} c_p^{MT}(s, N_a, t^{pd}, \Phi_{onfarm}^{crop}) + \pi^l (\alpha_{kp}^{MT} Nb_p^{MT})$ where, when necessary and depending on the profile and the management type, π^l = transport costs (\$/km/head) of animals going from phase k to phase p with average distances depending on location.

To calculate the profit of the lineage group, the quantity of some products (meat and milk), as well as the value of others (manure, the use of animals as walking financial capital, and insurance) are defined below.

The quantity of meat (m) produced per profile is obtained by: $Q_p^m = S_p^{MT} \rho_p^m$.

The quantity of milk (mi) produced per profile is obtained by: $Q_p^{mi} = Nb_p^{MT} \rho_p^{mi}$.

The value of the use of animals as walking financial capital (f) and insurance (i) is defined as :

$\hat{V}_{f,i} = Nb_p^{MT} \rho_p^m \tau$ where τ is the gain per unit of value taking into account the gain as walking financial capital and insurance (Weiler et al., 2014).

The manure produced by animals is considered primarily used on on-farm crops, and then, on pastures. In the case of a surplus of manure (ma), its value is defined as:

$$V_{ma\ surplus}^{\hat{}} = N_{masurplus}^h \pi^{N_{synth}} \pi^{N_{water}} .$$

The value of GHG emissions is defined in the "GHG emissions, nitrogen losses, and carbon footprint unit" as: $V_{GHG}^{\hat{}} = \pi^{cb} GHG^h$.

The profit function of the lineage group is defined as:

$$profit_{LG} = \sum_p (Q_p^m \pi^m + Q_p^{mi} \pi^{mi} + V_{f,i}^{\hat{}} + V_{ma\ surplus}^{\hat{}} + V_{GHG}^{\hat{}}) - \sum_p Nb_p^{MT} c_p^{MT}(s, N_a, t^{pd}, \Phi_{onfarm}^{crop})$$

The economic rent is chosen to compare lineage groups. The rent represents the profit per unit of surface, and is given by:

$$rent_{LG} = \frac{profit}{area} = \frac{\sum_p (Q_p^m \pi^m + Q_p^{mi} \pi^{mi} + V_{f,i}^{\hat{}} + V_{ma\ surplus}^{\hat{}}) - \sum_p Nb_p^{MT} c_p^{MT}(s, N_a, t^{pd}, \Phi_{onfarm}^{crop})}{\sum_{p \in LG} (A_{grazed}(1/s) + A_{har}(s_p, N_{a_p}, t_p^{pd}) + A_{crop}(\Phi_{onfarm}^{crop}))}$$

Finally, the rent per lineage group is maximised to represent the maximum economic benefit possible per unit of land:

$$Max_{s_p, N_{a_p}, \Phi_{onfarm}^{crop}} = \frac{\sum_p (Q_p^m \pi^m + Q_p^{mi} \pi^{mi} + V_{f,i}^{\hat{}} + V_{ma\ surplus}^{\hat{}}) - \sum_p Nb_p^{MT} c_p^{MT}(s, N_a, t^{pd})}{\left(\sum_{p \in LG} (A_{grazed}(s_p, N_{a_p}) + A_{har}(s_p, N_{a_p}) + A_{crops}(s_p, N_{a_p})) \right)}$$

The maximisation of the rent allows determining the nitrogen application rate (N_a), the stocking rate (s), and the share of crop produced on-farm (Φ_{onfarm}^{crop}).

IV.5. PERFORMANCE CALCULATIONS

The last module of this model is to analyse and calculate the performances of lineage groups including environmental impacts. Net profit is calculated for each lineage group to then choose the lineage group with the maximum profit. To obtain each lineage group coefficient, one option could be to assess the environmental impacts of each cattle farming co-products (meat, milk, manure, drought power, walking financial capital, insurance) and each profile and perform an economic allocation for GHG emissions calculation.

This part does not constitute a module of the model in itself but is rather a way to use the model's

results.

The economic values of co-products can be assessed indirectly by breaking down the economic value of a lineage group into the profile level and performing an allocation of GHG emissions to the various outcomes based on their economical value (Weiler et al., 2014).

Table 9: Units used in the economic allocation

Unit	Value	Explanation
\hat{V}_{pr}^{LG}	€/year	Total net economic value of product pr within a year
\bar{V}^{LG}	€/year	Total value for the lineage group
Q_p^{mi}	kg/year	Quantity of milk produced per profile per year
S_p^{MT}	#	Number of animal head going to slaughter per profile per year
π^x	€/kg (for f and mi) €/head (for m)	Price (x corresponds to N_{synth} = synthetic fertilizer (of the most common N fertilizer), mi = milk, m=meat)
Q_p^N	kg	Quantity of manure used as fertilizer per profile
$V_p^{f,head}$	€	Economic value of cattle sold due to reasons of finance
b_f	€	Average interest rate in the country
stock value _p	€	Economic value of the average cattle stock per profile
b_i	€	Cost that owner would need to pay to purchase insurance coverage equal to the capital value of their head
\dot{GHG}_p^{MT}	eqCO2/head/year	GHG emissions per head
\hat{GHG}	eqCO2/product/year	GHG emissions per product (kg milk, kg meat, kg manure used as fertilizer, €/head for walking capital, €/head for insurance) and per LG
\bar{GHG}	eqCO2/LG/year	Total GHG emissions per lineage group
\hat{A}	%	Allocation factor

We note $Pr = \{mi; m; ma; f; i\}$ the set of possible products (pr), with mi corresponding to milk, m to meat, ma to manure, f to finance, and i to insurance. We note L the set of animal profiles of a lineage group. We note \hat{V}_p^{LG} the value of product pr for the whole lineage group, obtained by summing over animal profile (p) productions (see Table 9):

$$\hat{V}_{mi}^{LG} = \left(\sum_{p \in LG} Q_p^{mi} \right) \cdot \pi^{mi}$$

$$\hat{V}_m^{LG} = \left(\sum_{p \in LG} S_p^{MT} \right) \cdot \pi^m$$

$$\hat{V}_{ma}^{LG} = \pi^{N_{synh}} \sum_{p \in LG} Q_p^N$$

$$\hat{V}_f^{LG} = \left(\sum_{p \in LG} V_p^{f, head} \right) \cdot b_f$$

$$\hat{V}_i^{LG} = \left(\sum_{p \in LG} stock\ value_p \right) \cdot b_i$$

The total value for the lineage group $V^{\bar{LG}}$ is: $V^{\bar{LG}} = \sum_{pr \in Pr} \hat{V}_{pr}^{LG}$.

Total GHG emissions for the lineage group is: $G\bar{HG} = \sum_{p \in LG} Nb_p^{MT} G\dot{H}G_p^{MT}$ with $G\dot{H}G_p^{MT}$ the GHG emissions per head, as described in "GHG emissions and carbon footprint" unit.

Then, we perform an economic allocation based on the economic value of each farming product and we allocate total emissions to each product based on the rate of the product value in total products value, \hat{A} , at the lineage group scale.

$$\forall pr \in Pr: \quad G\hat{H}G = \hat{A} G\bar{HG} = \frac{\hat{V}_{pr}^{LG}}{V^{\bar{LG}}} G\bar{HG}$$

IV.6. DISCUSSION

The model presented in this part is a static and deterministic model with optimization, and is divided into three modules. The first module of the model aims at determining production areas and feed requirements and is done at the grid cell level with a functional unit being the animal profile. The expected result of the first module is a representation of each profile in each grid cell, along with an economic evaluation, allowing to take the diversity and multifunctionality of systems into account. Then, animal profiles are grouped together in a lineage group in the second module. The number of heads in each profile is determined at the lineage group level, to then be rescaled

per unit of area. Finally, in the third module of the model, impacts, and benefits are assessed at the animal profile level to then be aggregated at the lineage group level. In these modules 2 and 3, the economic profit of the lineage group is calculated using the value of each product: milk, meat, manure, insurance, and walking capital, allowing to group related animals together and calculate their economic benefit. Through the optimization, several variables of module 1 are calculated. Thanks to the results of this module, an environmental analysis can be performed through an economic allocation. GHG emissions of each lineage group can then be evaluated for example allowing to define which lineage group is the most efficient depending on the objective (economic or environmental performance). All lineage groups are evaluated for each grid cell but only one is selected based on the preferred objective.

At the end of the third module, the economic rent, representing the profit per unit of surface, is maximized. The relevance of this choice can be discussed at the world scale. Indeed, in some countries, local dynamics, such as the Common Agricultural Policy (CAP) in the European Union, is a large determinant of the revenues perceived by herders and a strong driver of livestock farming evolution. Extensification could maximise the rent if costs are minimized. For example, if input costs, feed costs, or labor costs increase. By taking the multifunctionality of livestock farming into account, extensification could be favoured over intensification. The CAP subsidies could enter the calculation of the rent when looking at the private profit. As there is not enough information about government subsidies worldwide, they are not entering the calculation.

As long as the combination of management type and lineage group is considered, the part of the rent that is being maximised depends on variables that were not determined before, such as the share of feed produced on-farm (0 or 1). This part is therefore linear. As the maximization of the rent corresponds to the determination of grazing practices, choosing to not take subsidies into account works well. If we were to compare management types and lineage groups, subsidies could play, however, a major role.

Although several management types and lineage groups can be located on one grid cell, the maximisation function can only select one lineage group per grid cell. This is a limitation of the model as, in reality, it is common that diverse management types coexist on small areas, next to each other, or even within the same farm (e.g., grazing animals coexisting with confined animals with cut-and-carry fodder in the same area). Either these management types belong to the same

lineage group, which then does not pose any issue for the model, or they belong to different lineage groups, which in this case could not be modeled. One solution to counter that limitation could be to have non-linearity or heterogeneity within each grid cell.

Grid cells are also linked through the nomadic movements of animals. Indeed, these movements imply that cattle move from one grid cell to another, linking these cells through grazing and fertility transfer (i.e., manure deposition). These movements are difficult to account for and are hardly represented in already existing models such as the ORCHIDEE-GM model. Hence, they are not represented in this model. In the model, the number of animals by grid cell is constrained by the resource on that grid cell.

Herd composition and management could have diverse consequences that cannot be directly represented in the model. In case of multiple species grazing on the same grid cell (e.g., a herd composed of cows, sheep, goats, etc., having complementary feeding behaviour) might affect grazing efficiency, increasing gain per hectare and individual animal's weight gain (d'Alexis et al., 2015), hence having effects on the carbon balance of pastures as well as the biodiversity. The multiplicity of species within a herd would also be beneficial for animal health as it reduces the impact of gastrointestinal parasitoses for small ruminants (d'Alexis et al., 2015; Arquet and Mahieu, 2019).

The study by Perrot, Caillaud, and Chambaut (2012) found by analysing milk production costs in mixed-intensive dairy farms in France, that economies of scale exist for these farms. We cannot, however, know in the model if many animals are present on the same farm as the model is ultimately per unit of area and not at the farm scale. Thus, this model cannot emphasize if there is a benefit for farms to grow larger. This economy of scale, however, encompasses only one aspect of sustainability (i.e., the economic aspect), and the analysis of some less intensified, medium-scale mixed dairy farms in France by the same study of Perrot, Caillaud, and Chambaut (2012) shows better environmental results for these farms while still being profitable to the farmer, compared to intensive large-scale farms.

There is also a potential economy of scale when constructing barns for housed animals. Instead, in this model, the cost of a barn is calculated per head. The study by Mazur et al. (2015), however, finds that a significantly lower investment cost for barns, as well as their equipment (e.g., milking

system) and exploitation costs, are observed in barns with more livestock. Therefore, to account for these economies of scale, a coefficient could be added when calculating the costs for the lineage group.

Finally, the minimisation of costs to determine fertilisation levels were only used for pastures in this model. It could be possible to add nitrogen application rates on croplands for on-farm crops as a variable of choice, by having crop yields depending on the nitrogen application rate (see the "Relation to land" unit). We would therefore maximise benefits by minimising costs for crops grown on-farm by having a cost per unit of area linked with a nitrogen application rate per unit of area. This should also lead to an equalisation of the rents on croplands and grasslands. This option was not proposed in the framework of this model as I decided to focus on the part on the pastures and less on the cropping one due to the non-explicitly representation of pasture management and yields in global existing models, whereas it is crucial for assessing the impacts of many ruminants systems across the world.

The model has not been implemented, but stayed at a conceptual stage. The implementation could pass by the validation of some parts by some experts, especially the parts that are original to the model (e.g., the pasture management part). This model is destined to be used at a large scale, but as seen previously, could also be relevant at smaller scales, being useful for states and governments, the World Bank, advocacy, etc, while taking the appropriate safety precautions when implementing it.

IV.6. BIBLIOGRAPHY OF PART 3

ADEME, "Documentation Base Carbone – Bilan GES", Agence de l'environnement et de la maîtrise de l'énergie (ADEME), March, 2020, https://www.bilans-ges.ademe.fr/documentation/UPLOAD_DOC_FR/index.htm?agriculture - cheptels.html

Arquet, R., and Mahieu, M, Le pâturage mixte bovins-petits ruminants: l'exemple des Antilles, intérêt et limites (Association Française pour la Production Fourragère: 2019).

Bouwman, A.F., Van der Hoek, K.W., Eickhout, B., and Soenario, I., "Exploring changes in world ruminant production systems", *Agricultural Systems* 84, no. 2 (May 2005): 121-153,

10.1016/j.agry.2004.05.006.

Bowman, M.S., Soares-Filho, B.S., Merry, F.D., Nepstad, D.C., Rodrigues, H., and Almeida, O.T., "Persistence of cattle ranching in the Brazilian Amazon: A spatial analysis of the rationale for beef production", *Land Use Policy* 29, no. 3 (2012): 558-568, 10.1016/j.landusepol.2011.09.009.

Center for Global Trade Analysis, "GTAP Data Base", GTAP, September 26, 2022, <https://www.gtap.agecon.purdue.edu/databases/default.asp>.

Chang, J.F., Viovy, N., Vuichard, N., Ciais, P., Wang, T., Cozic, A., Lardy, R., Graux, A.I., Klumpp, K., Martin, R., and Soussana, J.F., "Incorporating grassland management in ORCHIDEE: model description and evaluation at 11 eddy-covariance sites in Europe", *Geoscientific Model Development* 6, no.6 (December 2013): 2165–2181, 10.5194/gmd-6-2165-2013.

———, Viovy, N., Vuichard, N., Ciais, P., Campioli, M., Klumpp, K., Martin, R., Leip, A., and Soussana, J.F., "Modeled changes in potential grassland productivity and in grass-fed ruminant livestock density in Europe over 1961-2010", *PloS One* 10, no. 5 (2015): e0127554, 10.1371/journal.pone.0127554.

Cournut, S., and Chauvat, S., *Référentiel travail dans 7 filières animales. Synthèse de 640 bilans travail bovins viande et lait, ovins viande et lait, caprins, porcs, volailles* (Paris: Institut de l'Élevage, 2010).

d'Alexis, S., Angeon, V., Arquet, R., and Boval, M., « Les systèmes mixtes d'élevage de petits ruminants et de bovins : Une alternative pour améliorer les performances animales au pâturage », *Innovations agronomiques*, no. 43 (2015) : 10.

Das, R., Sailo, L., Verma, N., Bharti, P., Saika, J., Imtiwati, and Kumar, R., « Impact of heat stress on health and performance of dairy animals : a review », *Veterinary World* 9, no. 3 (March 2016) : 260-268, 10.14202/vetworld.2016.260-268.

Dawson, I., Park, S., Attwood, S., Jamnadass, R., Powell, W., Sunderland, T., and Carsan, S., "Contributions of biodiversity to the sustainable intensification of food production", *Global Food*

Security 21 (June 2019): 23-37, 10.1016/j.gfs.2019.07.002.

Fagon, J., and Sabatté, N., Référentiel travail en élevages bovins lait: Synthèse de 190 bilans travail (Paris: Institut de l'Élevage, 2010).

FAO, Global Livestock Environmental Assessment Model: Version 2.1 – Data reference year: 2010 (Rome: Food and Agriculture Organisation of the United Nations, 2017).

_____, Livestock activity data guidance (L-ADG) – Methods and guidance on compilation of activity data for Tier 2 livestock GHG inventories (Rome: FAO and Global Research Alliance on Agricultural Greenhouse Gases, 2020), 154p.

_____, "Agroecology and the Sustainable Development Goals (SDGs)", Agroecology Knowledge Hub, Food and Agriculture Organization of the United Nations, September 21, 2022, <https://www.fao.org/agroecology/overview/agroecology-and-the-sustainable-development-goals/fr/>

Foray, S., and Gac, A., Elevage bovin et environnement: Les chiffres-clés (Paris: Institut de l'Élevage, 2018).

Gac, A., Dollé, J.B., Le Gall, A., Klumpp, K., Tallec, T., Mousset, J., Eglin, T., Bispo, A., Peyraud, J.L., and Faverdin, P., Le stockage de carbone par les prairies: Une voie d'atténuation de l'impact de l'élevage herbivore sur l'effet de serre (Montpellier: Institut de l'Élevage, 2010).

Gerber, P., Steinfeld, H., Henderson, B., Mottet, A., Dijkman, Falcucci, A., Tempio, G., and Opio, C., Lutter contre le changement climatique grâce à l'élevage – Une évolution des émissions et des opportunités d'atténuation au niveau mondial (Rome: Food and Agricultural Organization of the United Nations, 2014).

Grandin, B.E., de Leeuw, P.N., and de Souza, M., "Labour and livestock management", in ILCA Systems Study (Addis-Ababa, 1991), p71-81.

Havlik, P., Valin, H., Herrero, M., Oberstein, M., Schmid, E., Rufino, M., Mosnier, A., Thornton, P.K.,

Böttcher, H., Conant, R.T., Frank, S., Fritz, S., Fuss, S., Kraxner, F., Notenbaert, A., "Climate change mitigation through livestock system transitions", *Proceedings of the National Academy of Sciences* 111, no.10 (March 2014): 3709-3714, 10.1073/pnas.1308044111.

Herrero, M., Havlik, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blummel, M., Weiss, F., Grace, D., and Oberstein, M., "Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems", *Proceedings of the National Academy of Sciences* 110, no.52 (December 2013): 20888-20893, 10.1073/pnas.1308149110.

Ickowicz, A., Mbow, C., Assouma, M., Lecomte, P., and Hiernaux, P., "Elevage pastoral au Sahel: un bilan carbone à l'équilibre", *Inter-réseaux Développement rural*, 2017, <https://www.inter-reseaux.org/publication/le-pastoralisme-a-t-il-encore-un-avenir-en-afrique-de-louest/elevage-pastoral-au-sahel-un-bilan-carbone-a-lequilibre/>.

IPCC, "Emissions from Livestock and Manure Management", in *IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use*, 2006, p10.1-10.87.

———, *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, eds. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S., Switzerland: IPCC, 2019.

———, *Climate Change 2022: Impacts, Adaptation and Vulnerability - Working group II Contribution to the Sixth Report of the Intergovernmental Panel on Climate Change*, eds. H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama, Cambridge, United Kingdom and New York, USA: Cambridge University Press, 2022.

Kreuter, U.P., and Workman, J.P., "Comparative profitability of cattle and wildlife ranches in semi-arid Zimbabwe", *Journal of Arid Environments* 35, no.1 (1997): 171-187, 10.1006/jare.1995.0137.

Kulovic, M., "Freight transport costs model based on truck fleet operational parameters", *Promet-Traffic-Traffico* 16, no.6 (2004): 321-325.

Lanholm, D.M., Pradhan, P., Wegmann, P., Sanchez, M., Salazar, J.C., and Kropp, J.P., "Reducing deforestation and improving livestock productivity: greenhouse gas mitigation potential of silvopastoral systems in Caqueta", *Environmental Research Letters* 14, no.11 (October 2019): 114007, 10.1088/1748-9326/ab3db6.

Lépée, P., "De la fauche au stockage: évaluer le coût d'une chaîne de récolte de l'herbe", *Fourrages* 206 (2011): 137-141.

Mattos, M.M., and Uhl, C., "Economic and ecological perspectives on ranching in the Eastern Amazon", *World Development* 22, no.2 (1994): 145-158, 10.1016/0305-750X(94)90066-3.

Mayer, R., and Olsen, T., "Estimated Costs for Livestock Fencing", Iowa State University, 2012, <https://www.extension.iastate.edu/agdm/livestock/html/b1-75.html>.

Mazur, K., Barwicki, J., Borek, K., Wardal, W., "Economic analysis of non-litter cattle barns", *Agricultural Engineering* 153 (July 2015): 95-106, 10.14654/ir.2015.153.110.

Mischler, P., "Polyculture-élevage: des avantages, vraiment", *L'agriculteur Normand*, Mai 25, 2017, <https://www.agriculteur-normand.com/polyculture-elevage-des-avantages-vraiment>.

Mosnier, C., Duclos, A., Agabriel, J., and Gac, A., "Orfee: A bio-economic model to simulate integrated and intensive management of mixed crop-livestock farms and their greenhouse gas emissions", *Agricultural Systems* 157 (October 2017): 202-215, 10.1016/j.agsy.2017.07.005.

Perrot, C., Caillaud, D., and Chambaut, H., "Economies d'échelle et économies de gamme en production laitière. Analyse technico-économique et environnementale des exploitations de polyculture-élevage françaises", *Rencontres autour de la recherche sur les ruminants* (July 2013): 33-36.

Robinson, T., Thornton, P., Franceschini, G., Kruska, R., Chiozza, F., Notenbaert, A., Cecchi, G., Herrero, M., Epprecht, M., Fritz, S., You, L., Conchedda, G., and See, L., *Global livestock production systems* (Rome: Food and Agriculture Organization of the United Nations and International

Livestock Research Institute, 2011).

Rotz, C.A., and Shinnars, K., "Hay harvest and storage", in *Forage Harvesting and Utilization*, eds. Fahey G.C., (American Society of Agronomy, 2007), p601-616.

Schaphoff, S., von Bloh, W., Rammig, A., Thonicke, K., Biemans, H., Forkel, M., Gerten, D., Heinke, J., Jägermeyr, J., Knauer, J., Langerwisch, F., Lucht, W., Müller, C., Rolinski, S., and Waha, K., "LPJmL4 – a dynamic global vegetation model with managed land – Part 1: Model description", *Geoscientific Model Development* 11, no.4 (April 2008): 1343-1375, 10.5194/gmd-11-1343-2018.

Seré, C., and Steinfeld, H., *World Livestock Production Systems—Current Status, Issues and Trends*, eds. FAO Animal Production and Health Paper 127 (Rome: Food and Agriculture Organization of the United Nations, 1996).

Shang, M.Z., and McEwan, K., "The make-or-buy decision of feed on livestock farms: Evidence from Ontario swine farms", *Canadian Journal of Agricultural Economics* 69, no.3 (March 2021): 353-368, 10.1111/cjag.12269.

Singh, B., and Craswell, E., "Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem", *SN Applied Sciences* 3 (March 2021): 3:518, 10.1007/s42452-021-04521-8.

Smith, A., Snapp, S., Chikowo, R., Thorne, P., Bekunda, M., and Glover, J., "Measuring sustainable intensification in smallholder agroecosystems: A review", *Global Food Security* 12 (March 2017): 127-138, 10.1016/j.gfs.2016.11.002.

Souty, F., Brunelle, T., Dumas, P., Dorin, B., Ciais, P., Crassous, R., Müller, C., and Bondeau, A., "The Nexus Land-Use model version 1.0, an approach articulating biophysical potentials and economic dynamics to model competition for land-use", *Geoscientific Model Development* 5, no.5 (October 2012): 1297-1322, 10.5194/gmd-5-1297-2012.

Tedeschi, L., Muir, J., Riley, D., and Fox, D., "The role of ruminant animals in sustainable livestock intensification programs", *The International Journal of Sustainable Development and World*

Ecology 22, no.5 (August 2015): 1-14, 10.1080/13504509.2015.1075441.

Thévenot, A., Aubin, J., Tillard, E., and Vayssières, J., 'Accounting for farm diversity in life cycle assessment studies—the case of poultry production in a tropical island', *Journal of Cleaner Production* 57 (October 2013): 280–292, 10.1016/j.jclepro.2013.05.027.

Trepel, M., "Assessing the cost-effectiveness of the water purification function of wetlands for environmental planning", *Ecological Complexity* 7, no.3 (September 2010): 320-326, 10.1016/j.ecocom.2010.02.006.

Udo, H., and Steenstra, F., *Intensification of smallholder livestock production, is it sustainable?*, (Yogyarkarta: The 5th International Seminar on Tropical Animal Production, 2010).

Van laer, E., Moons, C., Sonck, B., and Tuytens, F., "Importance of outdoor shelter for cattle in temperature climates", *Livestock Science* 159 (January 2014): 87-101, 10.1016/j.livsci.2013.11.003.

Vertregt, N., and Penning De Vries, F.W.T, "A Rapid Method for Determining the Efficiency of Biosynthesis of Plant Biomass", *Journal of Theoretical Biology* 128 (1987): 109-119.

Weiler, V., Udo, H., Viets, T., Crane, T., and De Boer, I., "Handling multi-functionality of livestock in a life cycle assessment: the case of smallholder dairying in Kenya", *Current Opinion in Environmental Sustainability* 8 (2014): 29-38, 10.1016/j.cosust.2014.07.009.

Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., and Shen, Y., "Managing nitrogen for sustainable development", *Nature* 528 (November 2015): 51-59, 10.1038/nature15743.

TAKEAWAY MESSAGES AND PRESENTATION OF PART 4

Takeaway messages of Part 3

- 1. The model compares production systems (Part 2), represented by practices and is divided into three original steps;*
- 2. Step 1 represents management types and profiles at the grid cell level, thanks to various modules;*
- 3. Step 2 groups profiles together in lineage groups;*
- 4. Step 3 represents the net benefits of lineage groups followed by performance calculations (economic profit and environmental impacts of each profile aggregated at the lineage group level).*

While working on the second and the third parts of the thesis, questions were raised concerning the evolution of current farming systems and the mechanisms of this evolution, as well as if the conceptual framework developed in Part 2 worldwide (and the model developed in Part 3, per se) would be flexible enough to be adapted at a smaller scale (i.e., at the national or subnational scale). Therefore, starting from the management type typology, questions and interests were raised concerning the evolution and the potential future impacts of production systems in a specific zone (Kenya and Senegal), on the environment, the economy, and the society, leading to the development of Part 4.

To tackle the issues of the difficulty to change scale for the framework of Part 2, and the evolution of farming systems in the future at a (sub)national scale, the following part of the thesis presents a case study of the evolution of dairy systems in Kenya and Senegal. This case study, centred around a qualitative foresight study, allows putting into practice the management type typology developed in Part 2 and identify future evolution paths for dairy farming, by identifying potential evolution scenarios for dairy farming in Kenya and Senegal and discussing potential impacts of these scenarios. This work is realized based on fieldwork and farm visits, and local experts and dairy sector stakeholder interviews.

The change of scale studied in the following part concerns the framework developed in Part 2 without considering a change of scale in the model developed in Part 3. One question that could

be asked is whether the model developed in Part 3 at the world scale can also be applied at a national or subnational scale. But this question will not be treated in the following part.

V- PART 4 : FORESIGHT STUDY ON DAIRY CATTLE FARMING SYSTEMS

V.1. BACKGROUND AND OBJECTIVES

Based on the framework developed in Part 2, which describes and classifies current cattle systems, and the model developed in Part 3, which aims at analyzing the economical and environmental impacts of cattle systems, questions have been raised about the potential perspectives and the evolution of these cattle farming systems (what could these systems look like in the future?), as well as their potential future impacts on the environment, the economy, and the livelihoods of herders. The focus of the foresight study developed in this Part 4 is therefore on the future of cattle systems in two countries (Kenya and Senegal) and its implications.

To carry on a study that could answer these questions, the focus is made on the African continent and dairy cattle farming. This choice was made regarding the current and future challenges of dairy cattle farming in Africa, especially in terms of climate change, growing population and demand, as well as insecurity and conflicts in some regions.

This study was linked to the Africa-Milk project. The Africa-Milk project supports the co-design and implementation of technical, organizational, and institutional innovations to increase and secure local milk sourcing in four countries: Senegal, Madagascar, Burkina Faso, and Kenya. The overall consortium includes African research organizations (ISRA, INERA, UoN, FIFAMANOR), WUR, and CIRAD in Europe, all with strong experience in African milk production and sustainable development. Kenya and Senegal have been selected for this foresight study as they possess diverse and contrasting agro-climatic and production contexts, and are also representative of their respective region. Thanks to that diversity, we believe that dairy systems in these two countries could be also very diverse in the future due to several factors such as land pressure, current development policy and potential ones in the future, and investment and development capacities, among others.

This research work has several objectives, in particular (i) to identify potential scenarios for future cattle systems based on the current systems existing in both countries, (ii) to assess the potential resilience of future systems, meaning their capacity to adapt to transformations (demographic,

climate change, growing insecurity), (iii) to identify the constraints and opportunities to these transformations, and (iv) to use anticipation as a transformation process of the present that could guide future actions and behaviours. Based on the cattle systems typology, previously designed in Part 2, the foresight study will aim at defining several plausible trajectories for dairy farming systems as well as the resilience of these systems in the context of major sustainability issues, by identifying potential future impacts of cattle systems, to open a qualitative way of assessing impacts rather than a quantitative one, as it has been done in Part 3.

This foresight study therefore aims at validating the conceptual framework developed in Part 2 at a smaller scale (a sub-national scale) and to use it in an other way than the one represented by the model developed in Part 3. By doing so, this study opens up to other indicators than the ones presented in Part 3, such as sustainability, resilience, and evolution/adaptation, allowing us to take a different view at the intensification pathways described in Part 1.

Some limitations have been encountered during the thesis period which made it difficult to expand to other countries. Firstly was the Covid-19 pandemic which made traveling to some countries difficult, if not impossible. Secondly, another side effect of the pandemic was that it slowed down the evolution of the thesis, only allowing traveling after two years of PhD, implying a lack of time to prepare and carry out correct field visits and work.

This study was conducted in Kenya and in Senegal thanks to a graduate fellowship at the International Livestock Research Institute (ILRI) based in Nairobi, Kenya from February, 10 to May 31 2022 (see graduate fellowship work plan and activity reports in Annexe 3, farm visits photos in Annexes 4 and 5, and field visits guide in Annexe 6).

V.2. ANTICIPATION VERSUS FORESIGHT

Anticipation has a broad meaning and covers various tools and methods (CIRAD, 2021). It is recognized as a transdisciplinary science on how to use the future in the present. Anticipation is precisely defined by Bourgeois (2015) as the sense of expectation of an occurrence, predicting it, and occasionally the act of preparing for it. Anticipation covers all efforts to "know the future". Systems of anticipation are incorporated in all phenomena, conscious or unconscious, physical or ideational; from a tree that loses its leaves in the autumn through to human planning.

Foresight is a systematic, participatory and multi-disciplinary approach to exploring mid- to long-term futures and drivers of change Bourgeois (2015). Foresight provides a space for different stakeholders and experts for systemic thinking and to develop anticipatory knowledge. It explores future changes by anticipating and analysing possible future developments and challenges both qualitatively and quantitatively and supports stakeholders to actively shape the future vision for today's strategies and actions (Bourgeois, 2015).

“Foresight does not aim to predict the future or to unveil it as if it was already prefabricated – but rather to help us build it. It invites us to consider the future as something that we create or build, rather than as something already decided. The future is not already a fact. It is not predetermined. On the contrary, it is open to many possible futures.” (Downey, Heydebreck and de Jouvenel, 2005).

V.3. A FORESIGHT METHOD: THE FUTURES WHEEL

Many foresight methods are based on expert knowledge of scenario building. Contrary to the territorial foresight method that identifies potential futures based on drivers (Mosnier et al., 2020), the method used in this study should allow us to identify potential futures and consequences based on a change or a disruption in the current dairy farming system. Such studies could allow us to adapt the present to future issues and consequences and to understand better future opportunities and threats.

The futures wheel method is an anticipation method that seeks to develop the consequences of today's issue in the longer-term future. Along with first order impacts, the futures wheel analyses second-order impacts, and beyond (Inayatullah, 2008). The futures wheel was invented in 1971 by Jerome C. Glenn (Glenn, 2009) and helps to organize, understand and clarify different future elements and their possible influences (Toivonen and Viitanen, 2016).

The futures wheel is a method for identifying primary, secondary, and tertiary consequences of trends, events, emerging issues, and future possible decisions through structured and participatory brainstorming (Glenn, 2009; Bengston, 2016). A trend or an event is written in the middle of the futures wheel; then primary, secondary, and tertiary consequences are drawn wheel-like from the centre. This ripple effect continues until a useful picture of the implications of the event or trend is

clear (Glenn, 2009). Despite its simplicity, the futures wheel is seen as an effective method to investigate the future and allows investigation of several possible development paths for the future (Glenn, 2009).

Subsequent variations of the futures wheel have been called the Implementation Wheel, Impact Wheel, Mind Mapping, and Webbing, and are used in a wide variety of situations (Glenn, 2009).

The Futures Wheel is most commonly used to (Glenn, 2009):

- think through possible impacts of current trends or potential future events;
- organize thoughts about future events or trends;
- create forecasts within alternative scenarios;
- show complex interrelationships;
- engage workshop participants in thinking together about the future;
- nurture a futures-conscious perspective.

V.3.1. Strengths and weaknesses of the futures wheel

The futures wheel method is easy to use and can be carried out with minimal training and equipment (Bengston, 2016). This allows the use by anyone who wishes to process future research or understand events and trends. This method also helps identify feedback loops in a group's collective thinking process and helps to collect rich data sets and knowledge (Bengston, 2016). Rather than thinking linearly, the futures wheel helps to think more network-oriented and complex, allowing experts to perceive better links between consequences as well as unforeseen and difficult-to-perceive implications (Bengston, 2016). The result of this process is a clear, visual map of potentially complex interactions.

As the futures wheel depends on experts' knowledge and interactions, the output is no better than the collective judgments of these experts (Bengston, 2016). The futures wheel can produce a large number of consequences, resulting in a difficult-to-analyze final outcome (Bengston, 2016). This could also potentially lead to misinterpretation of results (Bengston, 2016) and thinking that consequences highlighted thanks to the futures wheel are not truly representative of the future reality.

V.3.2. Detailed method

At first, the change or disruption to examine is defined and described and placed at the centre of the futures wheel. This change could be a trend, an innovation, a new policy, etc. The facilitator, a person in charge of the good conduct of the brainstorming, writes down the change. In this study, the change/trend will be identified prior to the brainstorming (Bengston, 2016).

To produce valuable outputs, participants should represent diverse cultural and ethnic perspectives, knowledge, experiences, gender, and age. One main principle of the futures wheel is that a diverse team of participants will investigate the change/field more effectively than individual experts (Bengston, 2016). As this study focuses on a specific scientific topic, it is necessary that all participants possess knowledge and expertise in that field (Bengston, 2016).

Branching from the centre of the futures wheel, participants propose ideas for both positive and negative first-order consequences, answering the question: "If this occurs, then what might happen next?". All ideas should be welcomed, even low-probability consequences, as soon as these consequences are deriving directly from the change, and they are clear and specific. The facilitator must ensure that (Bengston, 2016).

Following first-order consequences, participants identify second-order consequences by repeating the same process. Therefore, for each first-order consequence, participants answer the question, "If this occurs, then what might happen next?". The facilitator writes down all ideas, both positive and negative (Bengston, 2016).

The futures wheel allows the identification of broad trajectories based on direct and indirect consequences of a change, allowing to potentially prioritize them (Mulder, 2019). The futures wheel also allows to (Bengston, 2016):

- Highly desirable, low-likelihood consequences (and policies or management actions designed to increase their likelihood);
- Highly undesirable, high-likelihood consequences (and policies or management actions designed to decrease their likelihood);
- Surprising consequences, including those that could have catastrophic or extraordinarily

positive impacts;

- Differences in scoring from alternative points of view;
- Information and monitoring needs for developments that are highly uncertain.

V.4. ARTICLE: FORESIGHT STUDY ON DAIRY FARMING SYSTEMS IN CENTRAL KENYA AND NORTH OF SENEGAL

This part is based on an article published in *Frontiers in Sustainable Food Systems, section Land, Livelihoods and Food Security* in 2023 under the following citation: Perin L and Enahoro D (2023) Foresight study on dairy farming systems in Central Kenya and north of Senegal. *Front. Sustain. Food Syst.* 7: 1061834.doi: 10.3389/fsufs.2023.1061834.

V.4.1. Introduction

Dairy farming plays a crucial role in many countries in Africa, particularly among pastoralist and agro-pastoralist populations, generating a significant part of the incomes of many households (Diop et al., 2009). Milk is in addition a central component of many local diets, contributing strongly to food and nutritional security (Kibogy, 2019). Demand for dairy products, including milk, has been rising in Africa, reaching a growth rate of 4 % per year recently (ILRI, 2018; Kibogy, 2019). Rising income, population growth, urbanization and changing lifestyles are the main drivers of the increased milk consumption (Ochungo et al., 2016; ILRI, 2018). Kenya is currently one of the countries with the highest rates of per capita consumption of milk in sub-Saharan Africa (i.e., around 82 liters in 2019), including cow, sheep, goat, and camel milk, alongside Sudan, Mauritania, and Botswana (Kibogy, 2019; FAO, 2022). Milk consumption per capita is lower in Senegal (at around 12 litres in 2019) and has grown at a relatively modest rate of around 1 % annually over the last decade (FAO, 2022). However, milk is an important part of the diet, and its production an important income earner for many in parts of the country.

In Kenya, the annual per capita consumption of milk is expected to reach 200 litres by 2030 (Kibogy, 2019). Kenya is the leader in milk production among eastern African countries (ILRI, 2018; Africa-milk, 2019a). It is estimated that Kenya's livestock sector contributes to 12 percent of national gross domestic product (GDP) (Kimany, 2021) and the dairy sector is the largest

agricultural sub-sector in terms of income and employment creation (Bebe et al., 2003; Africa-milk, 2019a). An estimated two million actors derive livelihoods from the dairy value chain in Kenya (Kibogy, 2019; Africa-milk, 2019a).

Agriculture makes a significant contribution to the economy of Senegal, with a share of agriculture in GDP at 17 percent in 2020 (The Global Economy, 2022). Milk production in the country is mainly provided by cattle (followed by goats and sheep), with approximately 3.7 million heads in 2020 (Ministère de l'agriculture, de l'agroalimentaire et de la forêt, 2014; FAOSTAT, 2022). National milk production has increased over the past decade, with the produced milk being consumed mainly within the household and sold on the markets (GRET/APESS, 2016; Africa-milk, 2019b). However, due to a largely unstructured local dairy value chain (Africa-milk, 2019b) as well as the large quantities of milk and milk products being imported annually, only ten tons of milk equivalent are processed yearly in the country's dairies, accounting for less than 10 % of the national milk production (Africa-milk, 2019b).

Faced with various challenges such as climate change and increased demand for milk and other livestock products, dairy systems in Kenya and Senegal are evolving (FAO and GDP, 2018). This raises many research questions which if answered could aid our understanding of how dairy systems are currently evolving and what changes to expect in the future. This study focused on four such questions: (i) how are dairy systems evolving in Kenya and in Senegal? (ii) what factors are driving dairy system evolution in both countries? (iii) what are the potential consequences of these changes, and (iv) how do the ongoing changes enable or limit the resilience of dairy systems in the face of current and emerging challenges (climate change, growing population, insecurity, and conflict)? In this study, these questions have been answered using a series of interviews of herders and dairy sector stakeholders. An inventory was done of their answers, including their interpretations of dairy systems in Kenya and Senegal, and analyzed to provide answers to the specific questions of this research. The specific objectives of the inventory and analysis of stakeholder perspectives carried out in the study were to identify, for dairy farming systems in the study countries, plausible scenarios of system evolution that represent the major tendencies in these countries. This was done without attempting to explore all possibilities of evolution of the dairy systems. This study further sought to identify, also through the interviews, the drivers and potential consequences of scenarios recognized by the dairy system stakeholders, and their implications for resilience of the dairy systems to current and future

challenges. A literature review was conducted to initially characterize the dairy systems in Kenya and Senegal. This review provided the context for determining what stakeholders to engage with, where, and how. It also provided a knowledge base against which data emerging from the interviews could be compared.

The next section presents an overview of dairy farming systems in Kenya and Senegal compiled from the literature, followed by a description of the methods used to answer the research questions posed, after which the results of the foresight study are presented and their implications discussed. The discussion on implications allows to put the responses into perspectives while capturing the perspective of interviewees.

According to the literature, dairy farming systems in Kenya can be divided into three general categories: grazing systems, zero grazing systems, and semi-zero grazing systems (van der Lee et al., 2016; Kibogy, 2019) (see Table 10). These systems mainly differ based on their management practices, such as in the choice of cattle feeds, housing, grazing practices, and animal breeds.

Three dairy farming systems are also observed in Senegal: pastoral (also called sylvo-pastoral) systems, agro-pastoral systems, and intensive systems (see Table 11; Dieye et al., 2005; Magrin et al., 2011).

Table 10: Description of the dairy farming systems in Kenya

Grazing	<i>Short summary</i>	Cattle graze on pastures with or without feed supplementation and low to medium external input levels.
	<i>Breed</i>	Local - Zebu purebred (uncontrolled) ¹ or crossbred (controlled) ²
	<i>Milk production</i>	~2-5 L/cow/day
	<i>Market access</i>	Poor market access, mainly for self-consumption or milk sells directly to consumers
	<i>Land availability</i>	High
	<i>Location</i>	<p>Uncontrolled¹ grazing: Pastoralist areas, Western and Eastern Region</p> <p>Controlled² grazing: Central Region, Rift Valley</p>

1 Uncontrolled grazing : cattle roam on communal lands in search of water and fodder, with unimproved pastures, limited supplementation, and low levels of use of external inputs.

2 Controlled grazing : cattle graze on private lands, fenced, or divided in paddocks, with use of artificial

Semi grazing	<i>Short summary</i>	Cattle are partly confined, mixing grazing during the day and confinement at night with feed supplementation.
	<i>Breed</i>	Exotic - Fressian crossbred or Ayshire crossbred
	<i>Milk production</i>	~6-10 L/cow/day
	<i>Market access</i>	Medium market access, milk sells to consumers or cooperatives
	<i>Land availability</i>	Medium
	<i>Location</i>	Central Rift, Western Region, Eastern Region, South Rift
Zero grazing	<i>Short summary</i>	Cattle are always stall-milked and stall-fed, using cut- and carry fodder as well as concentrates and supplements, with high external input levels and high level of management.
	<i>Breed</i>	Exotic - Fressian or Ayshire crossbred or purebred
	<i>Milk production</i>	~7-12 L/cow/day
	<i>Market access</i>	Market oriented, milk sells to traders or dairy cooperatives
	<i>Land availability</i>	Scarce
	<i>Location</i>	(Peri)-urban areas, Central Region, Central Rift, South Rift

Sources : Author's compilation using Bebe et al., 2003; Makoni et al., 2014; van der Lee, Bebe, and Oosting, 2016; Odera-Waitituh, 2017; FAO, 2018b.

Table 11: Description of the dairy farming systems in Senegal

	Pastoral	Agro-pastoral	Intensive
<i>Short summary</i>	Cattle are mobile on long distances (nomad herders), extensive, mostly for self-consumption	Agriculture/livestock integration, mostly multifunctional objective (manure, draught power, production, self-consumption)	Stall-fed and stall-milked with a production objective
<i>Feed</i>	Grass, residues (dry season)	Grass, residues, crop concentrates	Grass (mainly fed as cut-and-carry), residues, crop concentrates, supplements
<i>Breed</i>	Local - Zebu Gobra	Crossbreed - Zebu Gobra, Djakoré, Ndama	Exotic - Montbéliarde, Jersiaise, Holstein, Gir

insemination, possible supplementation, and medium level use of external inputs.

<i>Milk production</i>	~0.5-2 L/cow/day	~6L/cow/day	/
<i>Market access</i>	Low	Medium	High
<i>% of national livestock</i>	32%	67%	1%
<i>Location</i>	Ferlo region and around the Senegal river	Other areas of the country	(Peri)-urban - Niayes zone, Dakar, Thiès

Source : Dieye et al., 2005.

V.4.2. Methods

Three research questions, namely (i), (iii), and (iv), were answered using a foresight method called the futures wheel where technical experts and key stakeholders of the dairy systems in Kenya and Senegal were interviewed. Research question (ii) was answered using a combination of the same foresight method and literature review.

Expert and stakeholder knowledge was obtained from individuals representing a diversity of local actors from the dairy value chain in both countries (herders, dairy cooperatives members, consultants, university professors, public and private sector, etc). A foresight tool called the futures wheel was used to conduct interviews of the experts and stakeholders. Along with first-order impacts of a trend or a change (i.e., impacts being a direct consequence of the change), this qualitative foresight method analyses second order impacts (i.e., the consequence of the consequence), and beyond (Inayatullah, 2008) through a structured brainstorming (Glenn, 2009; Bengston, 2016). The futures wheel was invented in 1971 by Glenn (2009) and helps to organize, understand and clarify different future elements and their possible influences (Toivonen and Viitanen, 2016). Despite its simplicity, the futures wheel is seen as an effective method to investigate the future and allows to investigate several possible development paths for the future (Glenn, 2009). The futures wheel method was chosen as it is a method that seeks to outline an issue or a change, and outline its consequences within the context of the longer-term future (Inayatullah, 2008).

The futures wheel method was utilized with all experts and stakeholders interviewed, with little variations in its application to interviews of herders versus non-herders. After gathering information on the production and practices, the following two questions were posed to the

herders regarding the future of dairy systems: (1) "What do you wish for you and your children in the future?" and (2) "How do you think dairy activities will change?." The future here is characterized as the coming 10 to 15 years and/or when children become old enough to be herders themselves. For non-herders, the equivalent question posed was « In your opinion, how will dairy activities change in the future, and what would be the consequences of this change?." After obtaining responses to understand how each expert foresees the evolution of dairy farming in their respective country, the futures wheel was then used to investigate perceptions about the consequences of the evolution of dairy farming. This component of the exploration mainly concerned the environment and the economy. Data were collected, aggregated, and analyzed with the use of an online tool (called Klaxoon) to organize the responses from the interviews into emergent scenarios.

The same methodology was applied in Kenya and in Senegal.

V.4.3. Results

The study focused on counties from the old Central and Rift Valley provinces of Kenya (specifically, Nyeri, Nyandarua, Murang'a, Nakuru, Bomet, and Kericho counties). In Senegal, the geographical focus of the study was an area in the north of Senegal spanning from the Senegal river to the Ferlo region (specifically, Saint-Louis, Louga, and Matam regions). These areas of Kenya and Senegal are important for dairy farming, having high numbers of dairy cattle (FAO, 2018b), and high milk production potential plus, high demand for milk and dairy products. Milk productivity per cow remains rather low in these regions, placing pressure on the dairy production systems to undergo changes such as organization of markets and supply chains as well as re-structuring of production systems to reach their potential.

V.4.3.1. Present situation for the foresight study

In total, twenty-eight experts and stakeholders in Kenya and twenty-five in Senegal were interviewed (see Figure 1), with half of them being herders (twenty-six herders in total). Among these herders, twelve were herders in Kenya coming from Bomet or Nyandarua counties, all belonging to dairy cooperatives, and fourteen herders in Senegal coming from Richard Toll, Saint-Louis and Dahra areas with only four being affiliated to a dairy cooperative. Most

herders – 50 percent in Kenya and 78 percent in Senegal – were aged 50 years old or above, as it is common in the study locations of both countries that the household head remains in charge of cattle until his sons inherit the cattle herd. Most of the interviewed herders in Kenya (seven) have adopted grazing systems, three practice semi-grazing, while two herders practice zero-grazing. Ten of the herders in Senegal are agro-pastoralists, three are pastoralists, and one practices intensive production (see Tables 12, 13). Herders interviewed in Kenya own between one and five cows, while the herders included in the study in Senegal possess between 3 and 15 lactating cows in herds of 15 up to 400 cattle. All herders combine dairy production with various other agricultural activities: small ruminant and poultry production mainly, but also fodder production, vegetable gardening, rice growing next to the Senegal river, and cereals, legumes, bananas and tea growing in Central Kenya.

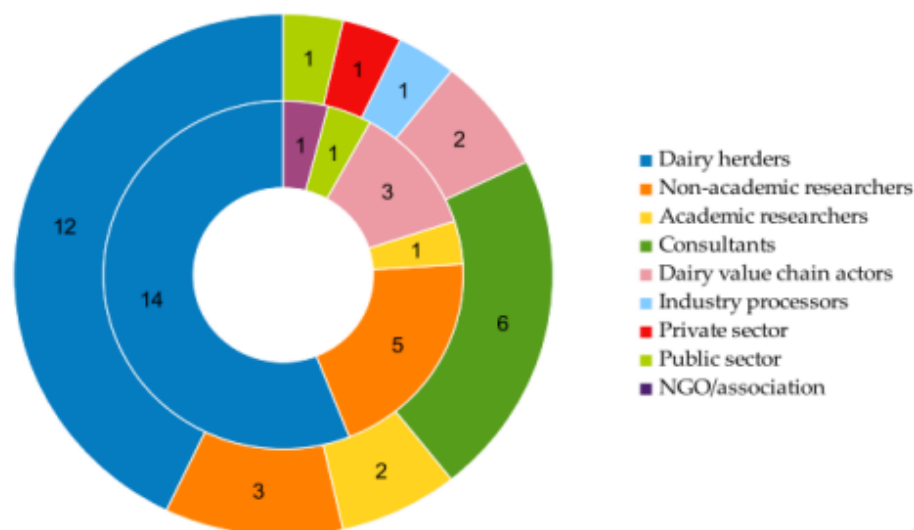


Figure 11: Number of interviewed experts and stakeholders in Kenya (outer circle) and Senegal (inner circle) according to their profession

Table 12: Characteristics of interviewed farmers in Kenya

Dairy systems	Age	Number of cows	Milk production (L/cow/day)
Grazing	36	2	8
	35	2	13
	36	5	8
	65	1	5
	63	1	5
	64	2	/
	62	4	/
Semi-grazing	45	3	6

	45	2	8
	37	4	11
Zero-grazing	55	3	8
	59	2	6

Table 13: Characteristics of interviewed farmers in Senegal

Dairy systems	Age	Total number of cattle (lactating cows)	Milk production (L/cow/day)	
			Local breeds	Crossbreeds/exotic
Agro-pastoralist	60	400 (10)	2	--
	66	50 (unknown)	1,5	--
	56	50 (10)	1,5	--
	54	30 (10)	1,5	--
	60	20 (5)	1,5	--
	50	15 (3)	--	17
	64	unknown (6)	--	17
	50	unknown (4)	--	12
	45	20 (6)	--	12
	54	150 (10)	4	--
Pastoralist	62	50 (/)	1,5	--
	65	40 (6)	1,5	--
	45	45 (13)	6,5	18
Intensiv	25	50 (15)	--	15 (exotic)

Other experts were interviewed in addition to the herders (see Figure 1), namely, non-academic researchers (three in Kenya and five in Senegal) affiliated with international research organizations, and academic researchers (two in Kenya being also professors and one in Senegal) affiliated with different universities. These researchers had expertise in agricultural economics, smallholder herder systems, livestock feeds, livestock production systems, animal health, and animal breeding. Six technical and advisory consultants were also interviewed in Kenya that had expertise in dairy production, feeds, or milk quality. Interviewed dairy value chain actors included dairy managers and directors, and chairpersons of dairy cooperatives. Finally, experts were interviewed from other institutions in the public sector, the private sector and from herder associations.

Milk production among herders interviewed in Kenya varies between 5 to 13 L/cow/day, with an average of 7.8 L/cow/day, all with cross breeds cattle (mainly Freisian and Ayrshire). Milk productivity does not seem to correlate with production systems as both the lowest and highest values of milk production were reported in grazing systems (see Table 12). On the other hand, milk production among interviewed herders in Senegal clearly varies among production systems and is associated with differences in cattle breeds (see Table 13). For the local breed in Senegal (Gobra Zebu), milk production varies between 1.5 to 6.5 L/cow/day, with an average of 2.5 L/cow/day. Herders in Senegal possessing crossbreeds (mix between Gobra Zebu and exotic breeds such as Montbeliarde, Holstein, Normande, or Guzerat Zebu) have milk productivity varying between 10 and 20 L/cow/day. The intensive farm, with exotic breeds (mainly Holstein), has a production of 15 L/cow/day. It is also noticeable that the youngest herders in Kenya, i.e., aged between 30 and 40 years old, have the highest milk productivity with 10 L/cow/day on average, compared to the oldest herders, i.e., aged over 60 years old, with the lowest milk productivity of 5 L/cow/day on average (see Table 12).

V.4.3.2. Evolution of dairy farming systems

This section answers the research question (i) how are dairy systems evolving in Kenya and in Senegal?

Based on the futures wheel method, three major scenarios were identified and discussed by experts and stakeholders in central regions of Kenya as the important trends that are either happening currently or have potential to dominate in the future (see Table 14). The first evolution scenario identified is the emergence of commercial and intensive zero-grazing systems in which farms own around ten lactating cows, and mainly purchase feed externally. In that scenario, in the longer term (>15 years), it is envisioned that there will be fewer farms and fewer dairy herders than today, but these farms will have higher productivity and production. Smallholder operations (<5 cows) will slowly decrease in number, without disappearing completely and will serve mainly household own consumption needs. As some experts mentioned, the Rift Valley region still possesses larger land size than Central Kenya, implying that the shift toward zero-grazing systems in this region will likely occur at a slower pace.

Table 14: Evolution scenarios for dairy farming systems in central Kenya

	Commercial and intensive scenario	Small-scale intensive scenario	Cooperative scenario
Farming systems	Zero-grazing	Zero-grazing	Zero-grazing
Number of farms (compared to nowadays)	Few	Unchanged	Few
Number of cows per farm	~10	~5	30-100
Feed origin	Off-farm	Off-farm/on-farm	Off-farm
Management	Commercially managed (trained manager)	Family managed	Commercially managed (highly trained manager)

The second scenario identified in Kenya is the shift from extensive grazing to intensive zero-grazing small-scale dairy farms. In this scenario, most dairy farms will remain as small-scale family managed farms (<5 cows), without an increase in herd size. Most experts agreed that extensive grazing systems would still exist but at a smaller extent. Some argued that small-scale intensive zero-grazing systems are not economically sustainable, as the cultural attachment of people to dairy breeding activities would still be very present, leading to unproductive and non-sustainable activities, therefore mainly maintained for own-consumption purposes.

The third scenario in Kenya envisions the grouping of small-scale herders into cooperative farms with around 30 to 100 cows per cooperative, and herders as the shareholders. Cattle belonging to each herder are kept together on one piece of land and managed together by the cooperative. In this context, herders could then allocate time and land to fodder and food production on their own non-communal land. According to some experts, this scenario is likely not going to happen in areas with larger land sizes, as herders with higher access to land would continue processing milk on their own.

The first two scenarios are seen as most likely by interviewed experts and stakeholders.

In Senegal, using the same method, two evolution scenarios emerged from the discussions with experts and stakeholders (see Table 15). According to interviewed experts and stakeholders, the evolution scenarios will occur more slowly in Senegal than in Kenya in the medium-to-long term (>20 years). This slow pace is attributed to many challenges and uncertainties facing the sector in Senegal. The first identified scenario is the complete settlement of

herders, with a decrease in herd size (maximum 20–30 crossbreeds or exotic breeds), and the slow disappearance of pastoralism. Due to lack of water and forages during the dry season, pastoralism would evolve toward total settlement of cattle. Under this scenario, animal feeds would either be produced off-farm or will come from by-products of agriculture (sugar cane, rice, straw). This intensification scenario would make multi-objective farms shift to specialized production and would imply a decrease in the total number of farms and herders as these turn to other activities.

The second scenario in Senegal is a partial settlement of some herders that have access to markets and/or directly to consumers. These herders would have a small sedentary production herd (maximum 5 crossbreed lactating cows) situated close to collect centers or consumption centers while with the rest of the herd (local breeds) would be kept under more extensive and nomadic conditions. The extensive components of the herds would still be able to take advantage of natural dry forages and exploit areas unsuitable for agriculture and would still produce cattle meat, which is important culturally in Senegal. In this second scenario, dairy systems in Senegal would still exist in their current forms, albeit with a higher proportion of agro-pastoralists and intensive farms as well as improved conditions for pastoralists practising semi-intensive systems.

Table 15: Evolution scenarios for dairy farming systems in north of Senegal

	Full settlement scenario	Partial settlement scenario
Farming system	Agro-pastoralism and intensive	Agro-pastoralism mainly
Number of cows per farm	<30	~5 lactating cows (within a big herd)
Breeds	Crossbreeds or exotic breeds	Crossbreeds
Feed origin	Mainly off-farm and use of crop's by-products	Mainly on-farm and use of residues and crop by-products
Number of farms (compared to nowadays)	Very few	Few
Presence of pastoralism	Reduced	Unchanged

In both scenarios identified in Senegal, integration of livestock with crop agriculture is needed to utilize residues and by-products for cattle feed. Agriculture could continue to be rain-fed or may shift toward irrigation when this is possible (e.g., at locations close to rivers, lakes, or other water sources).

V.4.3.3. Drivers of change

The results presented in this section were obtained during interviews with various experts and stakeholders, and from the literature search. The section answers the research question (ii) what factors are driving dairy system evolution in both countries?

Kenya

Central Kenya and the center of the Rift Valley are dominated by “improved” grazing and semi-grazing systems. Since the independence of the country in 1963, a gradual shift toward zero-grazing has largely been observed, especially in some counties of these regions (e.g., Kiambu county, at the periphery of Nairobi). At that period, the government encouraged farming and delivered ownership title and loaning facilities so local farmers could own their private piece of land, especially in Central Kenya and the Rift Valley. In other areas of the country, such as the southern Rift Valley, lands are still owned communally. These rural development policies aimed to improve rural livelihood, including income, education, health and nutrition, reduce inequality, and enhance growth of the rural sector (Kirori, 2003). However, the process of distributing land ownership titles may have led gradually to land division over time. Traditionally, when a farmer dies, his sons inherit the land by dividing it. Average land size has therefore decreased from average 5 acres in 2010–2015 to between 0.5 and 2.5 acres on average today (Kimuge, 2021) and from 2.6 to 5 cows per farm between 1996 and 2020 (IFCN, 2021). Furthermore, high costs and difficulties in acquiring new land provide an incentive in Kenya for individuals to aspire to own their own plot of land, no matter the size (Hlimi, 2013). In addition to land fragmentation, this tradition results in habitat fragmentation, deterioration of land quality, tenure insecurity and conflict, among others (Hlimi, 2013). Zero-grazing systems are therefore seen as a solution to continue dairy farming in the future, even with smaller pieces of land per unit.

One major factor driving the adoption of zero-grazing in Kenya has also been the National Dairy Development Project (NDDP), initiated in the 1980s under the Kenya Ministry of Agriculture, Livestock Development and Marketing. This project has been promoting establishment of intensive and stall-feeding units by farmers, in combination with adoption of the use of good quality fodder for feed (mainly Napier grass – *Pennisetum purpureum*) (Reynolds et al., 1996). Pilot farms with a zero-grazing model have also been established by

international organizations and researchers, where farmers from Kenya, and from other African countries, are trained.

According to the interviewees, the gradual expansion of zero-grazing systems in regions where infrastructure is available is mainly driven by: better access to inputs (feed, artificial insemination, veterinary services), training, growing demand in urban areas, climate change, cultural change (young people are less willing to inherit farms), high cost of labor, and promise of high milk production, productivity, and income.

Senegal

Dairy systems in the north of Senegal are largely dominated by agro-pastoralists and pastoralists. Few intensive farms are also present, with exotic breeds imported mainly from Europe. Sedentary systems – agro-pastoralists and intensive farms – are mainly present close to urban areas and next to the Senegal river and water points. While sedentary systems are inclined toward milk production, traditional pastoralists are more oriented toward production for own-consumption and calf breeding (live animal sales). These systems are facing major challenges related to resource access during the dry season.

Experts and stakeholders in Senegal indicated that the government of Senegal developed irrigated rice agriculture along the Senegal river in the 1960s, which directly affected the traditional patterns of cattle movements. As natural fodder growing close to the river became unavailable, herders and their animals were pushed further south in search for forages. Following some recent difficult years with high cattle mortality and unavailability of forage due to droughts since 2011 (Reliefweb, 2018), evolution of the dairy production seems to be toward restricted animal movements as a climate change adaptation strategy. This is particularly true for herders close to the Senegal river, where feeding from agricultural residues and by-products (rice or sugar cane) is available perennially, and where the location of dairies and urban markets nearby provide ready access to markets (e.g., Laiterie du Berger in Richard Toll and mini-dairies).

In 2018, the Laiterie du Berger introduced “mini-farms” to their supplier herders. These mini-farms allow herders to keep a small number of productive cows (often crossbreeds) under sedentary conditions. According to dairy experts, other than milk production, mini-farms could allow the breeding of high value calves having higher economic value to the herder. This in turn can

improve the genetic quality of the herd. Alongside a small, sedentary and productive herd, herders keep a mobile herd that could better utilize available dry forages due to their mobility.

Driven by these changes – closing of nomadic patterns along the river, droughts affecting the availability of natural forages and water, the opening of new markets in the form of dairies – the evolution of dairy farming systems in Senegal seem toward (partial) sedentary lifestyle. According to experts, other drivers of change are: economic opportunities that are improving incomes and livelihoods, the growing demand for local milk and dairy products, access to training for herders, and increased school attendance of pastoralists' children (so that they are no longer readily available to care for the family cattle). In addition, increased scarcity of grazing lands, including due to the increase of agricultural and urban land use leads to more intense competition for land which is noted to sometimes lead to conflicts, with, for example, agribusiness establishments located around rivers or production basins cutting off traditional paths for nomadic livestock migration and preventing access to water points.

V.4.3.4. Potential consequences of the evolution of dairy systems

This section answers the research question (iii) what are the potential consequences of these changes?

Kenya

Direct and indirect environmental and socio-economical consequences were identified for the three potential scenarios of dairy farming evolution in Kenya (see Figure 12). They were identified by experts and stakeholders using the futures wheel method.

Multiple impacts were identified. The main positive environmental impacts identified by at least four experts for the three scenarios are: minimal dependence of feed production on climatic events due to the increased distribution of production to various regions of the countries, decrease in methane emissions per cow due to better feeding practices and better breeds, increased potential for biogas production, and reduced over-grazing and damage to biodiversity. Negative impacts that were identified include accumulation of waste (manure and feed waste) from increased production, higher nitrogen and phosphorus pollution, and decline in animal health due to increased confinement.

For socio-economic impacts, experts and stakeholders identified the possibility to have better nutrition and food security due to an increase in milk production, and a boost in the country's economy and in herder livelihoods due to increased net incomes. Some experts argued that a transition to zero-grazing is not economically sustainable as production costs (mostly feed) will remain too high for dairy farming to become profitable, especially for small-scale herders. Without financial support, most herders would not be able to practise zero-grazing, resulting in less farm employment and decreased numbers of smallholders. To other experts, intensive and commercial farms are seen as attractive for employment even though they would only benefit a small number of people as the number of farms is likely to decrease.



Figure 12: Map of the main potential direct and indirect impacts of the three evolution scenarios for dairy farming systems in Central Kenya and central Rift Valley

Senegal

In Senegal, the futures wheel method identified direct and indirect environmental and socio-economical consequences of two potential scenarios of dairy farming evolution (see Figure 13).

Many of the potential impacts of evolution scenarios in north of Senegal that were identified by experts and stakeholders are like the ones reported from Kenya: livelihood improvements, high production costs, air and water pollution, reduction in over-grazing, increase of manure burden, disease spread, etc. The envisioned increase of milk production and productivity is also explained by use of more productive animal breeds and better cattle feeding explained, which in turn are traced to, in this case, agriculture/livestock integration. This is in contrast with the findings from Kenya, where the use of feeds purchased from external or off-farm sources was identified as the main reason for increased milk production and productivity.

Concerning herd size, at national and farm levels, farm sizes could either decrease due to better milk productivity per cow, or the attractiveness of milk production and its income leads to an increase in herd size leading to an increase in environmental impacts and in meat availability.



Figure 13: Map of the main potential direct and indirect impacts of the two evolution scenarios for dairy farming systems in northern Senegal

V.4.3.5. Resilience of future dairy systems

This section answers the research question (iv) “how do the ongoing changes enable or limit the resilience of dairy systems in the face of current and emerging challenges (climate change, growing population, insecurity, and conflict)?,” and derives from interviews of experts and stakeholders from the dairy value chain.

V.4.3.5.1. Resilience to climate change

Intensification or semi-intensification is seen by some experts and stakeholders as a solution for reducing the impacts of dairy farming on climate and the environment and as a mean for these systems to be less strongly impacted by climatic events (e.g., droughts, erratic rains, high temperatures). However, according to other experts as well as based on field observations, it seems that dairy systems will nevertheless have to face several challenges linked to climate change. These include:

1. Feed scarcity, particularly during the dry season, and decline in pasture quality (soil quality, diversity of fodder species);
2. Water shortages and/or difficulty to access water (high price, monopoly of water points by agribusinesses, conflicts over water);
3. Threats to animal well-being (heat stress, lack of movement) and animal health (high mortality rate, reproduction issues, spread of diseases);
4. Milk quality declines due to animal diseases, potential contamination from externally produced feed, unhygienic milking practices, and suboptimal milk storage and transportation.

To address these challenges, future dairy systems will need to adopt a range of climate change adaptation strategies. Results emerging from the futures wheel suggested that the main climate threat to intensive sedentary systems, in both Kenya and Senegal, is the difficulty in supplying cattle with quality feed. Therefore, when land is available in abundance, integration with agriculture

to gain sufficiency in fodder production, and not depend on off-farm feed, is needed. On the contrary, when land is largely unavailable, herders must rely on externally produced feed that could be less impacted by adverse climatic events. In this context, various areas producing feeds

commercially and unaffected by the adverse events could sustain affected areas. However, externally produced feed is more prone to market price fluctuation related to economic or political events, as well as raise potential feed quality issues that require increased government regulations and/or the enforcing of standards. In either case of land availability, an additional strategy to limit climate impacts is to store fodder when they are available at a lower price (e.g., during the rainy season) which can then be provided to the herd during the dry season.

Finding a balance between productivity and environment protection and adaptation could be the key for sustainable milk production in the future. Practices identified by experts and stakeholders to maintain this balance include the use of locally adapted seeds (e.g., short cycle, highly digestible), and animal breeds (crossbreeds), biodiversity protection and reforestation, soil management and productivity, establishment of protected areas for natural fodder regeneration, integrated fodder production (circulation of nutrients through feed and manure, irrigation), and use of off-farm feeds (fodder conservation and productivity, new technology such as hydroponics).

The expert and stakeholder knowledge, particularly that emerging from the interviews of herders, suggested that the resilience of intensified dairy systems to climate change will also depend on the level of sensitization of herders. Further, focusing solely on strategies that address economic and productivity concerns, without considering sustainability and environmental issues, and the maintaining of equilibrium within production systems, should be avoided. To this end, providing information and training to herders and other dairy value chain actors, about how to manage emerging environmental challenges, will be key for resilience and adaptation. Such training could be implemented by NGOs, associations or cooperatives, while aligned with relevant government policies, but will need to take into account the culture and traditions of herders and others in the dairy systems.

Finally, according to some experts and stakeholders, settlement and intensification of herders might be an issue in the long-term since the herders could lose flexibility and adaptation capacities. In case of extreme climatic events, herders cannot adapt their feeding practices as they used to when they were more mobile. On the other hand, as settlement limits movements of animals in search of feed, it also limits unnecessary energy expenditure, allowing animals to allocate energy more effectively to milk production. However, intensification and settlement

might not be the only viable options for the future. For herders who own reasonable tracts of land, (semi-)grazing systems could be a better solution as it addresses some issues that arise from the confinement of animals such as poor hygiene of animal facilities, or non-autonomy regarding farmers' cattle feeding options.

To improve sustainability of dairy systems in the future, cooperation, diversity and adaptation of each dairy production system to local constraints and challenges, depending on land availability, agro-climatic context, and market access is the key.

V.4.3.5.2. Resilience under growing human population and higher food demand

The populations of Kenya and Senegal grew at the rates of 2.25 percent and 2.7 percent, respectively, in 2020 (The World Bank, 2022). Study interviewees thought that intensive and semi-intensive systems could increase milk production and productivity to supply the increasing demand for milk and dairy products in both countries. According to the expert and stakeholder interviews and observations from the field, dairy farming is facing three main challenges to meet the growing demand in milk and dairy products:

- High production costs (especially in relation to feeds, water management, and cattle reproduction);
- Market access as milk must be collected, transformed, and distributed to consumers – mainly in urban centers. There emerges a strong need for appropriate infrastructure, road networks, and re-organization of the dairy value chains;
- Territorial pressure with the increase of urban and agricultural lands.

From the futures wheel implementation, it emerged that direct sale of milk to consumers by herders or cooperatives could help Kenya better meet the increasing demand for local milk and allows herders to sell milk at a good price. When direct sale is not possible (e.g., when producers are located far from consumption centers), the organization of herders within cooperatives and/or (mini)dairies could help. Having higher numbers of dairies could increase the absorption capacity for locally produced milk and help fight against milk supply instability throughout the year. This can only be possible if the needed resources are available (especially feed – with an association with agriculture residues and by-products), and if producers have good access to markets. For the dairy value chain to be stronger and better organized (in terms of milk

collection, transformation, and sales), there is a strong need for policy oriented toward supporting them. One question for the future is therefore to define the desired role, within the economy and territory, of dairy farming in the overall agricultural development of the country.

Milk production and stability throughout the year will likely help to decrease milk price volatility, according to experts, as there are strong differences in milk production quantities between dry and wet seasons. Based on the expert and stakeholder discussions, increase in milk production could also boost the national economy as well as farmers' livelihoods, and decrease imports of milk and other dairy production in the long term.

In Senegal, experts proposed the imposition of taxes on imported milk and dairy products to promote growth of the local dairy industry, at least in the short term. However, this will lead to increases in the prices of imported dairy products, and potentially to negative socio-economic impacts on vulnerable consumers in the short term. In the long-term, restrictions on imports could spur development of the local dairy sector, with potential to help (particularly dairy producer) households move out of poverty, as has been demonstrated previously in Bangladesh (FAO, 2009).

V.4.3.5.3. Resilience to insecurity and conflicts

Insecurity and conflicts over resources and land emerged as a common theme in the stakeholder interviews conducted in Senegal. According to experts and dairy system actors, the conflicts arise mainly due to confrontations between herders and farmers as cattle graze on agricultural lands. This phenomenon was less emphasized in the interviews in Kenya. Increased settlement of animals could improve the situation in Senegal as the movements of animals outside of a producer's own land decreases, creating fewer opportunities for conflicts with farmers. Keeping productive cattle enclosed close to the farms or homesteads could also prevent cattle theft even if cattle of high value (e.g., crossbreeds or exotic breeds) would be more prone to theft. However, settlement of herders could also create conflicts with farmers over land and water as herders would prefer to settle down on land with access to water points.

Animal movements may need to be more organized in the future to avoid conflicts with, as proposed by experts, movement calendars agreed within communities/regions, or the

establishment of well managed and dedicated places for pastoralism (e.g., Ranch de Dolly in Senegal). Under such arrangements, cattle could in addition benefit from increased ease of veterinary and extension services to extend veterinary health coverage to the animals.

V.4.6. Discussion

V.4.6.1. A general trend for the evolution of dairy systems in Kenya and Senegal

Dairy sectors in Kenya and Senegal have a wide range of effect on society, contributing to livelihoods, food security and nutrition, while being a major consumer of natural resources, and present public health threats (FAO, 2018a). Dairy farming systems will likely undergo major changes. Potential evolution scenarios in Kenya and Senegal, identified in the result section, can be thought to represent global trends of change without being fully exploratory. Hence, not all possible evolution scenarios are explored in this study, but only those observed during field trips as well as elicited during the interviews of dairy system actors and stakeholders. Scenarios identified for both countries were found to be quite similar, as they are following a current trend.

Intensification seems to be the preferred and foreseen evolution scenario in both countries by the majority of interviewees. However, the pace of evolution will appear to be different in Kenya than in Senegal. Intensification of dairy production is already happening in some parts of Kenya, such as urban and peri-urban areas, due mainly to land unavailability. Further, as they observe increased productivity and higher incomes of other dairy producers, many dairy herders in the country express their desires to experience the same. On the contrary, dairy systems are evolving more slowly in north Senegal than observed for Central Kenya, which is a commercially oriented region for dairy production. Many stakeholders expressed during interviews that the study region in north Senegal might not experience major changes within the next few coming decades. This could be due to the specific agro-climatic context of this part of Senegal inducing many challenges such as water and feed availability and could also reflect strong pastoralist culture and tradition.

V.4.6.2. Ideas for the main focus areas in dairy research and policy

One focus area to consider by dairy research and policy when intensifying production is the

environmental impacts of such growth in production. Even if methane emission can decrease on a per cow basis, for example owing to improvements in the quantity and quality of the animals' diet (Kasyoka, 2020), there is a possibility of higher greenhouse gases (GHG) emissions overall due to higher input levels and increased numbers of animals. Intensification of dairy production systems also opens new constraints and opportunities regarding manure management. If poorly managed, manure can lead to increased levels of water and air pollution. However, manure could also serve positive functions in the system, for example if used to produce biogas – a combination of methane and carbon monoxide generated during anaerobic digestion of manure (KENPRO, 2022) as witnessed during field visits. Many households in Africa face insufficient energy supply and rely on wood and other non-sustainable fuel sources for cooking, contributing to both increased GHG emissions and deforestation. Biogas could be a solution as an alternative source of energy to deal with issues of GHG emissions and manure disposal (KENPRO, 2022). Manure can also be collected and transformed to be used as organic fertilization in crop production.

Cattle diseases are a major public health issue. Extensive grazing systems have a higher prevalence rate for East Coast Fever and Brucellosis (FAO, 2018a), and many studies observed higher prevalence of nematode gut parasites and liver fluke in these systems (Arnott et al., 2015). In the meanwhile, other health and well-being issues tend to emerge within high confinement systems, such as lameness, mastitis, uterine diseases, and various infectious diseases (Arnott et al., 2015).

Another area to focus on would be market access and the dairy value chain organization. As milk production and productivity are expected to increase with intensification, according to stakeholder opinions, systems with higher capacities for milk to be collected, transformed, and distributed to consumers will be needed. Milk collection and transformation system and dairy systems evolution are mutually influencing each other transforming the dairy value chain to commercialize locally produced milk (Wane et al., 2017). As an example, the Laiterie du Berger in Senegal is a unique collect and milk commercialization firm linking market accessibility with key factors in dairy production systems evolution such as feed access, contracts with herders, and animal settlement (Wane et al., 2017). Market accessibility here solely concerns formal markets. Concerns were also raised during some interviews about the evolution of informal markets and their effect on prices paid to herders. Specifically, milk prices paid to farmers could decrease when sold through formal

markets, whereas milk price would not change for consumers. On the other hand, deliberate policy and related support to dairy value chain actors will need to be effected to minimize potential for loss of milk quality often associated with an increased role of informal markets in the supply of dairy products (Grace et al., 2020).

Whereas intensifying their use of inputs (such as feeds) could improve herders' livelihoods through higher productivity and production, and increased incomes, the experts and stakeholders

interviewed highlighted challenges that herders face, including high production and investment costs. To enable herders in Kenya and Senegal to move to more intensified production, stakeholders identified the need for increased access to credit and other financing mechanisms, as well as access to relevant technical and management training. Interventions that seem to meet these criteria, and which are already being adopted in the study countries include the installation of biogas production units and solar panels, establishment of seed systems for forages and other feeds, creation of serviced mini-farms and use of improved genetics including crossbred cows for dairy production.

V.4.6.3. Evolution of Kenya and Senegal within their respective region

During the course of the interviews, stakeholders were also asked about the evolution trend in neighboring countries of Kenya and Senegal and their respective regions. Regional trade – in feeds, milk, and live animals – seems to be similar between Kenya and its neighbors in East Africa, and between Senegal and neighboring countries in West Africa. The evolutionary paths of the dairy production systems in both countries may, however, differ.

Even if most countries in East Africa are moving toward zero-grazing, dairy farming systems in Kenya are somewhat different. Zero-grazing systems are currently more evolved in Kenya than in the other countries in the region, with Kenya being ahead in the area of technology adoption. Kenya is also the largest consumer of milk in East Africa with high levels of consumption per person. This high demand stimulates the national dairy sector but also attracts milk imports from neighboring countries. Compared to Kenya, for example, Ethiopia, Tanzania, Uganda, and Rwanda possess low levels of milk production and productivity. However, these countries are also slowly adopting zero-grazing. As they possess larger land size and good climatic conditions for

grazing systems, the adoption of zero-grazing is at a slower pace than Kenya. Due to low production costs in Uganda and Tanzania, there is also a possibility that these two countries could become more competitive than Kenya in the future.

Senegal possesses many similarities with other Sahelian countries – especially concerning their agro-climatic and political contexts. However, differences arise in production systems. Even though there is a settlement tendency all over West Africa, Senegal possesses more intensive and semi-intensive systems than other countries in the region, particularly in the Sahel, where pastoralism remains the dominant system. Moreover Senegal as a coastal country possesses a humid coast and therefore good climatic conditions for dairy farming and agriculture (e.g., Niayes region). Senegal also has high intensification and investment opportunities.

V.4.6.4. Potential future opportunities for women and youth

Previous studies have shown that most women in cattle-keeping communities have traditionally taken care of the family's cows, handled feeding and milking activities, and tended to sick animals (ILRI, 2021). Yet most women do not own the cattle, as men are often the owners and managers of the herd. Women in addition usually lack access to essential resources like land, labor, or finance (ILRI, 2021). According to stakeholders, intensification of the sector, if guided to support women, could enable women to be active in dairy farming and/or benefit from milk production increase, through participating in dairy cooperatives that could improve women's incomes and employment (Staal et al., 2020). Women interviewed in the study often noted that they are dependent on their husband for deriving the benefits from dairy farming activities. Against scenarios of increased intensification and settlement, most women indicated the wish to earn their own money to buy a house and to send their children to school while still taking care of the household. Investments in women-led farms could thus benefit their entire households, communities and nation (ILRI, 2022). It has also been found that increased participation of women in decision-making leads to better management of drought risks and decreases vulnerability to climate change (Grillos, 2018; ILRI, 2022).

According to the experts, youth are likely either turn to commercial dairy farms, shift to more productive crops (e.g., money crops such as avocados or horticulture in Kenya), or engage in other businesses. They will likely think commercial rather than traditional as they have less social

attachment to tradition and animals than the elders, and will likely participate in training to obtain skills such as harvesting, making silage, etc. Farmer replacement rates might then slowly decline, making farming activities, including dairy, not a priority for younger generations. Many interviewees also thought that farmers' children will have to take over the farm and animals given limited alternatives in the form of employment and education.

V.4.6.5. Strengths and weaknesses of the method

The contribution of this study lies mainly in the method used to interview a diverse group of dairy sector actors, experts and stakeholders, allowing participants to think about the future and of the links between the consequences and challenges associated with change (Bengston, 2016). However, it stands to reason that the output of the study is limited to the collective judgments of these experts and stakeholders (Bengston, 2016). There might also be potential biases concerning herders interviewed during the study, as in Kenya they were drawn from a pool participating in a dairy innovation platform close to urban and production centers. Hence, these herders are likely more familiarized with the evolution of dairy farming systems and have been targets already of sensitization and training on improved dairy production practices, making them more likely to include intensifying systems in their anticipation of the systems of the future. The futures wheel remains, however, an appropriate method for this study and for answering the research questions. Indeed, interviews of experts and key stakeholders allow to identify diversified evolution of dairy systems and cover a multitude of potential consequences. The multitude of interviewees allow us to have various points of views about the research questions.

V.4.7. Conclusion

As the dairy sector will undergo changes in the future, and will face challenges such as population growth, climate change and insecurity and conflicts, there is a need for a holistic and integrated approach for future thinking, as well as training and sensitization that builds on the initial conceptualization. Changes in dairy production systems can also affect the autonomy of herders, having consequences on livestock and the society: loss of traditions and knowledge, loss of social links between communities, employment crisis, land use competition, biodiversity issues, etc.

The evolution of dairy systems in Kenya and Senegal seems to go toward intensification with potentially fewer but more productive farms. This evolution is driven by various factors such as land fragmentation in Kenya and government incentives, climate change, and new market opportunities in both countries. This evolution of dairy systems will potentially induce various environmental and socio-economic impacts that will affect the resilience of dairy farms to future challenges. In particular, this study highlights several challenges related to climate change: feed scarcity, water shortages, threats to animal well-being and health, and a decrease in milk quality. Both countries are also facing a growth in population. The challenges associated with the population growth are the difficulty to access markets for some herders, land pressure, and high costs of production. Finally, reduced grazing for cattle on agricultural lands through limited or planned movements of animals could increase the resilience of dairy systems to insecurity and conflicts.

Intensification of dairy cattle production could provide opportunities to women and youth. But these changes will also come with several challenges. For example, increases in productivity and income would potentially benefit only herders capable of accessing intensified systems as production and investment costs are high. Issue on herders' turn-over will also be a challenge as young people tend to abandon agriculture, preferring to migrate to cities to study or start other businesses. Even if GHG emissions per animal could be lower due to an improved diet, manure burden and total GHG emissions would increase, due to high input levels of production and input use. Expansion of agricultural and urban areas might also lead to conflict over land and resources.

Encouraging herders to produce more and better, while being sustainable for the future, is needed. This can be accomplished through climate-smart practices, the design and implementation of appropriate dairy and other policies, efficiency of production, and efficient coordination of contributing activities (e.g., animal breeding and agriculture). Finding a balance between dairy production systems and choosing the most appropriate system depending on the agro-climatic context, land availability, socio-economic context, production objectives as well as local constraints and current and future challenges seems essential to maintain balance and hence, resilience.

V.4.8. Bibliography of Part 4

Africa-milk, "Kenya", Africa-milk, 2019a, <https://www.africa-milk.org/study-sites/kenya>.

———, "Senegal", Africa-milk, 2019b, <https://www.africa-milk.org/fr/study-sites/senegal>.

Arnott, G., Ferris, C., and O'Connell, N., *A comparison of confinement and pasture systems for dairy cows : what does the science say ?*, AgriSearch (Belfast, Queen's University of Belfast : 2015).

Bebe, B.O., H.M.J. Udo, G.J. Rowlands, and W. Thorpe., "Smallholder Dairy Systems in the Kenya Highlands: Breed Preferences and Breeding Practices", *Livestock Production Science* 82, no.2-3 (2003): 117–27, 10.1016/S0301-6226(03)00029-0.

Bengston, D., "The Futures Wheel: A Method for Exploring the Implications of Social–Ecological Change". *Society & Natural Resources* 29, no.3 (2016): 374–79, 10.1080/08941920.2015.1054980.

Bourgeois, R., A glossary of terms commonly used in future studies, Forward Thinking Platform(Rome, Global Forum on Agricultural Research (GFAR): 2015), 29p.

CIRAD, "Concepts et pratiques de l'anticipation dans la recherche et le développement: un référentiel, des postures et des outils", CIRAD, April 28, 2021, <https://www.cirad.fr/nos-activites-notre-impact/enseignement-et-formation/formation-professionnelle/catalogue-des-formations/concepts-et-pratiques-de-l-anticipation-dans-la-recherche-et-le-developpement>.

Dieye, P.N., Broutin, C., Bâ Diao, M., Duteurtre, G., and Ly, C., *Synthèse bibliographique sur les filières laitières au Sénégal*, (Repol: 2005).

Diop, A.T., Ickowicz, A., Diène, M., and Nzimulinda, J.C., "Production laitière dans la zone sylvopastorale du Sénégal: étude des facteurs de variation et modes de gestion par les populations locales", *Revue d'élevage et de médecine vétérinaire des pays tropicaux* 62, no.1 (2009): 39–47, 10.19182/remvt.10092.

Downey, L., Heydebreck, P., and de Jouvenel, H., Foresight and the Transition to Regional Knowledge-Based Economics: policy orientation report of the expert group, European Commission, Directorate-General for Research and Innovation. (Brussels: Synthesis Report of the Expert Group

'Blueprints for Foresight Actions in the Regions', Publications Office, 2005).

FAO, "Bangladesh: Social gains from dairy development", in *Smallholder dairy development: Lessons learned in Asia* (Bangkok: Animal Production and Health Commission for Asia and the Pacific, 2009).

———, *Integrated Snapshot - Kenya - Cattle and Poultry Sectors*, Africa Sustainable Livestock 2050 (Rome, Food and Agriculture Organization of the United Nations: 2018a).

———, *Livestock Production Systems Spotlight - Kenya - Cattle and Poultry Sectors*, Africa Sustainable Livestock 2050 (Rome, Food and Agriculture Organization of the United Nations, 2018b).

———, "Statistics", Food and Agriculture Organization of the United Nations, 2022, <http://www.fao.org/statistics/en/>.

FAOSTAT, "FAOSTAT", FAO, 2022, <https://www.fao.org/faostat/en/#home>.

Glenn, J.C, "The Futures Wheel", in *Futures Research Methodology - Version 3.0* (The Millenium Project, 2009), 1300p.

Grace, D., Alonso, S., Bett, B., Lindahl, J., Patel, E., Hung Nguyen-Viet, Roesel, K., Unger, F. and Dominguez-Salas, P., "Food safety and nutrition", in *The impact of the International Livestock Research Institute* (Nairobi: McIntire, J. and Grace, D. (eds),2009), p338-365.

GRET/APESS, *Promouvoir l'élevage Agropastoral Au Sénégal*, (GRET/APESS: 2016).

Grillos, T., "Women's Participation in Environmental Decision-Making: Quasi-Experimental Evidence from Northern Kenya", *World Development* 108 (August 2018): 115–30. 10.1016/j.worlddev.2018.03.017.

Hlimi, T., "Fragmentation and Subdivision of Land in Kenya", *Legal Aid Kenya* (blog), June 14, 2013, <https://legallaidkenya.wordpress.com/2013/06/14/fragmentation-and-subdivision-of-land-in->

[kenya/](#).

IFCN, *Dairy Report 2021*, 2021, <https://dairyreport.online/dairy-report/>.

ILRI, *USAID Kenya Crops and Dairy Market Systems Activity - Dairy Value Chain Assessment*, Technical Report (Nairobi, International Livestock Research Institute: 2018).

———, *Women's Empowerment Leads to Healthier People, Animals and Environments*, Livestock Pathways to 2030: One Health (Nairobi, International Livestock Research Institute: 2021).

———, *How Does Livestock Farming Support Gender Equality?* (Nairobi, International Livestock Research Institute: 2022).

Inayatullah, S., "Six Pillars: Futures Thinking for Transforming", *Foresight* 10, no.1 (2008): 4–21, 10.1108/14636680810855991.

Kasyoka, S., "New Study Finds That Severe Undernutrition of Cattle Increases Their Methane Production", *Sustainable Livestock Systems* (blog), May 22, 2020, <https://livestocksystems.ilri.org/2020/05/22/new-study-finds-that-severe-undernutrition-of-cattle-increases-their-methane-production/>.

KENPRO, "An Overview of Biogas, Its Benefits and Uses", *Kenya Projects Organization [KENPRO]* (blog), February 21, 2022, <http://www.kenpro.org/an-overview-of-biogas-its-benefits-and-uses/>.

Kibogy, M.R. *Kenya Dairy Industry: Status and Outlook* (Nairobi: 2019).

Kimany, J. *The Kenya Livestock Master Plan process initiated to enhance sustainable development and investment in the sector* (Nairobi, International Livestock Research Institute: 2021).

Kimuge, S., "Why Unchecked Land Subdivision Threatens Kenya's Food Security", *Business Daily*, July 28, 2021, <https://www.businessdailyafrica.com/bd/data-hub/why-unchecked-land-subdivision-threatens-kenya-s-food-security-3489164>.

Kirori, G., *Rural Development Policies in Kenya: A Critical Analysis* (Nairobi, University of Nairobi: 2003).

Lee, J. van der, B.O. Bebe, and S. Oosting. *Sustainable Intensification Pathways for Dairy Farming in Kenya*. A case study for PROIntensAfrica WP2, Deliverable 2.3 997 (Wageningen, Wageningen University & Research: 2016).

Magrin, G., Ninot, O., and Cesaro, J.D., "L'élevage pastoral au Sénégal entre pression spatiale et mutation commerciale" *M@ppemonde* 103 (2011): 17.

Makoni, N., Mwai, R., Redda, T., van der Zijpp, A., and van der Lee, J., *White Gold: Opportunities for Dairy Sector Development Collaboration in East Africa*, CDI report CDI-14-006 (Wageningen, Centre for Development Innovation: 2014).

Ministère de l'agriculture, de l'agroalimentaire et de la forêt, "Sénégal", *Les Politiques Agricoles à Travers Le Monde: Quelques Exemples* (Paris: 2014).

Mosnier, C., Dubosc, N., Abdoultalib, I., Candau, D., Carel, Y., Chauvat, S., Fougy, F., Guerre, E., Magnin, L., and Ramonteu, S., "Quelles évolutions possibles pour les systèmes de polyculture-élevage? Résultats d'ateliers participatifs et de modélisation dans quatre régions françaises?", *Cahiers Agricultures* 29 (January 2020): 30, 10.1051/cagri/2020028.

Mulder, P., "The futures wheel by Jerome Glenn", Toolshero, 2019, <https://www.toolshero.com/decision-making/futures-wheel-jerome-glenn/>.

Ochungo, P., Lindahl, J., Kayano, T., and Sirma, A.J., "Mapping Aflatoxin Risk from Milk Consumption Using Biophysical and Socio-Economic Data: A Case Study of Kenya", *African Journal of Food* 16 (August 2016), 10.18697/ajfand.75.ILRI08.

Odero-Waitituh, J.A., "Smallholder Dairy Production in Kenya; a Review", *Livestock Research for Rural Development* 29, no.7 (2017).

Reliefweb, "Senegal: Third Drought in Six Years Leaves 245,000 People Food Insecure", Reliefweb,

2018, <https://reliefweb.int/report/senegal/senegal-third-drought-six-years-leaves-245000-people-food-insecure>.

Reynolds, L., Metz, T., and Kiptarus, J., "Smallholder Dairy Production in Kenya", in *World Animal Review 87-1996/2* (Rome, Food and Agriculture Organization of the United Nations: 1996).

Staal, S., Wanyoike, F., and Ballantyne, P., *Impacts of Livestock Development Investment: Documented Positive Impacts of Livestock-Related Interventions in Africa, Asia and Latin America* (Nairobi, International Livestock Research Institute (ILRI): 2020).

The Global Economy, "Sénégal : GDP share of agriculture", The Global Economy, 2022, https://www.theglobaleconomy.com/Senegal/share_of_agriculture/.

The World Bank, "Population Growth (Annual %) - Senegal", The World Bank – Data, 2022, <https://data.worldbank.org/indicator/SP.POP.GROW?locations=SN>.

Toivonen, S., and Viitanen, K., "Environmental Scanning and Futures Wheels as Tools to Analyze the Possible Future Themes of the Commercial Real Estate Market", *Land Use Policy*, no. 52 (2016): 51–61, 10.1016/j.landusepol.2015.12.011.

Wane, A., Ndiaye, A., Touré, I., and Kane, I., "Marché du lait et (re)structuration de la mobilité pastorale dans un contexte d'incertitudes et d'opportunités. Cas du bassin de collecte de la laiterie du berger (LDB) au Sénégal", *Mobilité pastorale et développement au Sahel* (2017).

Takeaway messages of Part 4

- 1. The evolution of dairy cattle systems in Kenya and Senegal tends toward the (semi)-intensification of systems, especially the settlement of herders;*
- 2. Positive environmental impacts are identified with this evolution (less overgrazing, decreased methane emissions per animal) as well as challenges if systems are poorly managed (overall GHG emissions, manure burden, water pollution);*
- 3. Negative impacts on animal well-being and health are also identified by experts;*
- 4. Opportunities are identified with the evolution scenarios such as better market access and organisation, and women empowerment;*
- 5. Intensified systems identified by experts as a potential evolution could be resilient to higher food demand and climate change if adaptation strategies are implemented and encouraged by policies.*

VI- GENERAL DISCUSION

The research question driving this thesis is: *"How to analyse the environmental and economic impacts of a diversity of ruminant farming systems, and their intensification paths worldwide, at a global and at subnational scales?"*. To answer this question, four parts were developed in this work. After discussing ruminant farming systems and their intensification pathways in the Part 1, and despite a general lack of data, the Part 2 considers the diversity, the multifunctionality of systems, and the co-produced animals as well as their movements between systems in an original framework leading to two typologies at the world scale. The Part 3 proposes a conceptual model, without being implemented, to assess the economical and environmental impacts of cattle systems based on the framework developed in Part 2. Finally, the Part 4 validates the proposed framework developed in Part 2 at a national scale and proposes a new way of evaluating systems, by opening the analysis framework to other indicators of sustainability to go further in the evaluation of cattle farming systems, despite the lack of data at small scale, and the lack of some local systems.

VI.1. ACCOUNTING FOR THE MULTIFUNCTIONALITY OF RUMINANT SYSTEMS IN THE FRAMEWORK

The diversity of ruminant farming systems is partly represented in the conceptual framework (Part 2) by their multifunctionality, meaning the use of animals to produce manure, serve as draught power, and serve as walking financial capital and insurance, along with milk and meat production. In addition, the framework and the model (Part 3) are designed to perform impact assessment studies of these multifunctional farming systems at the world scale. These impact assessment studies allow us to emphasise economically viable production systems with reduced impacts on the environment, especially impacts on the overall livestock sector (e.g., global GHG emissions, carbon and nitrogen balances).

Therefore, impacts assessed by the model only concern the economy and the environment, omitting the social and cultural aspects of production systems, as these components are hardly modelled and quantitatively assessed, and are difficult to assess in monetary terms (Bettencourt et al., 2015). The model presented in Part 3 would therefore highlight economically performing systems, and eco-efficient systems. Eco-efficiency of systems is defined by the capacity of systems

to produce goods and services by having as little impact on the environment as possible, and by using natural resources and energy efficiently and sustainably (Kortelainen and Kusomanen, 2004; Wilkins, 2007). By only assessing the eco-efficiency of systems, the risk is to lose information on the social and cultural components of multifunctional production systems and minimising the contribution of some systems, such as pastoralist systems of the Sahel or Central Asia, or mountainous systems. These systems are, however, at the heart of the livelihood of many communities, having mainly social and cultural benefits, as the good and global understanding of the multifunctionality of the herd is considered an essential link in poverty reduction and rural economic development strategies (Moyo and Swanepoel, 2010; Alary, Duteurtre, and Faye, 2011). It should thus not be neglected in global sustainability studies of production systems.

Cultural benefits include the use of animals for the fulfilment of various traditional and religious rituals, ceremonies, and festivities such as bride wealth, ritual slaughters, and spiritual health (e.g., the role of cattle in the Hindu religion) (Alary, Duteurtre, and Faye, 2011; Bettencourt et al., 2015; Alders et al., 2021). In some countries, such as Timor-Leste, research has shown that animal-source food consumption is closely linked with cultural ceremonies having an impact on household nutrition (Alders et al., 2021). While social benefits include the role of animals as a social status in society, demonstrating wealth, identity and belonging to a certain community, it can also potentially give access to credits and loans (Randolph et al., 2007; Alary, Duteurtre, and Faye, 2011; Bettencourt et al., 2015). Animals are also a major part of the social relation chains in some communities, which are vertical relations (between generations), or horizontal ones (between communities) (Alary, Duteurtre, and Faye, 2011). Indeed, as an example, the disappearance of pastoralism was pointed out by experts in Senegal (in the foresight study in Part 4) as a potential cause of the loss of community links.

Livestock production systems have also impacts on human physical and mental health, and well-being. Contact with animals has been reported to enhance the physical, social, and mental health of people, producing relaxation and reducing stress and anxiety (Hassink et al., 2017; Alders et al., 2021).

Finally, among the social impacts of production systems, it seems also important to understand the role that gender plays in production systems (Bettencourt et al., 2015), as men and women often play different and defined roles. During field observations in Senegal (Part 4), roles in dairy farming

are gender-segregated as women attend to feeding, milking, and selling the milk on markets, while men are in charge of all major decisions concerning the herd (e.g., sales of animals, treatment, etc). In many countries, as also observed during field visits in Kenya, women are in charge of small ruminants, while men take care of large ruminants (Bettencourt et al., 2015). It seems, therefore, crucial to include some indicators linked with gender within the analysis of impacts in the model, such as the inclusivity of value chains and the role of women in ruminant farming systems.

Despite the difficulty to assess the cultural and social parts of livestock production systems, some authors have accounted for these components in assessment studies. Weiler et al. (2014) are performing allocations based on farmers' assessment and valuation of the role of cattle in their livelihoods in Kenya. Based on a ranking of the functions of cattle in their livelihoods (milk for home consumption, milk for sale, cattle sales when cash is needed, dowry, wealth), GHG emissions were then allocated depending on the importance of each function. Assessing multiple goods and services of livestock farming is also at the heart of the study by Ryschawy et al. (2017). In this study focusing on France, indicators quantifying goods and services (i.e., food quality and quantity, environmental quality, rural vitality, and culture) are used to assess them and their relationships (synergies and trade-offs).

By adding the social and cultural impacts of production systems to the economic and environmental ones, we can consider all components of sustainability. The definition given here to the term "sustainability" is the capacity of systems to resist and adapt to existing and future challenges. Based on the pillars of sustainability (i.e., economy, environment, social), agro-ecological intensification seems to be better suited to include a larger diversity of production systems than the dominant intensification, as agro-ecology encompasses all components of sustainability (see Part 1). According to the FAO (2022), agro-ecology is seen as a key to guiding the sustainable transformation of our food systems as it contributes to reaching many Sustainable Development Goals (SDGs) associated with livestock such as SDG1 (No Poverty) by supporting herders in reducing their production costs (whereas dominant intensification is associated with high levels of external inputs and high costs), translating into greater income, economic stability and resilience; SDG2 (Zero Hunger) by promoting the use of local and renewable energy, harness ecosystem benefits and services including biodiversity; SDG3 (Good Health and Well-being) by minimizing the use of external inputs; as well as other SDGs such as SDG5 (Gender equality), SDG8 (Decent Work and Economic Growth), SDG12 (Responsible consumption and production), SDG13

(Climate Action), SDG15 (Life on land), and SDG17 (Partnerships for the goals) (Schneider and Tarawali, 2021). Many of these SDGs are associated with the social and cultural components of sustainability (e.g., SDG3, SDG5, SDG12, SDG15), and thus cannot be taken into account by the framework and the model presented in this thesis.

If agro-ecological intensification should be favoured for ruminant production systems, which components should then be evaluated in an impact assessment study? It appears that the conceptual framework and the model lack the capacity to assess impact of systems on biodiversity, and on social components such as rural employment, woman empowerment, well-being, and knowledge sharing. Indeed, training and sensitization were highlighted as key to designing sustainable production systems in the study presented in Part 4. For assessing impacts on biodiversity, finding the right parameters seems difficult and complex. Parameters such as the Biodiversity Intactness Index or the Land Equivalent Ratio could be, however, used to describe the diversity of species at a particular point (Koch, Schaldach, and Göpel, 2019), and to indicate productivity benefits of biodiversity (Dawson et al., 2019), respectively. Concerning social and cultural impacts, one solution could be for these components to be discussed and qualitatively assessed to then be put in parallel with the quantitative assessment from the model, to obtain a complete assessment of the sustainability of systems. As discussed in Part 4, producing more while respecting the environment and considering the multifunctionality of systems (including traditions and culture, community and social links, etc) could be a key to guiding the future and sustainable transformation of systems.

Cultural impacts and social inclusion are potential drivers for the establishment of livestock development projects nowadays. In addition to these drivers, animal health, access to more inclusive services and value chains, resilience, low carbon emissions, nutrition and food security, and climate-smart agriculture are also major drivers of development projects, such as the KCSAP project (KCSAP, 2023), the World Bank PRAPS (La Banque Mondiale, 2021) or the GCF projects (Green Climate Fund, 2023). It seems therefore important to include indicators of these drivers within the model developed in Part 3 to be able to support and highlight livestock systems performing well with the above-mentioned drivers.

VI.2. DESIGNING A FRAMEWORK FOR RUMINANT SYSTEMS AT THE GLOBAL SCALE: STRENGTHS AND RISKS

Designing a framework to study ruminant production systems, as well as their intensification paths, at the global scale, induces necessarily strengths and risks. Firstly, one risk associated with the framework presented in Part 2 is the absence of combinations between management types and lineage groups in reality. For example, thanks to the contribution of many ruminant experts, we defined that the lineage groups with reproductive females going through a fattening management type before returning to their management type of origin are rare. These lineage groups are also associated with some management types such as the ones with a production objective. Therefore, traditional management types or agro-pastoral ones would not be associated with these kinds of lineage groups. Among all the combinations possible between the sixteen management types and the six lineage groups, not all are realistic and actually exist in the world. Depending on the region considered and its specificity, one could determine how many of these combinations exist.

Secondly, the framework has been submitted and approved by some experts (see Annex 1). There could be, however, a bias in the choice of experts selected. They were selected based on their area of expertise (covering as many regions of the world as possible) and their species of expertise (sheep, goats, cattle, camels) but their number (six in total) is not high enough to be fully representative of the diversity of ruminant farming systems.

Thirdly, knowing the increasing demand for animal-based products in certain parts of the world, Parts 2 and 3 could permit the designation of specific and highly productive areas suited for cattle production. Nonetheless, this would imply the risk of having some highly specialized territories for production depending on the demand, the local availability of resources such as land or water, as well as local challenges and constraints. For example, in South America, the Amazonian area is being deforested for the establishment of pasture-based cattle production systems (Cardoso et al., 2016). In addition to the negative environmental impacts of deforestation, this could also lead to smallholder exclusion to the profit of large farms that are more economically efficient due to economies of scale (Clay, Garnett, and Lorimer, 2020). This risk is, however, mitigated if one takes into account the capacity of systems to produce other services than milk and meat such as manure, or draught power.

The potential apparition of highly productive and specialized areas questions us on the conventional intensification of systems and where to put the boundary between the expansion of croplands and pastures, and the conservation of natural areas. These questions refer to the concept of land sparing and land sharing. Land sparing refers to the implementation of intensive production systems, and a strict separation between conservation and production areas, and is opposed to land sharing, where less land is set aside for conservation, but ecosystem-friendly management practices are promoted in productive areas with lower yields and aiming to maintain biodiversity (Tscharntke et al., 2012 ; Fischer et al., 2014; Koch, Schaldach, and Göpelet, 2019). Numerous studies point to the need for an integrated approach that supports sustainable or agro-ecological intensification to enable the cessation of cropland expansion, and the conservation of biodiversity in natural and agricultural systems (Koch, Schaldach, and Göpelet, 2019).

Another risk associated with the designation of specific and highly productive areas is the high density of farms, and therefore, of animals in a specific area. Indeed, a high concentration of animals leads to pollution of water due to excesses of nitrogen and phosphorus leading to eutrophication and hot spots of ammonia emissions, as well as risks associated with the nearby populations such as bad odours, and risks to public health (Herrero et al., 2009; Peyraud, Taboada, and Delaby, 2014; Gallego et al., 2019) due to the potential propagation of diseases and zoonoses. Other risks associated with a high density of livestock are the impoverishment of soil fertility, and a loss of biodiversity (Peyraud, Taboada, and Delaby, 2014).

While the high specialisation of territories would strengthen the capacity of the livestock sector to provide enough animal-based products to an increasing global population, it would also imply a high dependence on other regions, at the national or global scale, to supply certain inputs (e.g., feeds and forages, or manure). This dependence could lead to a weakening of the sector, being more sensitive to climatic, political or economic events, and thus potentially endangering the equilibrium and performance of the entire livestock production system.

VI.3. EXPERIENCING THE FRAMEWORK AT A SMALLER SCALE

As the primary question guiding this thesis is: "How to analyse the environmental and economic impacts of a diversity of ruminant farming systems and their intensification paths at macro scales?",

questions were then raised to know if a change in scale could still be relevant for the framework. The fourth part of the thesis aims to test its relevance at a small scale by focusing on the evolution and intensification pathways of dairy farming systems in Kenya and Senegal.

In the article presented in Part 2, the relevance of the framework for cattle systems in Kenya (dairy and beef systems) was already investigated, based on the available literature. This contextualisation of the framework to Kenyan cattle systems reveals that all systems found in the country can be linked to a management type from the typology. The same comparison is done for cattle systems in Senegal (see Tables 16 and 17). There is a difficulty to define precisely the systems in both countries from the available literature, as various descriptions exist and often overlap, without being systematically similar. Despite this difficulty, three general system categories can be defined for both countries: 1) extensive grazing systems, 2) semi-intensive systems often mixed with agriculture, and 3) intensive systems with confined animals. Even if, on the field, many variations exist of the three general system categories taken from the literature, specifically concerning feed availability and nature (e.g., feed residues or by-products, trees, natural fodder, etc), it seems that all systems fall in these three categories. Based on field visits and observations, the characteristics of local systems are often more specific than the description given in the management types in the typology (Part 2). But the typology still enables it to encompass a large diversity of local systems.

The proposed framework, therefore, seems to work well at small scales when taking general system categories but, in reality, the diversity of systems and practices is so large that it would be impossible to take all variations into account within a global framework (at the world scale). Depending on local conditions and constraints, concerning feeds, topography, local climatic conditions, the presence of water points or trees, market access and the organisation of the supply chain, systems can vary locally. Despite these local variations, it seems that the management type typology works well at smaller scales (see Tables 16 and 17).

Table 16: Correspondence of dairy farming systems in Kenya with the management type typology developed in Part 2

Dairy farming systems in Kenya		Management type in the typology
Grazing	Small-scale solely livestock grazing systems	2 – Traditional pastoral dairy MT with a multi-functional objective
	Medium- to large-scale solely livestock grazing systems	7.1 OR 8 - Grass-fed dairy MT with a production objective or a multi-functional

		objective
	Mixed grazing systems	12.1 – Internally complemented grass-fed dairy MT with a production objective OR 7.1 OR 8 - Grass-fed dairy MT with a production objective or a multi-functional objective
Semi-grazing	Small-scale mixed semi-grazing systems	13 – Internally complemented grass-fed MT with a multi-functional objective
	Medium- to large-scale mixed semi-grazing systems	12.1 - Internally complemented grass-fed MT with a production objective
	Solely livestock semi-grazing	9.1 - Externally complemented grass-fed dairy MT with production objective
Zero-grazing	Small-scale mixed zero-grazing systems	14.1 – Zero-grazing dairy MT with grass, with a production objective
	Medium- to large-scale mixed zero-grazing systems	14.1 OR 15.1 - Zero-grazing dairy MT with grass or without, with a production objective
	Solely livestock zero-grazing systems	16.1 – Scavenging & backyard MT with a production objective

Table 17: Correspondence of dairy farming systems in Senegal with the management type typology developed in Part 2

Dairy farming systems in Senegal	Management type in the typology
Pastoral	1.1 OR 2 – Traditional pastoral dairy MT with a production or multi-functional objective
Agro-pastoral	5.1 OR 6 – Agro-sylvo-pastoral dairy MT with a production or multi-functional objective
Intensive	15.1 OR 16.1 – Zero-grazing dairy MT with or without grass, with a production objective

By also including some territorial specificities, such as resources, the framework could be experienced at smaller scales. As the framework has been primarily constructed to be used at large scale, its connection to smaller scales is not always an easy task. To overcome the difficulties, one could think of reducing the number of management types and lineage groups to fit the reality of a territory before connecting them to some territorial specificities such as the climate, the water availability, the land availability, etc.

VI.4. LIMITATIONS AND NEXT STEPS

This thesis opens possibilities for further improvements and work. For this thesis to be more complete, and to move towards the next steps, a proper application of the model would be necessary to move from a conceptual model to an applied one and perform the quantitative impact assessment. The implementation could help verifying that the model works well and could help improve it or the obtained results. For example, an improved result could be to obtain a global map showing the potential distribution of systems worldwide, to have more than one lineage group per grid cell, or to consider the diversity of species per grid cell. This last improvement should also be done primarily at the conceptual framework stage (Part 2) to include other ruminant species in the characterization of systems. Time was definitely a limit to this improvement. But more means (financial, working, expertise) would also have been necessary to perform such work at a macro-scale. Indeed, one limitation that has been already outlined in Part 2 is the lack of specific local data making this work difficult to perform at macro-scales. The use of specific country databases provided by international organizations (i.e., the FAO) could be a solution to that limit, even though data availability still remains an issue in many parts of the world. In global agricultural models, GLOBIOM, NLU, GLEAM, and IMAGE (see Part 2), much data are coming from various sources such as international organisations such as in GLOBIOM and NLU (Havlik et al., 2011; Souty et al., 2012)), from surveys, databases and literature like in GLEAM (Macleod et al., 2018; FAO, 2022), or from other models like in NLU (Souty et al., 2012). Often, data availability varies greatly according to the parameter in consideration or the country (Havlik et al., 2011; Macleod et al., 2018) before being harmonized.

Another improvement to the framework and the model is to be better suited to changes of scale. It seems that the typology appears too detailed for a small scale (a country scale), as it was designed for a world scale. The aim for choosing such a scale to build the typology is to study the effects of cattle farming felt at that scale such as the GHG emissions, the nitrogen cycle, and global trade. Building a framework and a model at a global scale asks for generalisation and simplification, but details are lost in return. Therefore a balance has to be found between simplifying and detailing, which was the aim of building the typology. To reach the goal to perform better at smaller scales, more details should be added to the typology (e.g., specific feed diet depending on the location and the season, specific pasture management practices, etc).

Finally, another point of improvement would be to expand the foresight study presented in Part 4 to other countries, targeting other continents, for example, Latin America (e.g. Brazil) or South-East

Asia (e.g., Vietnam), to compare with the African countries already studied. This could have allowed an even bigger diversity of production systems, climatic conditions, and economic and political contexts to compare. Senegal and Kenya were selected because of their diversity of production and agro-ecological contexts but also because of the importance of the dairy sector in these countries, and their potential growth in the future due to an increase in demand. These two countries were also selected as the majority of African countries are considered most at risk of climate change (Carleton, 2022), implying new constraints and challenges in the future to build sustainable and productive systems.

VI.5. BIBLIOGRAPHY OF THE DISCUSSION

Alary, V., Duteurtre, G., and Faye, B., "Elevages et sociétés: les rôles multiples de l'élevage dans les pays tropicaux", *INRA Productions Animales*, 24, no. 1 (2011): 145-156, hal-02642534f.

Alders R.G., Campbell, A., Costa, R., Guèye, E.F., Hoque, M.A., Perezgrovas-Garza, R., Rota, A., and Wingett, K., "Livestock across the world: diverse animal species with complex roles in human societies and ecosystem services", *Animal Frontiers* 11, no.5 (October 2021): 20-29, 10.1093/af/vfab047.

Bettencourt, E., Tilman, M., Narciso, V., da Silva Carvalho, M., and de Sousa Henriques, P., "The Livestock Roles in the Wellbeing of Rural Communities of Timor-Leste", *RESP* 53, no. 1 (March 2015): S063-S080, 10.1590/1234-56781806-94790053s01005.

Cardoso, A.S., Berndt, A., Leytem, A., Alves, B., de Carvalho, I., de Barros, S., Urquiaga, S., and Boddey, R.M., "Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use", *Agricultural Systems* 143 (March 2016): 86-96, 10.1016/j.agsy.2015.12.007.

Carleton, E., "Climate change in Africa: What will it mean for agriculture and food security?", International Livestock Research Institute, September 28, 2022, <https://www.ilri.org/news/climate-change-africa-what-will-it-mean-agriculture-and-food-security>.

Clay, N., Garnett, T., and Lorimer, J., "Dairy intensification: Drivers, impacts, and alternatives", *Ambio* 49, no. 1 (January 2020): 35-48, 10.1007/s13280-019-01177-y.

Dawson, I., Park, S., Attwood, S., Jamnadass, R., Powell, W., Sunderland, T., and Carsan, S., "Contributions of biodiversity to the sustainable intensification of food production", *Global Food Security* 21 (June 2019): 23-37, 10.1016/j.gfs.2019.07.002.

FAO, "Agroecology and the Sustainable Development Goals (SDGs)", Agroecology Knowledge Hub, Food and Agriculture Organization of the United Nations, September 21, 2022, <https://www.fao.org/agroecology/overview/agroecology-and-the-sustainable-development-goals/fr/>.

Fischer, J., Abson, D., Butsic, V., Chappell, M., Ekroos, J., Hanspach, J., Kuemmerle, T., Smith, H., and von Wehrden, H., "Land sparing versus land sharing: moving forward", *Conservation Letters* (May 2014): 1-9, 10.1111/conl.12084.

Gallego, A., Calafat, C., Segura, M., and Quintanilla, I., "Land planning and risk assessment for livestock production based on an outranking approach and GIS", *Land Use Policy* 83 (April 2019): 606-621, 10.1016/j.landusepol.2018.10.021.

Green Climate Fund, "Green Climate Fund", 2022, <https://www.greenclimate.fund/>.

Hassink, J., De Bruin, S., Berget, B., and Elings, M., "Exploring the role of farm animals in providing care at care farms", *Animals* 7, no.6 (June 2017), 10.3390/ani7060045 .

Havlik, P., Schneider, U., Schmid, E., Böttcher, H., Fritz, S., Skalsky, R., Aoki, K., de Cara, S., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., and Oberstainer, M., "Global land-use implications of first and second generation biofuel targets", *Energy Policy* 39 (2011): 5690-5702, 10.1016/j.enpol.2010.03.030.

Herrero, M., Thornton, P.K., Gerber, P., and Reid, R., "Livestock, livelihoods and the environment: understanding the trade-offs", *Current Opinion in Environmental Sustainability* 1, no. 2 (December 2009): 111-120, 10.1016/j.cosust.2009.10.003.

KCSAP, "Kenya Climate Smart Agriculture Project, KCSAP (2022), <https://www.kcsap.go.ke/>.

Koch, J., Schaldach, R., and Göpel, J., "Can agricultural intensification help to conserve biodiversity? A scenario study for the African continent", *Journal of Environmental Management* 247 (October 2019): 29-37, 10.1016/j.jenvman.2019.06.015.

Kortelainen, M., and Kuosmanen, T., "Measuring Eco-efficiency of Production: A Frontier Approach", *RePEc* (December 2004): 22.

La Banque Mondiale, "La Banque mondiale débloque 375 millions de dollars pour aider les pays du Sahel à exploiter pleinement le potentiel du pastoralisme", Communiqué de presse (mars 2021), N° 2021/114/AFR, <https://www.banquemondiale.org/fr/news/press-release/2021/03/30/world-bank-provides-375-million-to-boost-efforts-towards-realizing-the-full-potential-of-pastoralism-in-the-sahel>.

MacLeod, M.J., Vellinga, T., Opio, C., Falcucci, A., Tempio, G., Henderson, B., Makkar, H., Mottet, A., Robinson, T., Steinfeld, H., and Gerber, P.J., "A position on the Global Livestock Environmental Assessment Model (GLEAM)", *Animal* 12, no.2 (2018): 383-397, 10.1017/S1751731117001847.

Moyo, S., and Swanepoel, F.J.C., "Multifunctionality of livestock in developing communities", in *The Role of Livestock in Developing Communities: Enhancing Multifunctionality*, eds. Swanepoel, F., Stroebel, A., Moyo, S. South Africa: the technical centre for agricultural and rural cooperation (CTA), 2010.

Peyraud, J.L., Taboada, M., and Delaby, L., "Integrated crop and livestock systems in Western Europe and South America: A review", *European Journal of Agronomy* 57 (2014): 31-42, 10.1016/j.eja.2014.02.005.

Randolph, T.F., Schelling, E., Grace, D., Nicholson, C.F., Leroy, J.L., Cole, D.C., Demment, M.W., Omore, A., Zinsstag, J., Ruel, M., "Role of livestock in human nutrition and health for poverty reduction in developing countries", *Journal of Animal Science* 85, no.11 (December 2007): 2788-2800, 10.2527/jas.2007-0467.

Ryschawy, J., Disenhaus, D., Bertrand, S., Allaire, G., Aznar, O., Plantureux, S., Josien, E., Guinot, C.,

Lasseur, J., Perrot, C., Tchakerian, E., Aubert, C., and Tichit, M., "Assessing multiple goods and services derived from livestock farming on a nation-wide gradient", *Animal* 11, no.10 (October 2017): 1861-1872, 10.1017/S1751731117000829.

Souty, F., Brunelle, T., Dumas, P., Dorin, B., Ciais, P., Crassous, R., Müller, C., and Bondeau, A., "The Nexus Land-Use model version 1.0, an approach articulating biophysical potentials and economic dynamics to model competition for land-use", *Geoscientific Model Development* 5, no.5 (October 2012): 1297-1322, 10.5194/gmd-5-1297-2012.

Tscharntke, T., Clough, Y., Wanger, T., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J., Whitbread, A., "Global food security, biodiversity conservation and the future of agricultural intensification", *Biological Conservation* 151, no.1 (July 2012): 53-59, 10.1016/j.biocon.2012.01.068.

Weiler, V., Udo, H., Viets, T., Crane, T., and De Boer, I., "Handling multi-functionality of livestock in a life cycle assessment: the case of smallholder dairying in Kenya", *Current Opinion in Environmental Sustainability* 8 (2014): 29-38, 10.1016/j.cosust.2014.07.009.

Wilkins, W., "Eco-efficient approaches to land management: a case for increased integration of crop and animal production systems", *Philosophical Transactions of the Royal Society* 363, no.1491 (July 2007): 517-525, 10.1098/rstb.2007.2167.

VII- CONCLUSION

Following the increase in population, rising incomes and urbanization, ruminant production systems face the challenge to meet the growing demand for animal-based products in many parts of the world. Global challenges such as climate change and increased negative environmental impacts are pushing production systems to undergo changes to produce more while being sustainable.

To reach the goal of producing in a sustainable manner, one step could be to first understand and calculate the environmental performances of each production system along with their economic performances. The typologies and the conceptual framework developed in Part 2 allow us to capture the complexity of cattle farming at the global scale, and to account for animal movements between systems, thanks to the lineage groups.

Based on this framework, assessing the environmental and economic performances of each management type is possible through modelling. The objective of the theoretical model developed in Part 3 and based on the framework developed in Part 2, is to compare lineage groups based on their performances. In particular, two measures of performance, corresponding to the limits of a gradient of intensification objectives, are compared: (1) a private economic performance based on revenue generation or multi-objective maximization with (2) a combination of socio-environmental impacts and private economic performance. The latter corresponds to a combination of various livestock farming activities and economic profit with a penalization for negative impacts on the environment.

As the ruminant sector will undergo changes in the future to face challenges such as population growth, climate change, and insecurity and conflicts, there is a need for a holistic and integrated approach to future thinking. The foresight study presented in Part 4 aims at exploring future evolution paths for dairy farming systems in Kenya and Senegal. Along with evolution paths, drivers of evolution as well as potential environmental, economic and social impacts are discussed. In this part, social components of production systems are taken into account as they are at the heart of farmers' livelihoods in Kenya and Senegal, as well as in many other countries of the world. Encouraging herders to produce more and better, while being sustainable for the future, is needed. Finding a balance between production systems, and choosing the most appropriate one depending

on the agro-climatic context, land availability, socio-economic context, production objectives as well as local constraints and challenges seem essential to maintain diversity and hence, resilience.

By studying and classifying several ruminant farming practices over the world and building a conceptual model, a framework has been set for future impact assessment studies. Indeed this work opens the way for forthcoming studies on environmental and economic impact assessment. The goal of this conceptual framework is also to be able to perform holistic impact assessment studies, taking into account various environmental components such as GHG emissions, nitrogen balance but also economic components. As discussed in the previous part, the social and cultural aspects of systems should not be neglected. Bearing in mind and discussing these components of a farming system should also be a priority, along with environmental and economic impacts, to obtain a holistic view of production systems. Considering these three components of sustainability together should help to identify sustainable development pathways for ruminant farming in the future.

VIII- ANNEXES

ANNEXE 1: EXPERT CONSULTATIONS ON TYPOLOGIES

1.1. Objectives

The main goal is to conduct a series of consultations with experts (animal scientists, livestock economists, modellers, etc.), specialized in one region or country of the world. These consultations are associated with several objectives.

In retrospect, the first objective is the *validation of the MTs and LGs in the expert's preferred region*. Presentation, verification, modification and validation of the present MTs and LGs starting from the MTs and LGs proposed in the conceptual framework developed during the thesis. This implies describing and reconstructing the LGs, possibly from strands, and their different constituent elements (underlying MTs) to have an exhaustive list of the LGs and MTs present in the expert's preferred region as well as the approximate share of these LGs.

In retrospect, the second objective is to *understand the processes of choice of LGs/MTs in the expert's preferred region*. To obtain information about the choice processes underlying the presence of such and such LGs and their constituent MTs and the potential reasons for changing LG/MTs.

In retrospect, the third objective is the *calibration of missing parameters and the validation of existing parameters*. To obtain missing data on these LGs/MTs, which complement existing and available data from the literature, with a secondary objective of verifying whether the existing data are validated. These missing data concerns in particular: feed diet including composition and purchased feed vs. produced feed, pasture management parameters, on-farm crop and breeds (confirmation).

Prospectively, the objective is to *determine parameters for LG/MT that do not currently exist*. Engage in a thought exercise for non-existent or marginal LGs/MTs in the region and find parameters analogous to existing LGs/MTs. Also, get a sense of the choice processes leading to changes toward these non-existent LGs/MTs.

Experts have been interviewed online thanks to a questionnaire that has been previously tested with one volunteer expert. These individual interviews included a discussion phase, followed by the questionnaire.

1.2. Questionnaire

1- Preliminary information

1. Personal information: work, time spent working on ruminant farming, region of the world, when and for how long;
2. Information on the expertise: area of expertise (nature, size, scale), date of the expertise (past or present).

2- For each LG

- Does it exist in the region?
- Which MTs are involved in this LG (MT of origin or finishing MT)?
- For 100 births, how many animals belong to that lineage group?
- How is this lineage group evolving at the present time (e.g. change in the type of original management, increase or decrease)?

3- Have lineage groups been forgotten in the region?

4- For each MT

- What is the nature of this management type?
- Are there specificities for this type of management in this region?
- What are the reasons for a livestock herder to choose this type of management in this sector? (natural resources availability, economic reason, income generation, cultural/religious dimension, etc).
- What categories of feed is present in the animal ration of these types of management? (grazed grass, harvested grass, residues, roadsides, concentrated feed, cultivated fodder).
- How much grass is consumed in the diet? (mean over the year)
- What is the type of pasture fertilization?
- What is the approximate level of N fertilization per unit of area?

- What is the approximate time of confinement of the animals over the year (in a stable, building, etc.)?
- How is manure managed?
- What type of insemination is commonly practised?
- What types of cattle breeds are commonly used?
- What are the levels of milk/meat production?
- What are the types of pasture existing in this management type? (cultivated, rotational, multispecies)
- What is the share of grazed pastures versus harvested pastures?
- What are the pasture and grazing management practices used?
- What is the % of livestock herders concerned by this MT in the region or average #head/herder ?
- Costs aspects - Which costly inputs are present in this MT (machinery, water points, car/truck, fences, etc.) ?

5- For each non-existent MT in the region?

1. Are there current possibilities for moving towards these types of management in your preferred region?
2. What could be the objective of this type of management in this sector and in your region of predilection?
3. In which lineage group these types of management could fit?
4. What categories of feed is present in the animal ration of these types of management? (grazed grass, harvested grass, residues, roadsides, concentrated feed, cultivated fodder).
5. What is the average fertility rate?
6. What is the average mortality rate ?
7. What is the average yearly offtake rate?
8. What is the average live weight of a mature animal?
9. What type of insemination is commonly practised?
10. What types of breeds are commonly used?
11. What motivates the choice of the breed?

1.3. Results

In total, five experts were interviewed, specialising in different regions or countries of the world - naming Egypt, Sahel, Zambia, Vietnam and Saudi Arabia - and in various ruminant species - cattle and buffaloes, small ruminants, camels.

All ruminant production systems in each region of the world can be linked to a management type from the typology (see Table 18), each linked to a LG, which validates both typologies by experts.

Tableau 18: MTs identified by experts as present in region of specialization

	MT 1	MT 2	MT 3	MT 4	MT 5	MT 6	MT 7	MT 8	MT 9	MT 10	MT 11	MT 12	MT 13	MT 14	MT 15	MT 16
Zambia	X															
Sahel		X				X										X
Saudi Arabia	X	X					X	X					X	X		
Vietnam				X						X						
Egypt									X				X			

For each MT identified by experts, some additional parameters were explored (see Table 19).

Tableau 19: Parameters identified by experts for each MT

	MT1	MT2	MT4	MT6	MT7	MT8	MT9	MT10	MT13	MT14	MT16
LG	LG1	LG1	LG1	LG1	LG1	LG1	LG3	LG1	LG1	LG1	LG1
Nature of MT	Birth place	Birth place	Birth place	Birth place	Birth place	Birth place	Fattening non-reproductive cattle	Birth place	Birth place	Birth place	Birth place
Grass in the diet	> 50%	70-90%	70-90%	>90%	50-70%	50-70%		30-50%		30-50%	<30%
Fertilization	No or organic	None	None	None	None			Mineral or organic			None
Confinement of animals	<6 months	Never	12 months	Never	12 months		12 months	12 months	Never	12 months	Never

Manure management	Natural deposition at night	Natural days and nights	Natural deposition at night	Natural deposition at night	Natural deposition at night		Manure collection & management	Manure collection & management	Natural days and nights	Manure collection & management	
Insemination	Natural	Natural	Natural	Natural	Natural			Artificial	Artificial		
Breeds	Local	Local	Local	Local	Local		Crossed	Exotic	Crossed	Exotic	
Milk production	1500 - 4500 L/cow/year	2000L/lactation		2000L/lactation	3000L/lactation	3000L/lactation			7L/cow/day		
Meat production	100-130 kg/carcass	150-250 kg/animal		150-250 kg/animal	250 kg/animal	250 kg/animal	100 kg/veal			180 kg/carcass	
Type of pasture	Natural	Natural	Natural	Natural	Natural & cultivated			Cultivated			
Grazing management	Multi-species		Multi-species		Rotational & irrigation						
% herders concerned	30%	30-50%		45-50%	30-40%	15%	20-30%		70-80%	5%	

Another objective of this consultation was to consult experts on reasons to choose an MT by herders in each region:

- MT1: lack of choice due to natural resources availability (water, food, etc), natural resources availability (water, food, etc.), cultural / religious dimension, environmental/social choice, and for self-consumption;
- MT2: mainly economic reasons (little capital available), natural resource availability, cultural / religious dimension, and main income source;
- MT4: natural resources, environmental / social choice, and space constraints;

- MT6: natural resources availability, economic reasons (little capital available), for revenue diversification;
- MT7: generation of income, cultural / religious dimension;
- MT8: generation of income, cultural / religious dimension;
- MT9: generation of income, cultural / religious dimension, for revenue diversification;
- MT10: natural resources availability, generation of income;
- MT13: natural resources availability, economic reasons (little capital), cultural / religious dimension, for self-consumption, for revenue diversification, crop residues valorization;
- MT14: generation of income;
- MT16: generation of income, cultural / religious dimension.

Alongside the MT typology, the LG typology was also investigated in each region / country (see Table 20).

Tableau 20: Parameters identified by experts for each LG when present in their preferred region

	LG1	LG2	LG3	LG4	LG5	LG6
Present in all regions?	Yes	No	Yes	No	Sometimes, depending on the region	No
MTs involved	MT1, MT2, MT4, MT6, MT7, MT8, MT13, MT15, MT16		MT1, MT2, MT4, MT9, MT15, MT16 Fattening: MT9, MT13, MT15		MT15	
% animals belonging to that LG	>50%		20-50%		<20%	

Linked with Part 4 of the thesis, the potential evolution of MTs and LGs was discussed with each expert. Depending on the region or country considered, the evolution of MTs is not necessarily towards intensification, in the conventional sense of the term. Some experts foresee the emergence of sylvo-pastoral MTs with a multi-functional objective with or without an agricultural component.

These MTs could be very well adapted to some specific context (e.g., mountainous areas, arid and semi-arid areas) and allow a better quality diet for animals, based on grass, residues and cereals, with potential beneficial effects on production. These systems often imply high mobility.

For example, in the Sahel region, agro-sylvo-pastoralist MTs could become predominant, with a small portion of the herd being productive. The animal diet would be based on forage and crop residues (e.g., rice straw) with a portion being bought externally. In addition to an increase in milk productivity, the production of veal would be an extra income generation for farmers, as veal is sold for draught power mainly. These systems are nowadays very few in the Sahel region but could increase in the coming years.

Experts also foresaw more intensified MTs in the future such as pastoral MTs with food of industrial origin with a production objective, mainly for fattening purposes, and feedlots MTs with a production objective. With a potential increase in production, these systems could also come with drawbacks such as: overweight animals leading to fertility issues, health and well-being issues for animals, etc. In Vietnam, feedlot systems are developing. In Egypt, feedlots are also emerging, mainly in urban areas, with small herds fed mainly on concentrated feed and little green forages. Feedlots with large herds (thousands of heads) also exist in arid and rural areas of the country, based on irrigation.

LGs that experts foresee gaining importance in the future are LG1, linked to an intensification of production and increase in the number of animals belonging to grass-based MTs without mobility, and LG3, with an increase in animals moving from one MT to another, especially for diseased, unproductive, underweight or end-of-career females.

In conclusion, both MTs and LGs typologies were validated by experts and no other MT or LG needed to be added to the ones already present. It is certain that only a few experts, whose expertise concerned a few regions/countries of the world, were interviewed. Therefore the global diversity of ruminant systems was not fully investigated and one can only think that some specific MTs or LGs could be missing in the typologies. This series of consultations also showed that some MTs and LGs are little or not present. For example, it seems that sylvo-pastoral MTs with or without an agricultural component and with a production objective are not present as these systems are often associated with a multi-functional objective. All experts also reported that LGs with females

passing by a fattening MT before returning to their MT of origin are not present (LG2, LG4, LG6). It seems true that these LGs are quite rare and only exist in specific contexts (e.g., New Zealand).

ANNEXE 2: SOME DATA FOR THE MODEL

Table 21: Various rates and data for dairy and meat cattle (Foray and Gac, 2018)

	Dairy	Meat
Birth rate	0.9	/
Calves mortality rate before weaning	4-8%	6-9%
Culling rate	0.15-0.45	0.15-0.4
Renewal rate	0.15-0.45	0.15-0.4
Age at weaning	6 months	8 months

Table 22: Parameters for cattle in mixed systems in sub-saharan Africa in various agro-ecological zones (Otte and Chilonda, 2002)

	Semi-arid areas	Humid and subhumid areas	Highlands
Calf mortality rate (%)	20.70	21.70	20.80
Calving rate (%)	58.20	59.10	44.10
Offtake rate (%)	10.20	8.00	9.90
Weight of mature cow (kg)	239.0	230.0	200.0

Tableau 23: Parameters for sheep in pastoral systems in sub-saharan Africa in arid and semi-arid areas (Otte and Chilonda, 2002)

	Arid and semi-arid areas
Lamb mortality risk (%)	29.20
Lambing rate (%)	96.70
Offtake rate (%)	21.60
Weight of mature ewes (kg)	34.10

Table 24: Parameters for sheep in mixed systems in sub-saharan Africa in various agro-ecological zones (Otte and Chilonda, 2002)

	Semi-arid areas	Humid and subhumid areas	Highlands
Lamb mortality risk (%)	26.60	25.10	23.30
Lambing rate (%)	119.10	115.10	108.20
Offtake rate (%)	15.60	23.10	25.10
Weight of mature ewes (kg)	32.10	25.20	34.10

Table 25: Parameters for goats in pastoral systems in sub-saharan Africa in arid and semi-arid areas (Otte and Chilonda, 2002)

	Arid and semi-arid areas
Kid mortality risk (%)	30.80
Kidding rate (%)	108.20
Offtake rate (%)	23.20
Weight of mature does (kg)	27.30

Table 26: Parameters for goats in mixed systems in sub-saharan Africa in various agro-ecological zones (Otte and Chilonda, 2002)

	Semi-arid areas	Humid and subhumid areas	Highlands
Kid mortality risk (%)	28.30	28.30	19.30
Kidding rate (%)	126.20	127.60	120.10
Offtake rate (%)	16.70	23.30	/
Weight of mature does (kg)	29.70	25.30	31.80

Table 27: Parameters for non-traditional cattle systems in sub-saharan Africa (Otte and Chilonda, 2002)

	Beef ranching system	Small-scale dairy system	Large-scale dairy systems
Calf mortality risk (%)	10.10	14.10	7.10
Calving rate (%)	76.40	71.90	87.20
Female replacement mortality risk (%)	7.80	9.10	1.00
Weight of mature cow (kg)	450	320	414

Table 28: Production parameters for various cattle breeds (Foray and Gac, 2018)

	Average daily milk production (L/day)	Adult live weight (kg)	Carcass yield (kg/kg of live weight)	Age at first calving (months)
Charolais	6.90	700	0.53	35
Limousin	5.90	632	0.55	35
Salers	8.30	613	0.51	35
Holstein	26.30	645	0.47	30
Montbeliard	21.30	635	0.50	33
Normande	19.30	690	0.50	33

Table 29: Milk yield for various dairy cattle breed depending on the feeding strategy (Baumont et al., 2014)

Breed	Holstein		Normande	
	Low*	High**	Low*	High**
Milk yield (44 weeks - kg)	6022	8515	4798	6332

*Low feeding strategy: grass silage and haylage in the indoor diet, a lower stocking rate, and supplementation with grass silage during the grazing season.

**High feeding strategy: maize silage, grass silage, dehydrated alfalfa and concentrates in the diet (indoor), higher stocking rate, and supplementation during the grazing season.

Table 30: References for useful data for the conceptual model

Digestibility	Feedipedia – digestibility values presented in IPCC (2006) tables 10.2, 10 A.1, 10 A.2 GLEAM (FAO, 2017)
Herd management parameters	GLEAM (FAO, 2017)
Production parameters	GLEAM (FAO, 2017)
Pasture management	Chang et al., 2013

parameters	
------------	--

ANNEXE 3: WORK PLAN AND ACTIVITY REPORTS OF THE GRADUATE FELLOWSHIP AT ILRI

Work plan - Foresight study on dairy farming

Location	Kenya, Senegal
Duration	12 February 2022 – 31 May 2022 in Nairobi, Kenya
Partners/contacts	Africa-milk project (study's framework) Project coordinator : Eric Vall (eric.vall@cirad.fr) ILRI (hosting organization) Supervising team: Isabelle Baltenweck ; Dolapo Enahoro
Budget	~2500€

I. Introduction

This research project is based on previous work from Lucie Perin's PhD. During this work, a conceptual framework for describing and classifying cattle farming systems around the world has been built, based on three concepts: management type, animal profile and lineage group. Alongside, a management type typology has been also built, on which the foresight study will be

based. A management type is a combination of criteria to describe how cattle are bred throughout their life. One management type can be valid for a certain stage of life of an animal or change during its life. The typology identifies sixteen management types based on specific criteria: farming outcome (milk/meat), farming objective (production/multi-functional), feed diet, herd management and mobility, pasture and manure management, crops and other agricultural component integration.

This foresight study is based on the management type typology, which will be adapted to dairy farming in the Kenyan and Senegalese contexts.

II. Objectives and goals

The foresight study will aim at highlighting several consequences of a future change or development of dairy cattle farming and defining several plausible trajectories as well as the resilience of these systems in the context of major sustainability issues. This work will be part of an ongoing project: the Africa-Milk project, coordinated by the Selmet Unit (CIRAD, INRAE/Institut Agro). The Africa-Milk project supports co-design and implementation of technical, organizational and institutional innovations to increase and secure local milk sourcing, considering the potential of ecological intensification of milk production and the development of inclusive milk-sheds in four countries: Senegal, Madagascar, Burkina Faso and Kenya.

This research work has several objectives, in particular (i) to assess the resilience of dairy farms to future transformations (demographic, climate change, growing insecurity), (ii) to identify the constraints and opportunities to these transformations, (iii) to use anticipation as a transformation process of the present that could guide future actions and behaviours.

III. Draft planned activities

Planned activities	Timetable
Product 1: Foresight evaluation of dairy farming in Kenya	Jan.- March 2022
Activity 1.1: Organize interviews with experts outside from DIPs	Jan.-Feb. 2022
Activity 1.2: Organize online workshops with experts from 3 DIPs	Feb.-March 2022
Activity 1.3: Interviews of farmers during field visits during Africa-milk project	March 2022

visits	
Product 2: Foresight evaluation of dairy farming in Senegal	April-May 2022
Activity 2.1: Organize a workshop with experts from Dagana DIP + experts from outside the DIP (?)	April-May 2022
Activity 2.2: Interviews of farmers during field visit	April 2022
Product 3: Comparison of plausible futures in Senegal and Kenya and their respective regions	May-June 2022
Activity 3.1: Gather information, during workshops and interviews, on Kenya's representativeness in east Africa and Senegal's representativeness in the Sahel region	May 2022
Activity 3.2 : Comparison of results from products 1 and 2 and comparison of plausible futures in east Africa and the Sahel if relevant	May-June 2022

Activity 1.1:

- Experts from **DIPs** grouped for **online workshops** (approximately 3 hours – with a short preliminary questionnaire to prepare the workshop);
- **4-6 experts per workshop** (one importance point is to have a balance between DIPs in Kenya but also with Senegal to have a fair comparison);

Activity 1.2:

- Experts from **outside DIPs** for **online interviews or a workshop** (approximately 3 hours – with a short preliminary questionnaire to prepare the workshop);
- University professors and/or researchers – **3 experts?**

Activity 1.3:

- Accompany Africa-milk project **field visits (2/3 days on each study site?)**;
- Interviews with **farmers/managers** of study sites (paper questionnaire with oral interviews – 1 hour approximatively);
- Mukurweini Wakulima Dairy Ltd, Happy Cow Ltd, New KCC Ltd (?)

Activity 2.1:

- Experts from **Dagana DIP** grouped for an **online or in person workshop** (approximately 3 hours – with a short preliminary questionnaire to prepare the workshop);
- **4-6 experts per workshop** (could be a higher number as only one DIP is involved in Senegal while 3 are involved in Kenya ;

Activity 2.2:

- Accompany Africa-milk project **field visits (2/3 days on each study site?)**;
- Interviews with **farmers** of study sites (paper questionnaire with oral interviews – 1 hour approximatively);
- La Laiterie du Berger, Dagana.

IV. Implementation & method

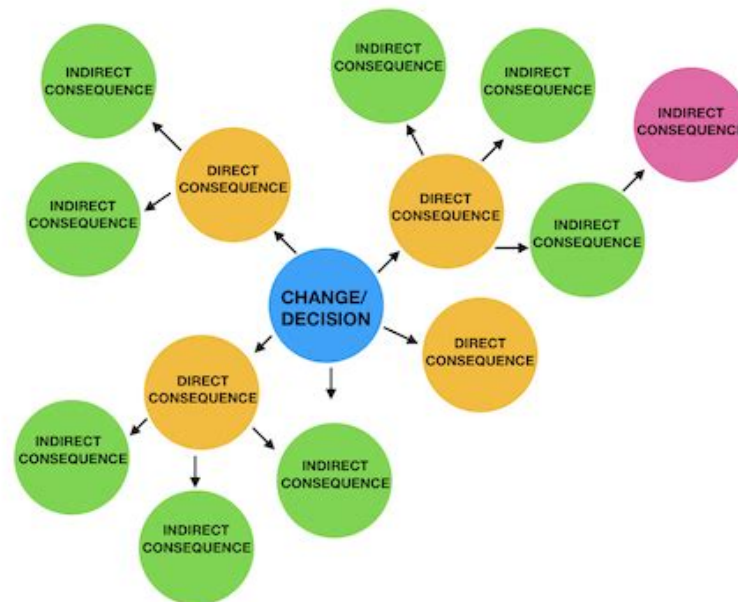
Workshops will be conducted with the **futures wheel** method – a method to graphically visualize direct and indirect future consequences of a change or development. This method allows to think and question the future in an organized way during brainstorming sessions.

The futures wheel (see Figure below) is a foresight method that provides a model of the future based on the consequences of an event or trend for obtaining a deeper understanding of the change being analyzed, so that the generated future model may be as accurate as possible³.

Figure: Template to build a futures wheel⁴

3 <https://online.visual-paradigm.com/knowledge/decision-analysis/what-is-futures-wheel/>

4 <https://study.com/academy/lesson/decision-making-wheels-definition-use-in-managerial-decision-making.html>



The objective of the futures wheel method is to find plausible futures for dairy farming thanks to the gathering of diverse local experts, proposing and discussing consequences of a change.

At the centre of the wheel is written a change, which is a situation that does not currently exist or is marginal. This change will be defined by the emergence, in majority, of one specific dairy system (i.e., > 80% of all systems). For example, more than 80% of all dairy systems of the country are industrial systems. This trend will be decided prior to the workshop/interview thanks to a small questionnaire.

Starting from that trend, direct environmental consequences (especially linked to climate change) and socio-economic consequences (especially linked to demography and insecurity) will be proposed and discussed among experts, over a defined timeline (between 10 and 50 years - tbd). These three fields of discussion (climate change, demography and insecurity) were chosen as they are major fields of current and future challenges in Kenya and Senegal. Then, indirect consequences will be discussed as shown on the figure above.

Draft plan of the course of a workshop (use Klaxoon online?):

1. Prior to the workshop, an information note will be sent to all participants including: a brief summary of the study and its goals, an explanation of the futures wheel method, some questions concerning cattle dairy farming in the country to decide on the trend (potential future trends for cattle dairy farming);
2. Write trend/issue in the middle;

3. Next, the leader of the brainstorming session draws an oval around the item and asks the group to say what necessarily goes with this item. As impacts or consequences are offered by the group, the leader draws short wheel-like spokes out from the central oval and writes these impacts at the end of each spoke;
4. Next, the leader asks the group to forget about the original item in the middle of the Futures Wheel and to give the most likely impacts for each of the primary impacts of the first ring of primary consequences;
5. At first, this process goes quickly, with participants listing second, third, and fourth order consequences with little or no evaluation. After the group evaluates and edits the wheel to be more "realistic." This step is similar to the clarification part in other brainstorming processes.

Interviews will also be conducted during study sites visits. These interviews will focus on the present and the future of dairy cattle farming, taking into account major changes such as climate change, population increase, instability. Questions will for example focus on: observed changes in the past (climatic, demand for dairy products, production, management, livelihood, etc), expected changes in the future (open questions and multi-answers questions), etc. Information will also be gathered on the cattle dairy farming systems and transformation/management process of milk during field visits.

After gathering information during workshops and interviews, a summary of findings and first results will be written and shares with experts that participated for a follow-up review.

Activity report N°1 – February 2022

Activities carried out:

- Online meeting with Africa-milk Kenya coordinators on 2nd February to review work plan and initiate activities;
- Reading of various literature on dairy farming systems in Kenya;
- Exchange with Robin Bourgeois (CIRAD researcher – foresight expert) on the methodology for this study;
- Preparing the preliminary questionnaire for experts;
- Presentation of research project to ILRI experts (17th February) – introducing my fellowship's work – contact with ILRI Dakar to exchange on work plan and contacts in Senegal;

- Workshop at University of Nairobi (UoN) – 24 & 25 February – meeting with various UoN professors and researchers.

Planned activities :

- Contact various experts in Kenya (list is established) and start interviews (still waiting for ethics application approval at ILRI);
- Online meeting with Africa-milk researchers in Senegal (potentially mid-March);
- Tour of Dairy Innovation Platforms (DIPs) in Kenya – 20 to 27 March. Fieldwork risk assessment form completed and approved by security officer at ILRI (waiting for DDG to approve).

Kenya :

Timeline	Activities
28 Feb. - 04 March	Contact experts from the list (phone & email) Contact ILRI experts – Karen Marshall, Todd Crane, Julie Ojango ?
28 Feb. - 19 March	Plan and carry on interviews with experts
20 – 27 March	Field trip – meeting with farmers (to be seen how the field trip is organized)
28 March – 13 April	Workshop with DIP's members (met during field trip)
13 April - May	Compile results

Sénégal :

Timeline	Activities
28 Feb. – 31 March	Contact DIP + Africa-milk colleagues to find contacts See with ILRI Dakar (Derek, Prosper) and exchange contacts
1 – 30 April	Plan and carry on interviews with experts
?	Field trip (?)
May	Workshop with PIL
May	Compile results

Activity report N°2 – March 2022

Activities carried out:

- Reading of various literature on dairy farming systems in Senegal;
- ILRI ethics approval obtained;
- Meeting with africa-milk Senegal (16 th March):

- x Agree to concentrate on the north of Senegal (as the DIP is situated in Richard Toll and it is a very dynamic region for dairy farming);
- x Creation of an excel table with contacts of experts;
- x Agree for a visit to Senegal (end April/beg May) – would be welcomed by africa-milk coordinators and DIP manager;
- Field trip from 20 th to 25 th March in Kenya with africa-milk coordinators:
 - x Bomet, Kericho, Nyandarua and Nyeri counties;
 - x Visit of farms, demo plots, dairy cooperatives and DIP meetings. 12 farmers interviewed.
- Initiation of experts interviews (Kenya): 8 already done (10 planned);
- Compiling first results obtained;
- Definition of research questions (with inputs from Dolapo Enahoro & Guillaume Duteurtre):
 - Q1: In what major ways are dairy systems evolving/transforming in the study countries ?
 - Q2: What (social, economic, environmental) factors do key actors perceive to be driving the identified dairy system changes in (selected areas of?) Kenya and Senegal?
 - Q3: What are the potential consequences of the identified changes in the dairy farming systems in Kenya and Senegal?
 - Q4: How do these changes enable or limit dairy systems from being resilient in the face of current and emerging challenges (climate change, increase in population, insecurity)?

Planned activities :

- April: finishing interviews and data collection in Kenya, starting to compile and analyse results;
- From mid-April: start online interviews with Senegal experts;
- End of April/Beg. May: plan trip to Senegal (potentially one week).

Activity report N°3 – April 2022

Activities carried out:

- End of interviews and data collection in Kenya : 28 persons interviewed in total + follow-up with experts in Kenya on some questions;
- Start compiling results and analyze them, beginning to write final report;

- Beginning of online interviews with Senegal experts
 - contact through ILRI (Derek Chan), CIRAD (Serena Ferrari), Laiterie du Berger (Arona Diaw);
 - 3 already done.

Planned activities :

- 3 to 14 May: fieldtrip to Senegal
 - 4-11 May : fieldtrip in north of Senegal (Saint-Louis, Dagana, Richard Toll) with a team of 4 persons (ILRI, Wageningen University)
 - 12-14 May: Dakar, meeting with Laiterie du Berger direction and ILRI researchers
 - Visit farms and farmers, Laiterie du Berger, milk collect routes, various partners of Africa-milk project and Laiterie du Berger.
- May: finish interviews with Senegal experts and compile results;
- End May: prepare end of fellowship report (31 May).

Activity report N°4 – May 2022

Activities carried out:

- Field-trip to Senegal – in coordination with researchers from ILRI and ISRA:
 - from 3rd to 14th May: Dakar, Richard Toll/Niassanté, Saint-Louis, Dahra/Linguère/Tiel;
 - meeting with farmers/herders (pastoralists, agro-pastoralists, one intensive farm) in all locations;
 - meeting with researchers from CIRAD in Richard Toll and director/collect coordinator of Laiterie du Berger;
 - visit milk collection points, dairies and transformation units, milk selling points, livestock markets.
- End of interviews for Senegal : 25 persons interviewed in total (including 14 farmers on the field) + follow-up with experts in Senegal on some questions;
- Preparation of a report and compilation/analysis of results;
- Exit presentation at PIL meeting (ILRI) : Thursday 26th May.
- End of fellowship: Tuesday 31th May.

Planned activities :

- In June: preparation of an article (to be published)



Fieldwork guide

PhD Lucie Perin

Foresight study on dairy farming systems in Kenya and Senegal



I- Background

This foresight study is part of Lucie Perin's ongoing PhD, and is based on previous work carried out during her PhD. During this work, a conceptual framework for describing and classifying cattle farming systems around the world has been built, based on three concepts: management types, animal profiles and lineage groups. Alongside, a management type typology has been also built, on which the foresight study will be based. A management type is a combination of criteria to describe how cattle are bred throughout their life. The typology identifies sixteen management types based on specific criteria: farming outcome (milk/meat), farming objective (production/multi-functional), feed diet, herd management and mobility, pasture and manure

management, crops and other agricultural component integration.

Based on this work, which describe current's cattle systems, questions have been raised about potential perspectives and plausible futures for cattle farming. To carry on a study that could answer these questions, the focus is made on the African continent and dairy cattle farming. This choice was made regarding current and future challenges of dairy cattle farming in Africa, especially in terms of climate change, growing population and consumption, as well as insecurity in some regions.

To focus on dairy farming in Africa, this study will be linked to an ongoing project: the Africa-Milk project⁵. The Africa-Milk project supports co-design and implementation of technical, organizational and institutional innovations to increase and secure local milk sourcing, considering the potential of ecological intensification of milk production and the development of inclusive milksheds in four countries: Senegal, Madagascar, Burkina Faso and Kenya. The overall consortium includes African research organizations (ISRA, INERA, UoN, FIFAMANOR), WUR and CIRAD in Europe, all with strong experience on African milk production and sustainable development.

Two countries, out of the four countries involved in Africa-milk, have been selected for this study: Kenya and Senegal. These two countries have been selected as they possess diverse and contrasting agro-climatic and production contexts, and are also representative of their respective region.

Objectives

This research work has several objectives, in particular (i) to assess the resilience of dairy farms to future transformations (demographic, climate change, growing insecurity), (ii) to identify the constraints and opportunities to these transformations, (iii) to use anticipation as a transformation process of the present that could guide future actions and behaviors. Based on a cattle systems typology, previously designed during Lucie's PhD, the foresight study will aim at defining several plausible trajectories for dairy farming systems as well as the resilience of these systems in the context of major sustainability issues.

II – Methods

Design and methods

This work is based on interviews/workshops with various local experts sharing their knowledge and discussing about the future of dairy farming in their respective country. These experts represent various actors of the sector. Workshops are conducted using a foresight method called the futures wheel method⁶, where various impacts of changes in dairy cattle systems will be identified by

⁵<https://www.africa-milk.org/>

⁶<https://jeasprc.org/wp-content/uploads/2020/08/06-Futures-Wheel.pdf>

experts and discussed, to analyze societal, economic and environmental transformations caused by changes in trajectory.

Protocol

This work is based on individual interviews, which will be conducted online or in person, as well as workshops, with various local experts on dairy production systems in Kenya and in Senegal (see summary of protocol below).

During in person interviews (approximately 20 min), which will be conducted mainly with farmers during field trips, several questions will be asked thanks to a paper questionnaire. This concerns:

- General information on the participant;
- Information about their farms (e.g. farming objectives, number of cows, breeds, etc);
- Information about their production systems in their country;
- Future of dairy farming (according to them, what could be the dominant dairy production system by 2030? and what would be the consequences of that change?).

Finally the last tool will be used during online and in-person interviews (approximately 1h) is the futures wheel. The futures wheel is a foresight method, where participants share their knowledge and discuss about the consequences of a change that might happen in the future. Various impacts of change in dairy production systems will be identified by experts and discussed, to analyze societal, economic and environmental transformations caused by changes in trajectory. Online interviews will be conducted through klaxoon, an online board app designed to conduct interactive discussion, while in-person workshops will be conducted thanks to a paper board, paper cards representing the various dairy systems and participatory discussions.

For in-person interviews on the field:

- members of DIPs : farmers, dairy cooperatives managers, etc
- diversity in age, gender, marital status, herd size, farming system...

With that criteria, we want to see how gender and socioeconomic considerations influence the evolution of dairy farming.

For online interviews :

- experts on dairy farming in Kenya: professors, researchers, government, NGOs, associations, industry, dairy chain actors, milk processors, consultants, etc. These experts are determined thanks to Africa-milk colleagues and coordinators (John Mburu and Asaah Ndambi for Kenya).

Output

The expected output is a visual and graphical map (futures wheel) mapping the potential trajectories of dairy farming in Kenya along with the consequences of these changes.

The futures wheel will be aggregation of all experts answers and ideas.

Guide for online discussion/interview

Every participants will have to sign the consent form before answering the initial questionnaire (google form).

The online discussion will be held thanks to the klaxoon app, an interactive tool to conduct workshops.

Introduction sentence: *After identifying potential future dairy systems in Kenya, I would like you to think what the future of dairy farming would look like (in ten years)? What would be the consequences (direct, indirect) of that change? What might happen next? Think about many effects: socio-economic, everyday life, environment, policies, technology, jobs, production...*

Some tips: Try to think about positive, negative, and neutral effects. There is no judgment, we want to get as many ideas as possible, even if some are less plausible.

Ideas for socio-economic effects:

- milk production & consumption
- competition/conflict over croplands/protected areas/housing
- wellbeing and livelihoods (family, money, diet, education, transport, diversification)
- solidarity btw farmers (sense of community)
- ownership (animals, land)
- markets access
- herd (size, breed)
- possibility of intensification (feed, herd management, farming equipment)

Ideas for environmental effects:

- competition for resources
- use of water
- GHG emissions
- biodiversity
- use of croplands and grazing lands
- adaptation/resilience to climate change
- input levels

After all interviews have been done, a follow-up with all experts will be done by sending the complete futures wheel and asking for any comments or feedback they may have regarding other experts answers and ideas.

IV- Appendix

Study participation consent form

Study : Foresight study on dairy production systems in Kenya and Senegal

Investigator: Lucie Perin, graduate fellow (ILRI, Nairobi), PhD student (AgroParisTech, Paris)

You are being invited to participate in a foresight research study conducted by Lucie Perin, funded by CLAND⁷, carried out under the Africa-milk⁸ project and as part as Lucie Perin's graduate fellowship at ILRI⁹ Nairobi. The purpose of this research is to investigate consequences of a change in dairy production systems in your country and draw plausible futures with their impacts. Your participation in this study is entirely voluntary, you can withdraw at any time or refuse to answer any question without any consequences of any kind.

If you agree to the term and participate in the study, you will be asked to complete a short online or in-person questionnaire (approximately 15-20 min), and participate in an online individual interview (approximately 1 hr) or a participatory workshop (approximately 1.5-2-hrs), which will be audio-recorded. Any information that can be identified with you will remain confidential. You will not be identified individually in any information we get from this study or in any of the research reports/publications.

By agreeing to this consent form, you are indicating that (i) you have read and understood this consent form and agree to participate in this research study, (ii) your understand that your personal details will not be included in study outcomes, (iii) you agree that non-personal data, obtained during interviews/workshops, will be included in the study outcomes and in any reports/publications that might come out of this study.

Name:

Signature:.....

Date:.....

⁷<https://cland.lsce.ipsl.fr/>

⁸<https://www.africa-milk.org/>

⁹<https://www.ilri.org/>

Initial questionnaire - herders

Name

Age Gender F M

Marital status (children).....

To which systems do they belong to? OGL OGM SZGL SZGM ZGL
ZGM Small-scale Medium to large-scale

Number of cows..... Number of lactating cows.....

Breed.....

Milk production (L/cow/day).....

Use of milk (sale, self-consumption).....

Price of milk when sold (KES/L).....

Production objectives : income manure production draught power
 self-consumption other.....

Other agricultural activities (crops, other livestock.....)
.....
.....

What do you wish for you and your children in the future (ten years)?

E.g. : increasing herd, change of production systems, feed, livelihoods (wedding, children, housing, lands)

.....
.....
.....
.....

Questionnaire initial – éleveurs

Nom

Age Genre F M

Statut familial (enfants).....

A quel systèmes appartiennent-ils? Pasteur Agro-pasteur Intensif
Petite échelle Moyenne à grande échelle

Nombre d'animaux..... Nombre de vaches allaitantes.....

Race.....

Production lait (L/vache/jour).....

Utilisation du lait (vente, auto-consommation, ..).....

Prix lait (CFA/L).....

Objectifs de production argent production fumier force de traction
auto-consommation autre.....

Autre activités agricoles (cultures, autres animaux.....).....

.....

.....

.....

Que souhaitez-vous pour vous et vos enfants dans le futur (dix ans)?
Par exemple. : augmentation du troupeau, changement du système de production,
alimentation, vie personnelle et familiale (mariage, enfants, logement, terres)

.....

.....

.....

Questionnaire workshop - DIP members

Name.....
Job title.....
Organization/institution.....

Which DIP do you belong to? Nakuru Bomet Nyandarua Nyeri

Are dairy systems in Kenya representative of dairy systems in the neighbouring countries (Ethiopia, Tanzania, Uganda, Somalia)? YES NO

If YES, which of the neighbouring countries are similar to Kenya regarding dairy systems?

Ethiopia Tanzania Uganda Somalia

Could you specify area(s) in which these similarities apply?

Climatic conditions Socio-economic & livelihood conditions Demography
Political tension and insecurity Type of dairy systems Levels of milk production
Market access and organization National policies regarding dairy farming and milk supply chain development

Other.....

If NO, how the situation in Kenya differs from its neighbouring countries?.....

Questionnaire atelier– membres PIL

Nom.....

Travail.....

Organisation/institution.....

Les systèmes laitiers au Sénégal sont-ils représentatifs des systèmes dans les pays du Sahel ?
(Mauritanie, Mali, Niger, Burkina Faso)? OUI NON

Si OUI, lesquels de ces pays sont similaires au Sénégal?

Mauritanie Mali Niger Burkina Faso

Pouvez-vous préciser les domaines dans lesquels ces similarités s'appliquent?

Conditions climatiques	Conditions socio-économiques	
Démographie	Tension politique et insécurité	Type de système laitier
Niveaux de production	Accès aux marchés	Politiques nationales sur l'élevage
laitier et développement des chaînes d'approvisionnement en lait		
Autre.....		

Si NON, en quoi la situation au Sénégal diffère des autres pays du Sahel?.....

.....

System cards Kenya

OGL



Open-grazing

Solely livestock

	Small-scale (OGLs)	Medium to large-scale (OGLI)
Farming objective	Multi-objective	Multi-objective + production
Feed	Grass	Grass + external complements (cereals) if no/few grass
Herd size	< 5 cows	~ 5-10 cows
Breed	Zebu (pure- or crossbreed)	Zebu (pure- or crossbreed)
Market access	Poor	Poor
Land availability	High	High
Location	Pastoralist areas	North Rift, South Rift

OGM



Open-grazing

Mixed

On-farm produced feed

	Small-scale (OGMs)	Medium to large-scale (OGMI)
Farming objective	Multi-objective	Multi-objective + production
Feed	Grass + crop residues	Grass + crop residues + cereals (if needed)
Herd size	< 5 cows	~ 5-10 cows
Breed	Zebu (pure- or crossbreed)	Zebu (pure- or crossbreed)
Market access	Poor	Poor
Land availability	High	High
Location	Rift, Central Region, Western and Eastern Region	Rift Valley

SZGM



Semi-zero-grazing

Mixed

On-farm produced feed

Stall-fed at night & stall-milked

	Small-scale (SZGMs)	Medium to large-scale (SZGMI)
Farming objective	Multi-objective	Production
Feed	Grass + crop residues	Grass + residues + complements at night (cereals)
Herd size	~1-3 cows	~3-10 cows
Breed	Exotic - Friesian or Ayrshire crossbred	Exotic - Friesian or Ayrshire crossbred
Market access	Medium	Medium
Land availability	Medium	Medium
Location	Central Rift, Western Region, Eastern Region	Central Rift, South Rift

SZGL



Semi-zero-grazing

Solely livestock

Stall-fed at night & stall-milked

	Small-scale (SZGLs)	Medium to large-scale (SZGLI)
Farming objective		Production
Feed		Grass + external complements at night (cereals)
Herd size		~3-10 cows
Breed		Exotic - Friesian or Ayrshire crossbred
Market access		Medium
Land availability		Medium
Location		Central Rift

ZGM



Zero-grazing
 Mixed
 On-farm produced feed
 Always stall-fed & stall-milked

	Small-scale (ZGMs)	Medium to large-scale (ZGMI)
Farming objective	Production	Production
Feed	Cut- and carry fodder + concentrates	Cut- and carry fodder + concentrates
Herd size	~1-4 cows	>5 cows
Breed	Fressian or Ayshire crossbred or purebred	Fressian or Ayshire crossbred or purebred
Market access	High	High
Land availability	Scarce	Scarce
Location	Central Region, Central Rift	Central Region, Central Rift, South Rift

ZGL



Zero-grazing
 Solely livestock
 Always stall-fed & stall-milked

	Small-scale (ZGLs)	Medium to large-scale (ZGLI)
Farming objective	Production	Production
Feed	External cut- and carry fodder + concentrates	External cut- and carry fodder + concentrates
Herd size	~1-4 cows	>5 cows
Breed	Fressian or Ayshire crossbred or purebred	Fressian or Ayshire crossbred or purebred
Market access	High	High
Land availability	Scarce	Scarce
Location	(Peri)-urban	(Peri)-urban

System cards Senegal

Pastoral



Forte mobilité

Uniquement bétail

Extensif

	Pastoral
Objectif d'élevage	Multi-fonction (auto-consommation + production)
Alimentation	Herbe pâturée + résidus en saison sèche
Race	Locale - Zebu Gobra
% du cheptel national	32%
Accès aux marchés	Faible
Disponibilité en terre	Forte
Localisation	Régions du Ferlo + fleuve Sénégal

Agro-pastoral



Animaux mobile

Mixte bétail/agriculture

Extensif

	Agro-pastoral
Objectif d'élevage	Multi-fonction (fumier+ force de traction), production, auto-consommation
Alimentation	Herbe pâturée + résidus + compléments
Race	Croisées - Zebu Gobra, Djakoré, Ndama
% du cheptel national	67%
Accès aux marchés	Moyen
Disponibilité en terre	Moyenne
Localisation	

Intensif



Stabulation permanente

Éleveurs citadins, activité secondaire

Investissement financier important

	Agro-pastoral
Objectif d'élevage	Production
Alimentation	Herbe (fauchée) + résidus + compléments (fanes d'arachides, son de blé, tourteaux)
Race	Exotiques - Montbéliarde, Jersiaise, Holstein, Gir
% du cheptel national	1%
Accès aux marchés	Fort
Disponibilité en terre	Faible
Localisation	(Péri) Urbain - Zone des Niayes, Dakar, Thiès

BIBLIOGRAPHY OF THE ANNEXES

Baumont, R., Lewis, E., Delaby, L., Prache, S., and Horan, B, "Sustainable intensification of grass-based ruminant production", *Grassland Science in Europe* 19 (2014): 521-532.

Chang, J.F., Viovy, N., Vuichard, N., Ciais, P., Wang, T., Cozic, A., Lardy, R., Graux, A.I., Klumpp, K., Martin, R., and Soussana, J.F, "Incorporating grassland management in ORCHIDEE: model description and evaluation at 11 eddy-covariance sites in Europe", *Geoscientific Model Development* 6, no.6 (December 2013): 2165–2181, 10.5194/gmd-6-2165-2013.

FAO, *Global Livestock Environmental Assessment Model: Version 2.1 – Data reference year: 2010* (Rome: Food and Agriculture Organisation of the United Nations, 2017).

Foray, S., and Gac, A., *Elevage bovin et environnement: Les chiffres-clés* (Paris: Institut de l'Elevage, 2018).

IPCC, "Emissions from Livestock and Manure Management", in *IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use, 2006*, p10.1-10.87.

Otte, M.J., and Chilonda, P., "Production parameters of ruminants in non-traditional systems", in *Cattle and Small Ruminant Systems in sub-Saharan Africa—A Systematic Review*; (Rome, Food and Agriculture Organization of the United Nations: 2002).