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Chapitre I. INTRODUCTION GENERALE

I.1 Durabilité et élevage dans le monde

D'un développement durable popularisé au renouvellement des pratiques et des approches de recherche

En une quinzaine d'années, à la fin du XX^ème^ siècle, la problématique du développement durable (**DD**) s'est progressivement imposée sur l'agenda politique et économique mondial. Ce vocable est aujourd'hui largement repris par l'opinion publique et les milieux les plus divers s'emparent aujourd'hui de la question.

La notion de DD est née d'inquiétudes écologiques : si les progrès économiques et sociaux réalisés ce dernier siècle sont aujourd'hui incontestables, ils laissent à voir nombre de phénomènes de dégradation, de cercles vicieux, de crises et d'évolutions inquiétantes en matière d'environnement.

Il ne s'agit pas de « stopper la croissance » (Meadows, 1972) ou même de « faire de la décroissance » (Georgescu-Roegen, 1979) mais plutôt de mener l'activité humaine mondiale vers une direction commune, un *compromis entre croissance économique, respect de l'environnement et satisfaction sociale*. Il existerait donc, dans le développement, un état d'harmonie (utopique pour certains) entre les objectifs poursuivis par les multiples sociétés.

L'idée de DD est fondée sur les principes de l'écodéveloppement des années 70 avec moins d'engagement philosophique et politique (Godard et Hubert, 2002). Pour permettre de resituer le contexte dans lequel se positionne cette thèse, certaines des idées qui forment l'armature du DD sont ici rappelées :

- une remise en cause de l'approche protectionniste de la nature pour une approche intégrant l'activité humaine dans la gestion des écosystèmes,

- un positionnement des choix techniques au centre du débat supposant qu'ils constituent la variable clef de l'harmonisation et le lieu de l'articulation principale entre sociétés et nature. En terme d'appui au développement, il s'agirait donc de viser l'adaptation des techniques aux caractéristiques naturelles (i.e. biophysiques) et sociales des différentes régions du monde au lieu de vouloir absolument adapter les milieux et les populations aux techniques inventées par et pour l'Occident développé.

- une volonté de concevoir des enchaînements productifs du type « rien ne se perd tout se transforme » qui permettent de boucler les cycles de matière en faisant des déchets une ressource.

Selon Godard et Hubert (2002) au regard des questions soulevées par le DD, il n'est pas possible de postuler la simple neutralité des activités de recherche et réciproquement la recherche ne peut rester insensible à ces changements idéologiques majeurs. Trois niveaux de réponse de la recherche, de la plus superficielle à la plus profonde, sont envisagés par les auteurs :

- le renouvellement des problèmes, sources de nouvelles questions de recherche inédites ou de modification de l'ordre de priorité des agendas de recherche, à propos d'objets de recherche inchangés.

- le DD comme nouvel objet de recherche devant déboucher sur une nouvelle spécialité scientifique donnant une place centrale au défi de l'intégration, c'est-à-dire la production de connaissances sur des phénomènes intégrés et non plus sur des phénomènes isolés de façon analytique.

- le renouvellement des façons de faire de la recherche, où démarches et pratiques seraient touchées, s'intéressant à l'émergence de problèmes transversaux favorables à des dispositifs de recherche finalisée et transdisciplinaire.

Cette thèse s'intéresse à la durabilité des pratiques d'élevages. Elle se situe entre le deuxième et le troisième niveau de réponse de par son fort degré intégratif (représentation du fonctionnement de l'entièreté de l'agro-écosystème « ferme d'élevage » homme inclus) et l'enrichissement des approches classiques de modélisation dans le domaine de l'agro-zootechnie (co-construction du modèle de simulation avec des éleveurs).

Des productions animales fortement questionnées en matière d'environnement

L'élevage est une activité majeure de l'économie agricole mondiale, il représente un moyen de subsistance essentiel pour bon nombre de populations défavorisées et il a une place déterminante dans l'alimentation et la santé humaine. En effet l'élevage contribue pour 40% au produit intérieur brut mondial issu de l'agriculture, d'autant plus que la part de ce secteur est grandissante. L'élevage est la source de revenu et d'emplois majeure de 36% des pays les plus défavorisés, c'est-à-dire près de 1 milliard d'humains. Le bétail est aussi, dans certains contextes, un signe extérieur de richesse et un moyen de capitalisation. De plus les produits alimentaires d'origine animale représentent 17% de l'énergie et 33% des protéines présentes dans l'alimentation humaine mondiale. Enfin l'élevage contribue à la sécurité alimentaire mondiale ; en effet les céréales actuellement utilisées pour l'alimentation animale pourraient être rapidement réaffectées pour l'alimentation humaine en cas de crise grave.

L'élevage est par ailleurs responsable, de façon directe ou indirecte, de nombreux phénomènes de dégradation et d'inquiétudes en matière d'environnement dans le monde ; ces mêmes inquiétudes qui ont donné tant d'importance à la problématique du DD ces dernières décennies. Le récent rapport de la FAO (Steinfeld *et al.*, 2006) liste tout un ensemble de points critiques tels que l'émission de gaz à effet de serre, la perte de biodiversité et la pollution des eaux de surface liés à l'élevage.

Selon ces auteurs, 18% de l'effet global de réchauffement de la planète seraient dû à l'élevage. Ce chiffre comprend les émissions issues des fermentations dans le rumen des animaux et celles de leurs effluents, de la conversion des forêts en terres agricoles (pâturages et cultures), de la consommation d'énergies fossiles pour les cultures destinées à l'alimentation du bétail, au transport des aliments du bétail et des produits animaux jusqu'aux régions de consommation, enfin à l'utilisation d'engrais minéraux.

L'élevage représente la plus importante activité humaine en terme d'utilisation des terres, elle occupe 70% des terres agricoles et 30% des terres émergées (banquise exclue). Plus précisément 26% des terres émergées sont destinées au pâturage et 33% des terres arables sont cultivées pour produire de l'aliment pour bétail. L'expansion de ces terres d'élevage est rapide et elle est responsable de la disparition de nombreux écosystèmes. Les fronts pionniers amazoniens constituent l'exemple le plus marquant de par la valeur et la vulnérabilité des écosystèmes atteints.

Certes l'élevage extensif, peu productif, occupe beaucoup d'espace, mais à l'opposé on trouve des systèmes d'élevage industrialisés et à haute densité. Le pendant d'une telle concentration est la séparation de l'élevage des terres cultivées et donc l'interruption du cycle des éléments nutritifs (N, P, K) qui conduit à un appauvrissement des régions de culture et un enrichissement des régions d'élevage. Il peut en découler une pollution des eaux de surface suite à une gestion inadaptée des effluents d'élevage. De plus, les effluents d'élevage émettent de l'ammoniac qui peut conduire à une acidification des pluies en zone d'élevage à très forte densité. L'élevage représenterait 68% de l'ammoniac total émis à l'échelle de la planète (i.e. 30 millions de tonnes).

Parmi les recommandations proposées par la FAO pour réduire l'impact de l'élevage sur l'environnement de notre planète se trouve en premier lieu l'amélioration de l'efficacité des systèmes de production. En explicitant de façon détaillée le fonctionnement de l'exploitation cette voie d'amélioration est largement explorée dans cette thèse.

I.2 Durabilité de la filière bovine laitière à La Réunion

Cette thèse a été réalisée à l'île de La Réunion (Fig. 1) en relation forte avec la question de la durabilité des EBL. Cette section montre en quoi l'enjeu du DD est particulièrement présent dans notre contexte d'étude.

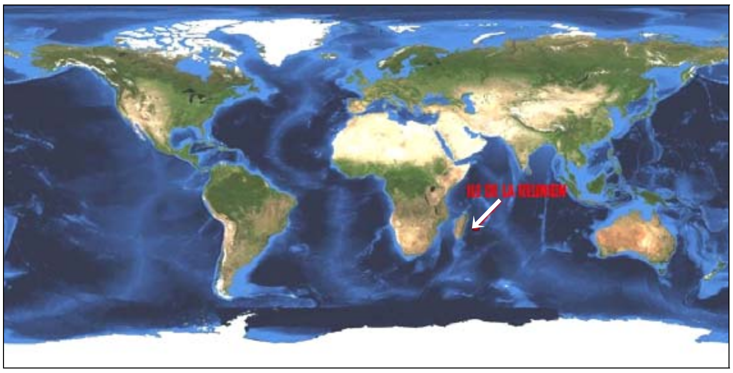

Figure 1. *Localisation de l'île de La Réunion*

Enjeux socio-économiques et croissance de la filière laitière

A La Réunion, l'importance économique et alimentaire (protéines animales produites sur l'île disponibles sous la forme de produits frais) de la filière bovine laitière ne constitue pas le seul enjeu de son développement. Les élevages bovins laitiers (EBL) sont essentiellement situés dans les Hauts de l'île (à une altitude supérieure à 500 m, Fig. 2) et leur implantation participe au rééquilibrage du peuplement, largement concentré dans les villes côtières (les Bas). Toujours sur le plan social, cet élevage contribue au maintien d'une population rurale active dans un contexte où le taux de chômage est élevé (> 30%).

La filière laitière à La Réunion a un peu plus de 40 ans. Depuis ses débuts la production laitière est en constante augmentation. Elle est passée de 7 millions de litres en 1992 à 24 millions en 2005. Cette progression a été permise tant par l'augmentation du cheptel (qui est passé de 2700 vaches laitières en 1998 à 5000 en 2005) que par l'amélioration de la productivité individuelle (production moyenne de lait par vache présente et par an de 4 900 kg en 1996 contre 6 100 kg en 2005).

Malgré cette production croissante, la production reste bien en dessous des besoins de la population de l'île (plus de 750 000 habitants). Ainsi, en 2000, la production locale ne couvrait que 30% du marché. Du fait d'une démographie en constante augmentation et de l'évolution des habitudes alimentaires, le marché du lait à La Réunion offre des perspectives de croissance intéressantes. La filière met en perspective la possibilité d'atteindre les 40 millions de litres en 2015.

Des contraintes pédo-climatiques et foncières prononcées

L'EBL à La Réunion est particulièrement contraint d'un point de vue climatique et foncier.

L'île présente des situations climatiques particulièrement contrastées, liées à l'altitude et à l'exposition aux alizés (Fig. 3 et 4). Certaines zones d'élevage sont soumises à des sécheresses périodiques (pluviométrie annuelle < 1m/an) d'autres sont hyper-humides (pluviométrie annuelle > 3 m/an). La diversité des zones agro-écologiques où les EBL sont rencontrés est illustrée en Annexe K par une série de photographies.

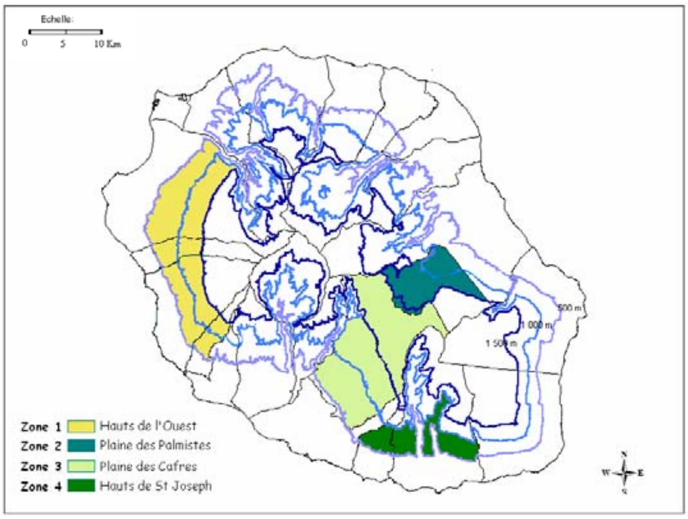

Figure 2. *Localisation des quatre zones d'élevage bovin laitier de La Réunion*

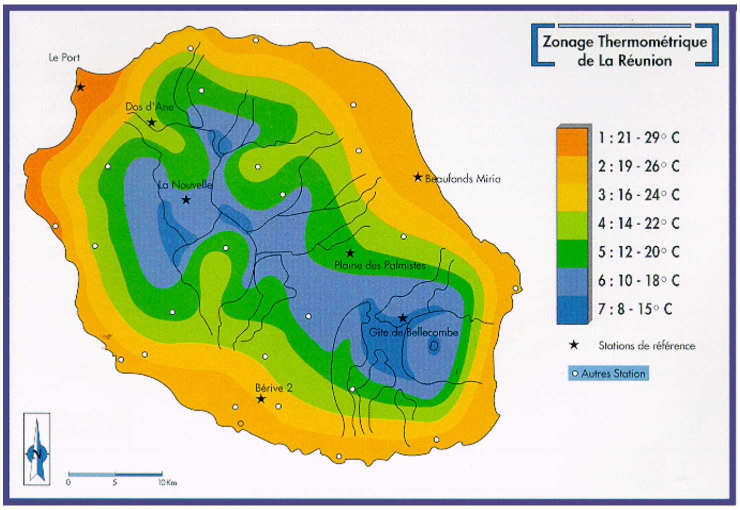

Figure 3. *Zonage thermométrique de La Réunion*

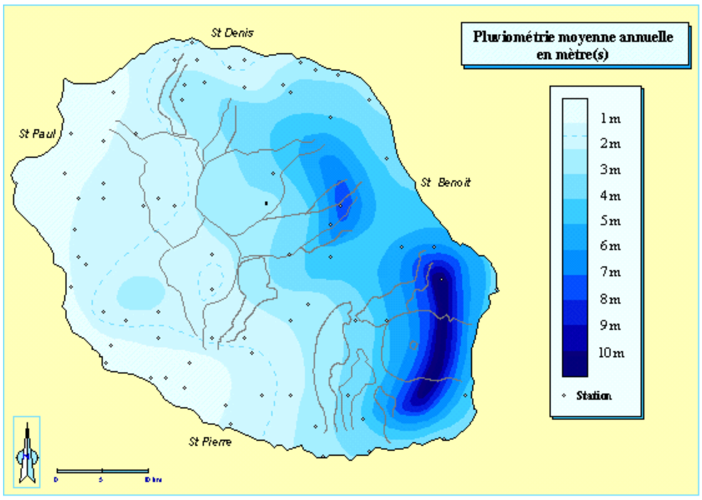

Figure 4. *Zonage pluviométrique de La Réunion*

Le relief prononcé et la pression foncière importante liée au dynamisme des autres secteurs agricoles et de l'urbanisme (densité démographique globale dépassant les 300 habitants/km^2) limitent les surfaces disponibles pour la culture de fourrages. Par conséquent les chargements animaux sont souvent élevés et les degrés d'autonomie fourragère limités au regard de l'objectif de production laitière. A l'image de ce qui s'est opéré dans diverses zones d'élevage en pays industrialisés (e.g. le grand Ouest Européen), ce déficit est partiellement comblé par l'utilisation d'importantes quantités d'engrais minéraux et d'aliments concentrés ; on atteint dans certains cas 65% de matière sèche apportée par les aliments concentrés dans la ration alimentaire des VL. Les possibilités d'augmentation des surfaces fourragères étant limitées, la croissance de la production passe nécessairement par une intensification du facteur terre, s'accompagnant de risques d'excès d'éléments nutritifs tels que l'azote (N) dans les sols. Viennent s'ajouter la mise en application de la réglementation européenne en matière d'épandage (La Réunion étant un département français) et la mise en place du Parc National des Hauts incluant bon nombre des EBL dans sa zone périphérique. Les indicateurs les plus fréquemment utilisés, notamment dans la définition des normes environnementales, sont relatifs à l'élément N ; cette thèse se centrera donc sur la gestion de l'N.

Des réponses techniques

Les préoccupations à caractère environnemental concernant la gestion de l'N sont maintenant partagées par la filière. Cette dernière mène une réflexion sur les alternatives organisationnelles et techniques susceptibles d'améliorer les performances techniques et le respect de l'environnement des EBL. Trois études sont en cours :

La 1ère porte sur un projet d'échange entre les surfaces cannières des Bas de l'île (59% des terres agricoles de l'île), en forte demande d'engrais, et les EBL des Hauts de l'île, en forte demande de substituts fourragers tels que la paille de canne à sucre.

La 2ième porte sur la production individuelle de compost chez les éleveurs. Ceci avec le double objectif de faciliter la fertilisation organique des prairies d'une part, et d'autre part, de mettre en place une filière d'engrais organique dont le principal débouché serait la vente auprès de maraîchers et de particuliers. Le compostage individuel en élevage laitier suppose un meilleur approvisionnement en ressource carbonée telles que la paille de canne à sucre.

La 3ème porte sur la mise en place de références techniques pour la prise en compte des apports d'engrais de ferme (compost inclus) dans le raisonnement de la fertilisation des surfaces fourragères.

Les grands enjeux mondiaux du DD de l'élevage en voie d'industrialisation et de concentration en périphérie urbaine se retrouvent donc à La Réunion. Le contexte réunionnais illustre particulièrement bien la *complexité des problématiques environnementales*, à savoir dans ce cas, la place importante que le secteur laitier a acquise en matière de progrès social et économique au cours des 40 dernières années et l'intérêt qu'il aurait à accroître sa production mais les fortes pressions sur l'environnement qu'il risque de générer si l'efficacité des systèmes de production n'est pas considérée.

I.3 Objectif et questions du projet GAMEDE

La problématique du DD des élevages, et c'est tout particulièrement le cas à La Réunion, est fréquemment abordée par une approche mettant en avant les « problèmes » environnementaux. La réponse dominante à ces problèmes reste aujourd'hui la mise en place de normes qui présentent le risque d'être mal vécues par les principaux concernés, à savoir les producteurs. L'*objectif finalisé du projet* GAMEDE a été d'explorer, via la modélisation informatique participative, une voie toute autre, visant aussi l'amélioration de la durabilité des productions animales mais en s'intéressant tout particulièrement à l'éleveur et à son outil de production : sa ferme d'élevage. La durabilité est donc considérée dans cette thèse uniquement à l'échelle de l'exploitation.

L'hypothèse sous-jacente à ce travail de modélisation est que la modification des structures d'exploitation (e.g. diminution des chargements animaux) ou/et de leur contexte socio-économique (e.g. mise en place de réglementations et de subventions) ne sont pas les seules voies d'amélioration ; le changement volontaire et raisonné des pratiques des éleveurs constitue une alternative pour l'amélioration de la durabilité des systèmes de production.

Dans le domaine environnemental, nous l'avons vu, les efforts de la filière se concentrent principalement sur la définition d'innovations techniques notamment par l'acquisition de références biophysiques issues d'expérimentations. La démarche complémentaire que nous envisageons réside dans la prise en compte des pratiques, des représentations et des stratégies de conduite des éleveurs pour une meilleure compréhension des changements induits par ces innovations sur les systèmes de production et pour un meilleur accompagnement de l'adoption de ces innovations.

En effet, le transfert des solutions techniques se heurte souvent à une faible ou une trop lente appropriation par les éleveurs. Une démarche reposant sur des discussions autour des sorties d'un modèle informatique a déjà été adoptée dans différents programmes de recherche finalisée avec un certain succès (Carberry *et al.*, 2002). Concernant la gestion de l'N en EBL, la complexité des systèmes étudiés rend difficile et coûteuse l'expérimentation démonstrative en conditions réelles des alternatives techniques envisageables et de leurs conséquences sur le système de production dans son ensemble. La construction d'un modèle informatisé représentant l'influence des pratiques de gestion sur l'ensemble des flux d'azote de l'exploitation semblait donc être une voie pertinente pour favoriser des échanges avec les éleveurs autour de représentations holistiques.

A ce stade de la réflexion, un ensemble de *questions de recherche* se posent :

- Comment construire un tel modèle ?

- A quelles conditions ce modèle représentant l'exploitation dans sa globalité peut-il permettre de mieux comprendre l'influence des pratiques des éleveurs sur la durabilité de leur exploitation ?

- La participation d'éleveurs à un tel projet de modélisation peut-elle faciliter la construction et l'utilisation ultérieure de cet outil d'aide à la décision qui leur est destiné ?

I.4 Contenu du manuscrit

Cette thèse répond à ces questions autour d'une série de publications qui peuvent être lues de façon indépendante. La logique liant l'ensemble de ces publications est ici présentée (Fig. 5).

Le chapitre II est à *caractère méthodologique*, il décrit comment en partant d'une approche analytique, cette dernière a été progressivement enrichie par la modélisation informatique et la participation d'un groupe d'éleveurs. Ce chapitre comprend trois communications dans des congrès avec comité de sélection.

La 1^{ière} communication (Vayssières *et al.*, 2006) montre que des grands types de pratiques plus respectueux de l'environnement peuvent êtres identifiés en croisant une approche de type bilan entrées-sorties (« farm-gate balance ») à une typologie de combinaison de pratiques. Mais cette approche croisée n'est pas suffisante pour expliquer la grande diversité de résultats environnementaux rencontrée en EBL à La Réunion. La nécessité de construire un modèle dynamique de simulation de l'ensemble des flux d'azote dans l'EBL a donc été confirmée.

La 2^{ième} communication (Vayssières et Lecomte, 2007) décrit l'approche globale de modélisation de l'ensemble des flux d'azote circulant dans l'EBL. Elle explique pourquoi, de notre point de vue, les approches de modélisation classiques doivent être revues quand on cherche à modéliser avec finesse un agro-écosystème aussi complexe, considéré de plus dans son entièreté.

La 3^{ième} communication (Vayssières *et al.*, 2007a) retrace l'historique du projet GAMEDE en montrant la place essentielle qu'ont occupée six éleveurs laitiers réunionnais pendant 4 des 5 années du projet de thèse.

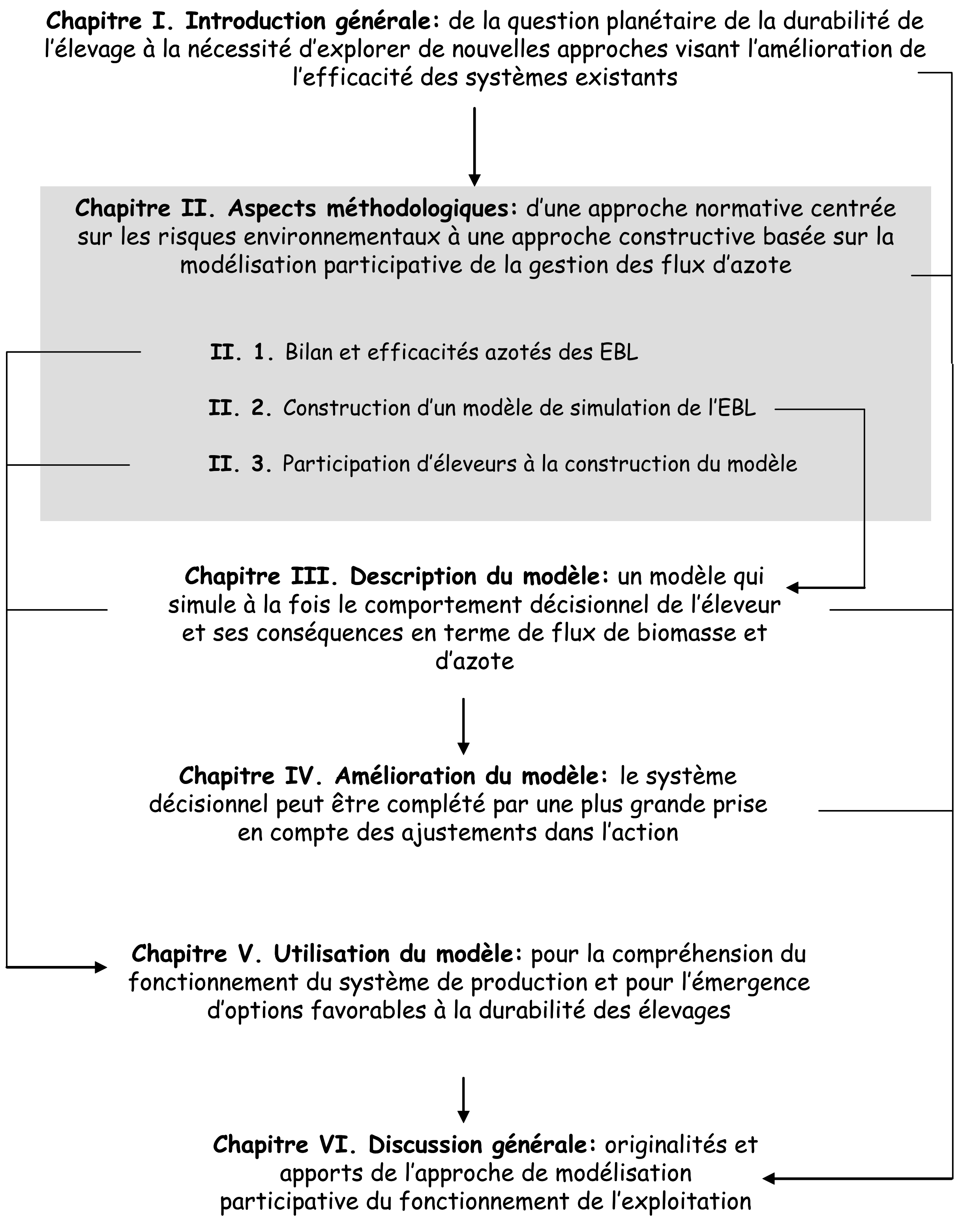

Figure 5. Articulation des chapitres de la thèse

Le chapitre III *décrit le modèle* GAMEDE (Vayssières *et al.*, in review). Le modèle ne se limite pas à la quantification des flux d'azote résultant des pratiques, il calcule aussi les performances techniques du système de production, sa pression sur l'environnement et la charge de travail qu'il génère pour l'éleveur. Ce chapitre insiste sur le haut niveau d'intégration atteint. En effet le modèle simule à la fois le comportement décisionnel de l'éleveur (quand et comment agir pour conduire l'exploitation ?) et le fonctionnement biophysique du système de production (repousse des fourrages, productions du troupeau, émissions d'azote sous forme gazeuse…).

Le chapitre IV *explore une voie d'amélioration* du modèle GAMEDE identifiée dans le chapitre précédent (Vayssières *et al.*, 2007b). Il s'agit du développement d'un système décisionnel plus élaboré, visant une simulation encore plus affinée et réaliste du comportement décisionnel des éleveurs. Une méthode originale d'enquête itérative, multi-étapes et multi-outils est proposée. Elle a abouti à la conception d'une structure originale permettant la modélisation de l'action avec prise en compte des ajustements face à l'aléa climatique et à l'indisponibilité temporaire des ressources.

Le chapitre V s'intéresse à l'*utilisation d'un tel modèle* vis-à-vis de l'enjeu du DD en élevages (Vayssières *et al.*, in review). Il montre l'intérêt des représentations apportées par le modèle pour la compréhension du fonctionnement d'un EBL pour les scientifiques, les techniciens et les éleveurs. Des simulations interactives avec ces différents acteurs du monde agricole ont été testées. Les simulations à la ferme avec l'éleveur se sont révélées particulièrement fertiles. Ce dernier chapitre permet aussi de resituer le modèle GAMEDE dans le courant des outils d'aide à la décision (**DSS**).

Enfin le Chapitre VI termine cette thèse en discutant les *apports de ce projet de modélisation* interactive à l'échelle de l'exploitation.

Chapitre II. DE L'ETUDE DES FLUX D'AZOTE A UN MODELE D'EVALUATION DE LA DURABILITE DES SYSTEMES DE PRODUCTION CONSTRUIT EN PARTENARIAT

II.1 Explaining the diversity of environmental performances according to a typology of farming practices combinations[2]

Introduction

A farm-gate budget is the most integrative measure of environmental pressure and seems most suitable as environmental performance indicator (Oenema *et al.*, 2003). The farm-gate budget can also be used to identify farming strategies which are not environmentally sustainable (Goodlass *et al.*, 2003). Taking the case of La Réunion tropical island, and focusing on the nitrogen (N) element, this paper applies the nutrient budget method to answer the question "Are some dairy farming models in the island more environmentally friendly than others?"

After an exceptional development period, the dairy sector (23,850,000 liters, 4,290 cows, 135 farmers) in La Réunion island (21°06'S, 55°32'E, 2700 km², 774,000 inhabitants) has to integrate environmental questions in the developmental orientation of the whole production chain, at the farm level in particular. However, development of grasslands is really limited by relief and dynamics of urbanization. In the majority of cases, the total utilised agricultural area (UAA) per dairy farm available to produce forage and spread manure is limited, with high stocking densities (often > 3 LU ha^{-1}). Therefore the farming models are generally based on high levels of inputs. Hence, it is important, to analyse the environmental impacts of the dairy farming practices in La Réunion.

[2] **Basé sur**: Vayssières, J., Lecomte, P., Guerrin, F., Bocquier F., Verdet C., 2006. Explaining the diversity of environmental performances according to a typology of farming practices combinations: the case of the dairy cattle breeding in La Réunion island. In: RAMIRAN 2006, 12th International Conference on "Technology for recycling of manure and organic residues in a whole-farm perspective", 11-13 September, Aarhus, Denmark, pp. 57-60.

Methodology

The sampling of the enquired farms was based on a technical-economical typology. 36 dairy farms were selected to represent all the farm types (assuming that the management style-diversity was covered). Semi-structured questionnaires were administered to the 36 farmers. They were questioned about their management practices which correspond to technical operations that generate biomass flows. As discussed by Hedlund *et al*. (2003), these interviews with local farmers were the basis for quantifying the biomass flows on a yearly basis.

In the present study, the chosen method of nutrient budgeting was the “farm-gate balance” (Simon *et al*., 2000). Total “N in” was the sum of N inputs in purchased biomass: concentrates, forages (including straw for mulching), animals, mineral fertilisers and manure. Total “N out” was the total amount of N in exported biomass: milk, animals and manure. The whole farm N surplus was calculated as (total N input – total N output)/ UAA. The farm N use efficiency was defined as N output/ N input. N contents of the different types of biomass were derived from data of previous works conducted in La Réunion.

Results

A principal components analysis was carried out on data from the 36 farms characterised by their practices. The two first axes (data not shown) could be interpreted as axes of “land desintensification”. i) The first axis characterised the “feed autonomy” of the farms. Feed autonomy can be defined as low use of concentrate and no import of forages by valorisation of on-farm produced forage. ii) The second axis expressed the “fertiliser autonomy” of the farms. Fertiliser autonomy is low use of mineral fertiliser per unit of UAA, significant on-farm recycling of manure. We propose a farm classification of five types. Type 1 and 2 cluster farms that have land intensive and technically intense practices. Farms of type 4 and 5 have land extensive practices. Type 3 is intermediate to 1-2 and 4-5 types.

Concentrates and mineral fertilisers are the main sources of N input (average values for all farm types: 51 and 41% of the N imports, respectively), similar to regions with intensive dairy farming systems (Hedlund *et al*., 2003). The average N surplus per hectare UAA among La Réunion’s dairy farms is higher than that found in the intensive milk production in other regions of the European Union (Kelm and Taube, 2003), like Flanders (Nevens *et al*., 2006). But this significant potential environmental impact has to be contextualised by considering the low density of dairy farms in La Réunion (1% of the total area of the island). Moreover, La Réunion farms have a better N efficiency (see Tab. 1) than Western European farms.

Tableau 1. *Means of farms' characteristics per type (2004).*

	Type 1	Type 2	Type 3	Type 4	Type 5	Average	Flanders[1] (2001)
UAA (ha)	15.7 +/- 11.1	8.2 +/- 0.7	17.3 +/- 11.1	23.1 +/- 25.9	30.3 +/- 25.7	18 +/- 14.5	32.5
Stocking density (LU ha^{-1})	5.3 +/- 11.1	5.1 +/- 0.7	4.0 +/- 11.1	2.7 +/- 25.9	3.0 +/- 25.7	4.2 +/- 2.1	3.0
N surplus (kg N ha^{-1} yr^{-1})	660 +/- 225	505 +/- 290	480 +/- 255	365 +/- 170	220 +/- 135	490 +/- 260	240
N Efficiency	0.27 +/- 0.13	0.31 +/- 0.13	0.21 +/- 0.18	0.21 +/- 0.20	0.36 +/- 0.16	0.25 +/- 0.16	0.22
Milk productivity (kg cow^{-1} yr^{-1})	6720 +/- 1355	6310 +/- 1155	5650 +/- 1180	5690 +/- 1255	5995 +/- 950	6020 +/- 1230	5830

[1] (Nevens *et al.*, 2006)

Extensive practices (types 4 and 5) appear to further lower N surplus. But N importation (intensification) is necessary to have higher milk productivity (types 1 and 2). Farms of types 1 and 2 compensate those N imports by exporting solid manure so they have a higher N efficiency.

Conclusions and perspectives

From an economical point of view, if subsidies are linked to milk production, farmers will still have to aim at a high level of milk production. Therefore, considering only land limitation the intensive models (with high milk productivity) would really be defensible. Whereas if subsidies become decoupled or in the case of pluriactivity development (type 4), the extensive model could be retained, also for land limited systems.

Combining the typology of practices with environmental performances of the farm types revealed "environmentally positive practices", like export of manure. Knowing the importance of sugar cane crop (59% of the total UAA of the island vs. 5% for the dairy farming), there is a high potential capacity of the sugar cane sector for accepting organic fertilisers from the dairy sector.

The current study was a first attempt to identify "environmentally positive practices" among dairy farms of La Réunion. At the same time, a whole farm model, called GAMEDE, was developed to simulate the influence of management practices on the N cycle in the dairy production system and the resulting sustainability of this system.

Conclusions intermédiaires et transition

Cette première communication confirme l'intérêt d'étudier la gestion de l'azote en EBL à La Réunion. Le croisement d'une typologie de combinaisons de pratiques avec une approche de type « farm-gate balance » permet d'identifier des stratégies ou associations de pratiques plus respectueuses de l'environnement.

Les résultats obtenus restent cependant triviaux ; par exemple, les systèmes intensifs sont identifiés comme exerçant potentiellement une pression plus importante sur l'environnement. Pour aller plus loin dans la compréhension de l'influence des choix de gestion de l'éleveur sur les résultats de son système il s'agissait de dépasser le niveau stratégique pour entrer dans la conduite opérationnelle de l'exploitation.

L'intérêt de modéliser la conduite au quotidien de l'exploitation et ses conséquences sur les flux d'azote du système proposé en introduction est donc bien confirmé à cette étape.

II.2 Modéliser les pratiques décisionnelles et les flux d'azote à l'échelle globale de l'exploitation[3]

Résumé

Rares sont les modèles de simulation qui représentent l'exploitation agricole dans sa globalité. GAMEDE (Global Activity Model for Evaluating the sustainability of Dairy Enterprises) représente les actions de conduite d'une exploitation bovine laitière complète et les flux de matières générés au sein de l'exploitation et avec son environnement. Ce modèle articule un système décisionnel (qui simule la réalisation de 19 opérations de conduite) à un système biophysique complexe constitué de six modules (représentant entre autres des mécanismes biologiques à la fois animaux et végétaux). Parvenir à un tel niveau d'intégration repose sur la complémentarité disciplinaire et suppose de revoir les approches de modélisation classiques. De même, les validations classiques confrontant le simulé à l'observé ne sont pas forcément les seules méthodes pertinentes quand on représente dynamiquement, à un pas de temps quotidien, le fonctionnement d'un agro-écosystème aussi complexe.

Abstract

Modelling decisional practices and nitrogen flows at the whole farm scale: the case of dairy farming in a tropical island

The simulation models that represent the farm as a whole are quite scarce. GAMEDE (Global Activity Model for Evaluating the sustainability of Dairy Enterprises) focuses on the management actions of a dairy farm and the subsequent matter flows within the farm and towards its environment. The model articulates a decision system that simulates the realisation of 19 technical operations with a complex biophysical model made of six modules representing both animal and vegetal biological processes. Aiming at such a level of integration supposes a multidisciplinary coordination and differs from the classical modelling approaches. In our case, the classical validations that compare simulated vs observed data are not necessarily the only pertinent methods when representing dynamically, on a daily basis, the functioning of such a complex agro-ecosystem.

[3] **Basé sur**: Vayssières, J., Lecomte P., 2007. Modéliser les pratiques décisionnelles et les flux d'azote à l'échelle globale de l'exploitation : cas de l'élevage bovin laitier en contexte tropical insulaire. In : 3R 2007, 14th Congress Rencontres autour des Recherches sur les Ruminants, 5-6 December, Paris, France, pp., pp 45-48.

Introduction

À La Réunion, du fait de fortes contraintes foncières l'élevage bovin laitier (EBL) est généralement basé sur une utilisation importante d'intrants (concentrés, engrais minéraux…). Une première évaluation de l'impact environnemental en terme d'excédents azotés à l'échelle des systèmes d'exploitation a montré que la diversité des pratiques individuelles se traduisait par une large gamme de performances environnementales (Vayssières *et al.*, 2006). Avec pour objectif de mieux comprendre et représenter l'incidence des pratiques de conduite dans ces élevages sur leurs résultats environnementaux, un modèle de flux de matière, GAMEDE, a été construit. Il représente les flux entre l'exploitation et son environnement et les flux au sein de l'exploitation. Cette communication a pour objectif de présenter l'approche de modélisation utilisée pour représenter l'exploitation dans sa globalité, éleveur inclus.

II.2.1 Approche de modélisation

II.2.1.1 Du système à la pluri disciplinarité

L'EBL peut être vue comme un ensemble de stocks reliés par des flux de matières de différentes natures (animaux, lait, effluents, fourrages…). Certains flux résultent d'actions décidées et réalisées par l'éleveur : les « flux actionnables », d'autres, découlent de processus biophysiques, qui ne lui sont pas directement accessibles : les « flux biophysiques ». L'existence de flux soumis à la décision de l'éleveur a conforté l'intégration d'un système décisionnel (**DS**) et d'un système biophysique (**BS**) dans GAMEDE. En référence aux travaux de Cros *et al*. (2001) le développement d'un DS en lien avec un BS est un moyen de représenter les pratiques des éleveurs. L'existence de ces deux systèmes nous a conduit à mobiliser des concepts et des méthodes à la fois des sciences sociales et des sciences biophysiques.

De plus, GAMEDE représente un système associant la conduite de cultures et l'élevage d'animaux. La nature du modèle a donc nécessité la mise en place d'un groupe de travail pluridisciplinaire. Ainsi, la conception de GAMEDE a mobilisé 6 éleveurs, 3 techniciens, 8 chercheurs biophysiciens (3 zootechniciens, 1 vétérinaire, 2 agronomes du végétal / sol, 1 écologue pastoraliste, 2 modélisateurs), 4 chercheurs en sciences sociales (1 ethnologue, 1 ingénieur de la connaissance, 1 ergonome, 1 économiste). Chaque acteur a participé pendant au moins une semaine au travail de modélisation.

II.2.1.2 Sept étapes de modélisation

Concernant la construction de GAMEDE, sept étapes de modélisation ont pu être identifiées :

i) Modélisation conceptuelle du modèle de flux de matière et description des phénomènes biophysiques à représenter.

ii) Représentation de la diversité des profils décisionnels des éleveurs laitiers et conception du DS.

iii) Inventaire puis sélection, dans la bibliographie, de modèles partiels permettant de simuler les phénomènes biophysiques à intégrer dans le BS, en tenant compte des objectifs de modélisation et des données disponibles à La Réunion.

iv) Implémentation puis paramétrage des modèles biophysiques partiels avec des données locales.

v) Simulation de scénarios réels avec les modèles partiels comprenant leur évaluation à dire d'experts.

vi) Compilation et implémentation des modèles biophysiques partiels et du DS sous la forme de GAMEDE.

vii) Simulation de scénarios réels (EBL réels) avec GAMEDE et évaluation du modèle.

II.2.1.3 Construction du système décisionnel

Dans cette étude une méthode multi-outils et multi-étapes a été mise en œuvre pour concevoir le DS et identifier les règles de décision en vue de son paramétrage. En effet, quatre types d'enquêtes en exploitation ont été mobilisés sur quatre années :

i) des immersions inspirées par les approches ethnographiques mais conçues pour identifier des règles de décisions opérationnelles (prises au quotidien) concernant des actions techniques (1 semaine par EBL en année 1),

ii) des enquêtes rapides de type entretiens semi-directifs (2 heures par EBL en année 1),

iii) des suivis de pratiques d'exploitation permettant l'observation de l'état du système de production : stocks de fourrage, composition du troupeau, hauteur d'herbe sur les parcelles (1 jour par EBL tous les deux mois pendant 2,5 ans en années 1 à 3),

iv) des réunions collectives (1/2 journée tous les 3 mois pendant 2,5 ans en années 2 à 4).

Les enquêtes rapides ont concerné 36 EBL (27% des EBL réunionnais). Les trois autres types d'enquêtes on concerné six éleveurs tout particulièrement choisis pour représenter la diversité des profils décisionnels (en référence à une typologie de combinaison de pratiques : Vayssières *et al.*, 2006) et des zones d'élevage (en référence à un zonage à dire d'experts). Ces six éleveurs ont étroitement participé à la conception de GAMEDE et plus particulièrement à la conception du DS.

II.2.1.4 Construction du système biophysique

Concernant le BS il préexistait un ensemble de modèles partiels traitant de façon précise des processus spécifiques. L'un des enjeux majeur a été d'adapter ces modèles au contexte local et de les coupler pour construire un unique BS global.

La construction du BS s'est opérée en deux temps :

i) Le premier a concerné la Reconstruction des modules (= modèles biophysiques partiels) à partir de modèles publiés. Pour chaque processus (listés en § II.2.2.3), la principale difficulté a généralement été de choisir dans une grande diversité de modèles disponibles (modèles mécanistes ou empiriques, modèles d'optimisation ou de simulation) un modèle adapté aux objectifs de représentation, aux données disponibles localement pour son paramétrage et, enfin, selon l'accessibilité de l'algorithme. Deux modèles, le Module de Conditionnement des Fourrages (MCF) et le Module d'Emissions Azotées (MEA) (décrits dans le § II.2.2.3), ont tout spécialement été conçus pour les besoins de GAMEDE faute de modèle adéquat dans la bibliographie. Dans tous les cas, les modules ont été paramétrés à partir de données issues d'expérimentations locales.

ii) Le deuxième temps a concerné l'Intégration de l'ensemble des modules dans un cadre unique, homogène et « actionnable » par le DS. L'assemblage des différents modules a porté une attention particulière à ce que les sorties de modules constituent les entrées d'autres modules afin de suivre le cycle de matière dans l'exploitation.

II.2.2 Description du modèle

II.2.2.1 Principes du modèle de simulation

GAMEDE est un modèle de simulation développé sous système dynamique hybride (Vensim®). Il représente les actions réalisées chaque jour par l'éleveur et l'état quotidien du système de production (e.g. les flux d'azote).

Les variables d'entrée de GAMEDE concernent : i) la structure de l'exploitation (taille initiale du troupeau, parcellaire, capacité de la fosse à lisier…), ii) la stratégie de l'éleveur sous la forme de règles de décision et iii) l'environnement de l'exploitation en terme météorologique (données quotidiennes de pluie, température, rayonnement, ETP…) et de disponibilité des intrants (fourrages, fertilisants organiques…).

Le DS de GAMEDE simule les actions techniques de l'éleveur en fonction de ses règles de décision, de l'état du système de production et de son environnement (Fig. 6). Le BS traduit les actions techniques en flux actionnables et simule les flux biophysiques tous deux déterminés par les conditions météorologiques quotidiennes. Une synthèse traduit les flux de matière en flux d'azote et calcule trois types d'indicateurs de durabilité : i) des indicateurs environnementaux (bilan et efficacité azotés), ii) des indicateurs sociaux (temps de travail et temps d'astreinte), et des indicateurs techniques (productivité prairiale et laitière). Un module d'évaluation économique, dont la forme conceptuelle est achevée, va prochainement être intégré à GAMEDE.

II.2.2.2 Contenu du système décisionnel

Le DS définit les actions techniques réalisées au jour le jour selon l'état du système de production, le temps de travail disponible, les priorités entre opérations et les contraintes de réalisation des actions. La forme conceptuelle du DS est la « Structure for Action Modelling » (**SAM**) conçue pour les besoins de GAMEDE (Vayssières *et al*., 2007b). Cette structure conceptuelle est suffisamment générique pour formaliser comment toute action technique est réalisée. La SAM est composée d'un ensemble de variables descriptives des opérations techniques et des règles de décision correspondantes. Ces règles ont été reconstruites par le chercheur modélisateur avec la participation des six éleveurs. La SAM prévoit la réalisation de l'action en trois temps : une première liste d'opérations techniques, les « opérations à réaliser », est produite. Un second sous ensemble d'opération est sélectionné dans cette première liste : les « opérations réalisables » compte tenu d'un ensemble de contraintes à vérifier relatives à la disponibilité des ressources (main d'œuvre, matériel, matière) et aux conditions climatiques. Dans un troisième temps les « opérations effectivement réalisées » sont caractérisées en vue de leur traduction en flux de matière. Chacune des trois étapes fait intervenir un type de règles particulier.

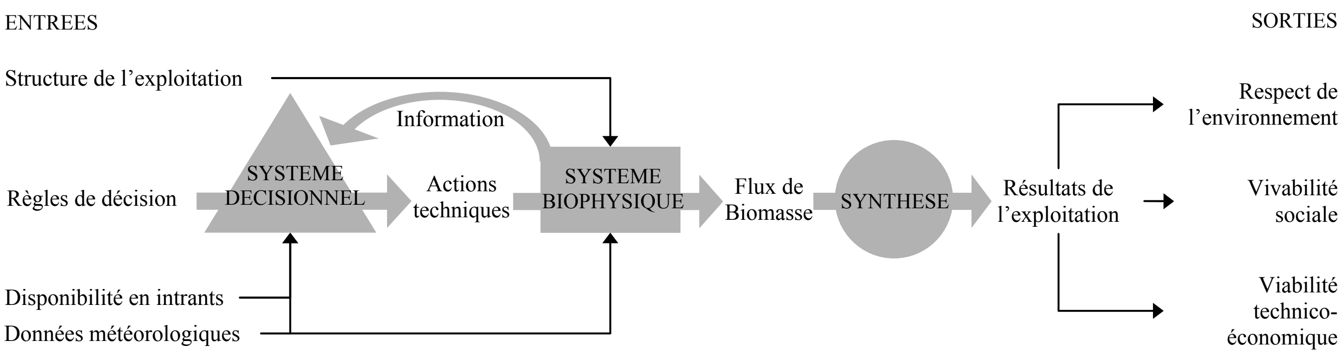

Figure 6. *Algorithme simplifié de GAMEDE*

En référence aux travaux concernant le modèle d'action (Duru *et al*., 1988), les opérations sont déclenchées et caractérisées soit par le plan d'action de l'éleveur (environ 90 règles de décision tactiques à renseigner), soit de façon contextuelle en autorisant des ajustements possibles par rapport au plan en fonction d'aléas (plus de 300 règles de décision opérationnelles à renseigner).

En termes mathématiques, la réalisation d'une opération technique est représentée par une variable binaire (Fig. 7).

II.2.2.3 Contenu du système biophysique

Le BS comprend six modules inter connectés. 1) Le Module de Production de Fourrages verts (**MPF**) simule la croissance de diverses graminées prairiales et de la canne à sucre dans quatre zones pédo-climatiques tropicales différentes (zones sèches d'altitude à zones côtières hyper humides). Cette croissance est fonction des pratiques de récolte et de fertilisation. Ce module végétal est inspiré de deux modèles de la bibliographie : le MCP pour la prairie (Leteinturier *et al*., 2004) et MOSICAS pour la canne à sucre (Martiné, 2003). 2) Le MCF simule l'évolution des fourrages prairiaux suite à leur enrubannage selon la nature initiale du fourrage, les conditions climatiques dans lesquelles le chantier est réalisé et la quantité de conservateur ; ce module original a été conçu à partir des données de Paillat (1995). 3) Le Module de Production Animale (**MPA**) simule la production de lait, de déjections animales et l'évolution du poids des animaux selon la ration ingérée en distinguant 21 classes d'animaux (veaux, génisses, vaches taries et en production). Ce module, basé sur le système UF/ PDI, a principalement mobilisé des équations du logiciel de rationnement INRAtion (Faverdin *et al.*, 2007), complétées par celles de CNCPS pour la production de déjections (Fox *et al.*, 2004). 4) Un Module de Démographie (MD) calcule les effectifs des 21 classes d'animaux selon des paramètres de reproduction/ mortalité et la stratégie de réforme/ renouvellement de l'éleveur. Ce module est inspiré de GEDEMO (Coquil *et al.*, 2005). 5) Le MEA simule le devenir des effluents d'élevage au cours de leur gestion (bâtiment, stockage, conditionnement, épandage) selon quatre voies possibles : restitution au pâturage, lisier, fumier et fumier+compostage. Ce module est original ; les facteurs d'émission sont issus de la bibliographie. 6) Le dernier Module concerne le Pâturage (MP). Il simule la défoliation et l'ingestion d'herbe pâturée par les animaux selon leur capacité d'ingestion (diminuée de l'ingéré à l'auge), le temps de pâturage et l'abondance de l'herbe disponible sur la parcelle. Le MP est essentiellement inspiré de SEPATOU (Cros *et al.*, 2003) et GRAZEIN (Delagarde *et al.*, 2004).

II.2.3 Originalité de l'approche et validation du modèle

L'originalité de GAMEDE est qu'il simule de façon dynamique, à un pas de temps quotidien et sur plusieurs années, la réalisation de la totalité des opérations de conduite, l'état des flux et des stocks de matière de l'ensemble de l'exploitation. Un schéma synthétique (Fig. 7) montre le type de représentations proposées par le modèle.

L'approche de modélisation constitue une autre originalité. Classiquement, la quantification des flux se fait en domaines expérimentaux (Modim-Edman, 2007). Ici la quantification a été réalisée in situ ; elle permet ainsi une validation d'un modèle destiné à représenter des systèmes réels sur la base de données recueillies dans des systèmes représentatifs de l'existant. Les limites sont que la précision, la finesse et l'exhaustivité des données recueillies atteignent rarement celles de données expérimentales.

II.2.3.1 Confrontation du simulé a l'observé en fermes réelles

La quantification des flux et des stocks de matières intra année en fermes réelles a pu être conduite sur deux années grâce au suivi des six exploitations. Ce suivi offre un jeu de données pour confronter le simulé à l'observé aussi bien en intra annuel qu'à une échelle annuelle.

En Fig. 7, l'exemple de la gestion des stocks d'enrubannage illustre la validation quantitative intra annuelle des flux et des stocks de l'exploitation. La gestion de ce stock comprend la récolte du fourrage et l'alimentation des animaux qui génèrent respectivement des flux entrants et sortants.

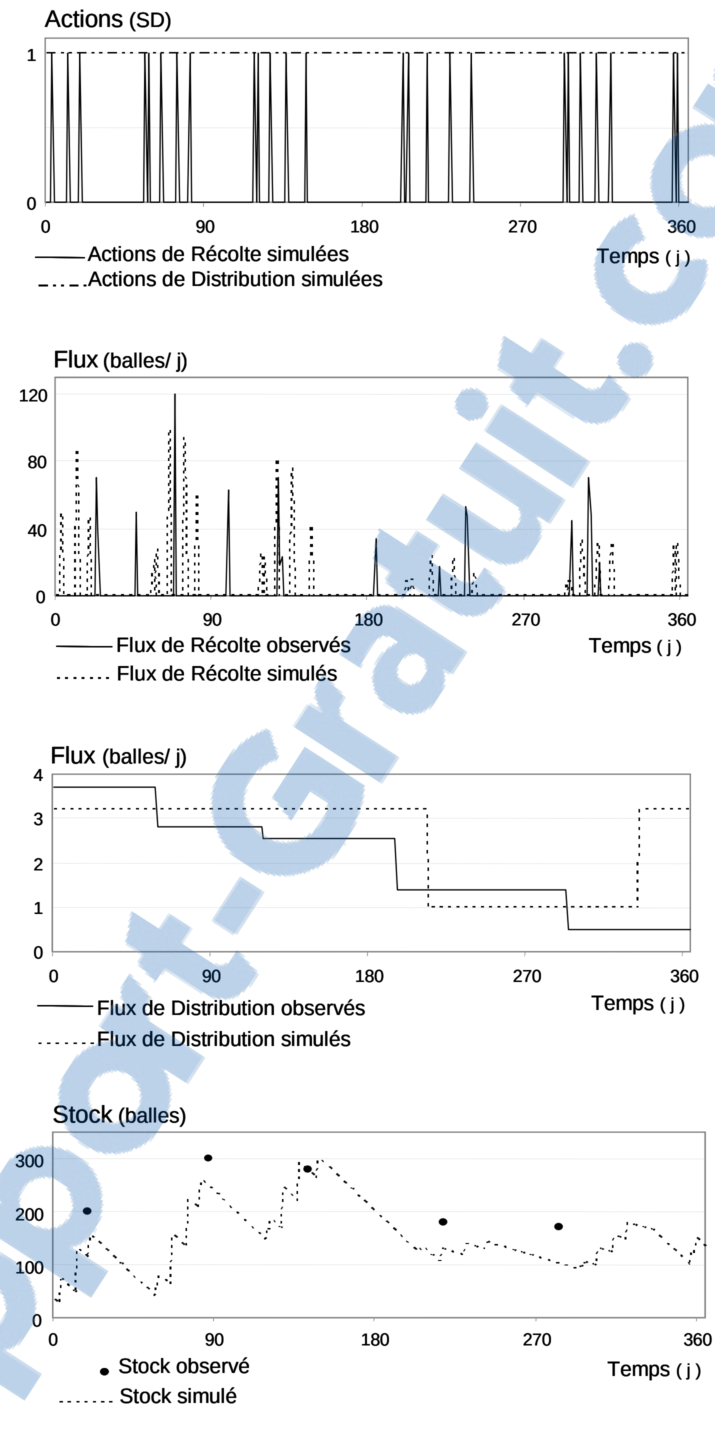

Figure 7. *Simulation dynamique des actions de conduite, des flux et des stocks : cas de la gestion du stock d'ensilage de l'exploitation 3 sur l'année 2006*

De même les bilans annuels peuvent êtres confrontés aux indicateurs observés (Fig. 8). Les bilans annuels proposés sont, pour les six exploitations, plus justes que les représentations intra annuelles. Ces écarts proviennent en particulier du fait que les actions de conduite, à l'origine de nombreux flux, sont en pratique souvent réalisées de manière différente de ce qui est prévu par le plan ; or les simulations ici proposées sont essentiellement basées sur le plan d'action de l'éleveur.

Des simulations avec des ajustements possibles de ce plan, sur la base des règles opérationnelles décrites par Vayssières *et al*. (2007b), son testées en chapitre IV.

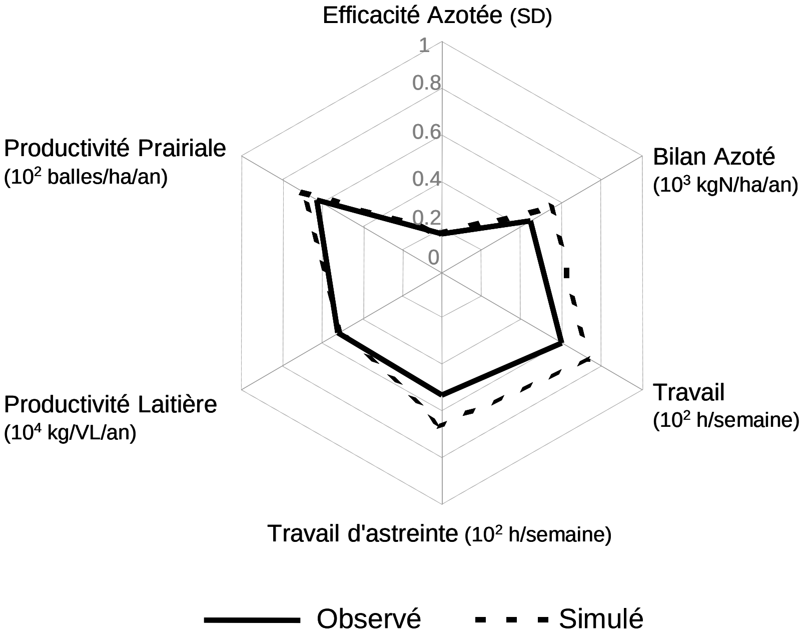

Figure 8. *Bilan annuel sur six critères de la durabilité de l'exploitation 3 pour l'année 2004*

II.2.3.2 Validations a dire d'experts

Chacun des six modules biophysiques a individuellement fait l'objet de validations à dire d'experts sur la base de simulations de scénarios réels et prospectifs. Pour chaque module, trois types d'experts sont intervenus successivement pour évaluer le réalisme des simulations : 1 chercheur du domaine biophysique concerné, 1 technicien compétent et 1 à 3 éleveurs dont les pratiques ont été simulées. Si l'on prend l'exemple du MPF, son réalisme a été évalué sur la base des productions de fourrages simulées dans plusieurs zones d'élevage et à différents niveaux de fertilisation.

Concernant la validation du modèle complet, l'évaluation du réalisme des simulations a suivi une démarche similaire mis à part le fait qu'elle a été précédée d'une phase importante de vérification de la cohérence globale des représentations produites par GAMEDE entre elles et avec la connaissance acquise sur les systèmes de production enquêtés. Cette vérification a concerné les actions, les flux/ stocks et les résultats d'exploitation. A titre d'exemples, il s'agissait de vérifier que l'azote ne s'accumulait pas anormalement dans un des stocks de l'exploitation ou qu'une stratégie attachant peu d'importance à la valorisation des effluents d'élevage conduisait bien à des risques de débordements de fosse à lisier plus importants. La vérification a été conduite par le premier auteur, modélisateur agro-zootechnicien. Le fait que ce dernier ait accompli à la fois le travail d'enquête et de modélisation dans six exploitations très différentes lui a permis d'acquérir l'expertise nécessaire à la vérification de la cohérence des représentations.

II.2.3.3 Validation par l'usage

Les perspectives d'application de GAMEDE sont multiples. il sera dans un premier temps utilisé auprès d'éleveurs pour évaluer avec eux les répercutions d'alternatives techniques qui pourraient être directement envisagées sur l'exploitation. L'encadrement technique est également intéressé par le modèle afin d'alimenter ses réflexions sur les modèles de productions innovants. Tout un ensemble de méthodes de validation, dites « validations par l'usage », pourront alors être envisagées selon les objectifs attendus :

- validation par la pertinence et la crédibilité (Rykiel, 1996) des réponses apportées aux décideurs dans le cas d'une utilisation en tant qu'outil d'aide à la décision,
- validation par l'importance des échanges et des réflexions générées chez les acteurs dans le cas d'une utilisation en tant que modèle d'accompagnement,
- validation par le progrès généré dans le cadre d'une utilisation comme outil de développement, de formation et/ ou de diffusion d'innovations.

Conclusion

GAMEDE, modèle de simulation du fonctionnement quotidien de l'exploitation dans sa globalité est à même de représenter une grande variété de stratégies et de structures d'élevages laitiers. Ces systèmes sont particulièrement complexes, d'autant plus qu'ils sont conduits dans des milieux pédo-climatiques variés (c'est le cas à La Réunion).

Centrée sur l'élevage, cette approche pluridisciplinaire (interventions de chercheurs de disciplines connexes), interactive (échanges réguliers entre éleveurs et chercheurs) et itérative, a nécessité de nombreux allez retour entre les formes conceptuelles et les évaluations du modèle.

Etant donné le niveau de finesse des représentations proposées par GAMEDE à propos d'un système particulièrement complexe, une réflexion sur la manière de valider ce type de modèle est d'actualité. La validation classique confrontant le simulé à l'observé peut être complétée par des validations globales impliquant les acteurs. Ces particularités doivent être prises en compte lorsqu'on représente un agro-écosystème dans sa globalité.

Remerciements

Nous tenons à tout particulièrement remercier les six éleveurs qui ont participé à la construction de GAMEDE, les nombreux chercheurs venus en appui scientifique au cours de ce travail de modélisation, et F. Bocquier en tant que relecteur attentif.

Conclusions intermédiaires et transition

Cette seconde communication s'intéresse plus particulièrement à la méthode générale de modélisation mise en oeuvre. Il y est évoqué qu'un groupe d'éleveurs a participé à ce projet de modélisation.

La communication suivante synthétise la manière dont cette modélisation participative a été conduite et ses conséquences sur la nature du modèle et sur la méthode de modélisation mise en oeuvre.

II.3 Farmers participation in designing a whole farm model[4]

Introduction

Designed with the participation of six milk farmers (**Fs**), GAMEDE is a Global Activity Model for Evaluating the sustainability of the Dairy Enterprises in La Réunion island. GAMEDE is a Simulation whole-farm model (**SFM**). By integrating the Fs' decisional processes, this simulation model describes the dynamical functioning of biomass flows at farm scale. Based on participative modelling experiences (Walker, 1998; Pahl-Wostl, 2005), the hypothesis was that the six Fs' participation will increase the capacity of the simulator to support farmers' decision. A reflective study, conducted by an external observer (**EO**), aimed to evaluate how GAMEDE has been shaped by Fs' knowledge.

Methodology

The main designer, a researcher (**R**), has been inquired by the EO to identify key events that have influenced the modelling process. The modelling activity has left traces: meeting reports, conceptual and electronic forms of the SFM, recordings of discussions between the Fs and the R. All those traces have been analysed to build the background history of the modelling project (Fig. 9).

[4] **Basé sur** : Vayssières J., Kerdoncuff M., Lecomte P., Girard N., Moulin C.H., 2007a. Farmers participation in designing a Whole Farm Model. In: Farming Systems Design 2007, International Symposium on "Methodologies for integrated analysis of farm production systems", 10-12 September, Catania, Italy, Vol. 2, Field-farm scale design and improvement, pp. 237-238.

Results

The dynamics of the project are described on four aspects: i) the different steps of the model designing, ii) the events of interactions between the Fs and the R, iii) the status of the R according to the Fs' point of view, iv) the modelling objectives.

We can define five steps in the model design: 1) the conceptual modelling that borrows concepts and mathematical functions to models of the literature or, when more pertinent for farmers, proposes original ways to formalise on-field observable processes (e.g. the decision making), 2) the contextualisation of the models of the literature (= setting the models in the case of biophysical models), 3) the computer development of the partial models, 4) the simulation of real scenarios, 5) the validation from Fs' and expert opinion (researchers). This five-step method has been applied to the designing of the six partial biophysical models and the whole SFM. Contrary to a more classical modelling approach, such as the "MAFATE" one (Guerrin, 2007), Fs did not only participate in steps 4 and 5, but also participated in initial steps (1 and 2).

The first year of research was conducted without the participation of the Fs, whereas the rest of the project was conducted with frequent exchanges with the six Fs. Immersions (I in Fig. 9) in the six farms have developed into a fruitful collaboration between the Fs and the R. The meetings were frequent during three years, including individual meetings six times per year and collective meetings three times per year. For the R, the main objective of those meetings was to show and validate from Fs' knowledge, step by step, the progress of the model design. Initially expected in the research centre, the collective meetings were finally organised in the six surveyed farms as demanded by Fs. Each collective meeting was the occasion for the host farmer to organise a lunch and present his farm. It was a sort of spontaneous Farm Field School (Minjawn *et al.*, 2002).

The status of the R from the Fs' point of view has changed during the modelling project: starting as an inspector he has been progressively recognised as a scientist. This status progression shows that the Fs have placed their trust more and more in the R.

The modelling objectives have also changed in contact with Fs. For instance the main objective advanced in the first year was "to evaluate the environmental impact of existing farming systems and to represent impacts of technical innovations (such as composting) on those farming systems". After the immersions, the evaluation of the sustainability was extended to technico-economical and social aspects. The evolution of these objectives led the R to define new components of GAMEDE; Fs were really concerned by timework surplus and economical costs of the technical innovations.

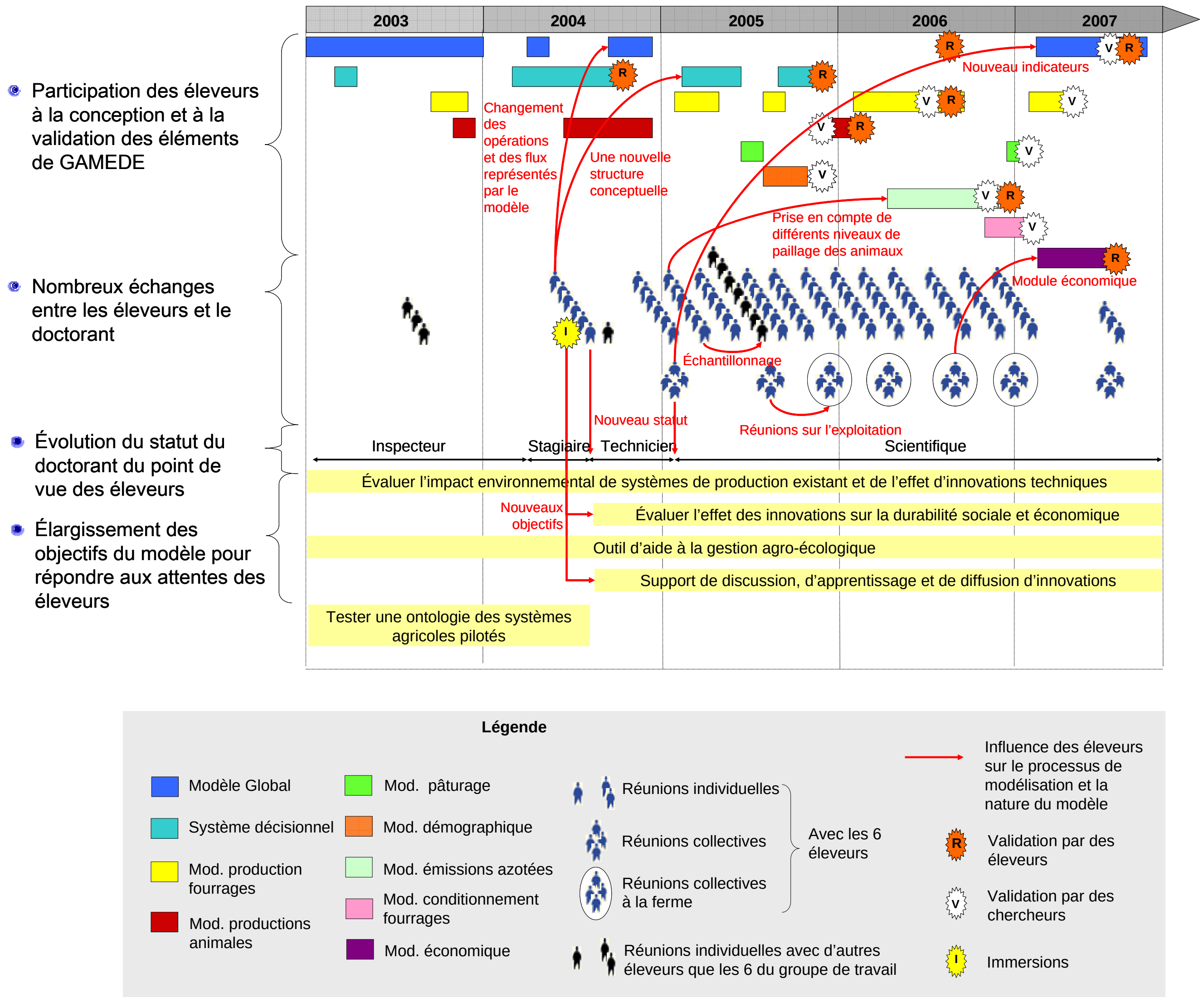

Figure 9. Background history of the modelling project

GAMEDE is composed of two systems: the decisional system (**DS**) and the biophysical system (**BS**). The most significant influences of Fs on the model concern the DS. It was initially proposed to use an existing modelling framework (Martin-Clouaire and Rellier, 2000) to model the decision-making about the drivers of the farm activities. But Fs' emphasis on the adjustments of their action plans led to develop the DS of the model. A Structure for Action Modelling (the **SAM**) has been specially elaborated to consider decision adjustment rules (Vayssières *et al*., 2007b).

The BS of the model has also been shaped by Fs' reactions. Keeping the example of composting, intra-year and inter-farms variability of mulching practices were observed and linked to straw availability. This led to the development of an original biophysical module that takes into account the effect of different level of mulching on composting efficiency (Vayssières, 2007).

Conclusions and perspectives

Fs' participation in the design of the SFM was helpful to choose the appropriate level of complexity of both the DS and the BS to represent with realism the functioning of the dairy farms.

Immersions in farms constitute a turning point of the project, the beginning of fruitful collaborations between Fs and R. The fact that the R has taken account Fs' point of view to define the organisation of the meetings had also a significant positive effect on participation. Participation of Fs was essential for the R to gain their confidence and thus to have greater access to data on the six farms, including sensitive data such as economic and manure-management data. Initially sceptical to computer models, Fs consider the experience as positive and see themselves as full contributors to the modelling process. Next step will be the use of the model as a discussion support tool to explore alternative innovations with the same individuals and later with other dairy farmers (Leeuwis *et al*., 1996; Carberry *et al*., 2002).

Conclusions intermédiaires et transition

Dans ce chapitre méthodologique, nous avons justifié a posteriori la construction d'un modèle représentant l'influence des pratiques de conduite sur les flux d'azote de l'exploitation.

Nous y avons décrit la méthode de conception, de développement et d'évaluation d'un tel modèle pour finalement se focaliser sur l'aspect participatif original de cette approche.

Le chapitre suivant décrit en détail le modèle GAMEDE.

Chapitre III. GAMEDE: A WHOLE-FARM DYNAMIC MODEL[5]

Abstract

Crop-livestock farms, especially dairy farms, are very complex systems. The interactions operating in such systems involve structural, decisional, biophysical, and environmental factors. Moreover, as farmers face a large range of management options, they need tools to support their decision-making to reach production levels complying with their objectives and their human and physical resources while controlling their effects on the environment. Computer models may serve both to explore this complexity and to help extension agents and farmers themselves test management scenarios for their farms.

GAMEDE, a whole-dairy-farm model, has been developed to represent dynamically the effect of operational decisions on biomass flows within the system, distinguishing between "actionable" (i.e. man-controlled) and biophysical flows. This article describes the model dealing with decisional and biophysical processes. Output indicators such as milk and forage crop productivity, work time, nitrogen balance, and nitrogen efficiency help assess the system's overall performances.

Six farms with different structures, agro-climatic conditions, and management strategies were used for validation. The results indicate that the model is able to explain the differences found in their sustainability indicators at the year scale. The infra-year variability of biomass flows and stocks is also well explained.

Keywords: Whole-farm model; Biomass and nitrogen flows; Dynamical simulation model; Dairy farming; Model performances.

[5] **Basé sur**: Vayssières, J., Guerrin, F., Paillat, J.M., Lecomte, P. GAMEDE: a Global Activity Model for Evaluating the sustainability of Dairy Enterprises. Part I – Whole-farm dynamic model. Agricultural Systems, in review.

Introduction

The sustainability of agricultural production according to its environmental, technico-economic and social dimensions has become a major stake for agricultural stakeholders and public policy-makers. Numerous issues are raised in assessing the effects of multiple change factors (evolutions of agricultural policies, climate, techniques, resource availability, consumer demand, regulation rules), the causal chains leading to these effects, and the strategies to guarantee the sustainability of agricultural production systems (Hubert *et al*., 2000).

Heavily constrained by land and forage availabilities, environmental regulations, competition with imported products, and the expected revision of subsidy policies, the milk sector in La Réunion island in the Indian Ocean must find new means to improve its productive capacity to guarantee its future. The local market demand would allow milk production to be doubled within the next few years (from 20 million up to 40 million litres year^{-1}). Although this objective would generate benefits in terms of employment and food supply autonomy, it would also increase the issues linked to livestock effluent disposal and competition for land with other agricultural and non-agricultural sectors. In this context, the milk industry focuses on innovations likely to improve the technical and economic efficiency of dairy farms and the social perception of the sector. Efforts are currently being made, on the one hand, to better manage the nitrogen flows at the farm level and, on the other hand, to search for synergies with the sugar cane and the market-gardening industries within territories. With this latter aim, a project is about to be implemented for supplying the dairy farms with sugar cane straw taken from the sugar mills. Its objective is, first, to use the straw as a supplementary forage resource and, second, to foster the production of composted manure instead of slurry (as is currently the dominant case) in order to improve the recycling of organic products within the farms and to develop a new sector: organic fertilizers for agriculture. This situation encountered in La Réunion is emblematic of the challenges that livestock farming systems are facing worldwide, due to the expected doubling of the animal products demand in the next fifty years and the dramatic environmental and social impacts likely to happen, as recently reported by FAO (Steinfeld *et al*., 2006).

To deal with these issues, in keeping with Thornton and Herrero (2001), we advocate building simulation models allowing the impacts of change factors on farming systems to be assessed. According to these authors: "To a large extent it is the complexity of the management options that makes these systems so complicated". Hence, our main objective is to help agricultural stakeholders devise sustainable management strategies that can be 'attainable' (in practice) rather than simply 'feasible' (in theory). With this aim, it is necessary to model explicitly the dynamical interaction between human activities and biophysical processes jointly operating within a farm. The human activity dimension is too scarcely adequately modelled (Garcia *et al*., 2005b), but many efficient models exist for simulating biophysical processes. The issue is thus to know how to integrate these models in a coherent global whole-farm model capable of answering the questions posed by the management needs of the intended users: scientists, extension agents, and farmers themselves. This issue of model component integration and reuse has been deemed crucial for farming system modelling and decision support by many authors (Holzworth *et al.*, 2007; van Evert and Lamaker, 2007; Bergez *et al.*, 2007).

This paper describes the integration of six modules accounting for the biophysical processes in a dairy farm (forage production, forage conditioning, herd demography, milk, dejecta and animal biomass productions, grazing, quality of fertilizers, and nitrogen gaseous emissions) together with a decisional system accounting for the farmer's strategy and technical operations. Most of the six biophysical modules are made of mathematical models from the literature, but the decisional system stems from our own original works. The result is a dynamic simulation model, called GAMEDE (Global Activity Model for Evaluating the sustainability of Dairy Enterprises) developed in the context of La Réunion. This island is recognised as a "real life laboratory" to study agriculture. Concerning dairy farming, one finds:

- a variety of pedo-climatic areas (dry mountain-top areas to hyper humid coastal areas),
- a variety of forage crops (both C4 and C3 plants),
- a variety of decisional profiles and management practices: mechanised management as in Europe and manual management as in developing countries.

This article (Part I) describes the main features of GAMEDE. It is organised as follows: i) an overview of the model and definitions of inputs and outputs, ii) a description of how a decisional system (**DS**) has been defined to interact with a biophysical system (**BS**), iii) an explanation of the use of existing models to represent the main biophysical processes in the BS of GAMEDE, iv) and a discussion of the realism of representations given by the model from both quantitative and qualitative validations. The companion article (Part II) illustrates typical applications of the model and situates GAMEDE in Decision Support Systems aiming to support farm management. In these two companion articles, we do not extensively describe the modelling approach, for this see Vayssières and Lecomte (2007).

III.1 Model overview

III.1.1 Computing characteristics

GAMEDE is a hybrid dynamical system as it incorporates both continuous and discrete variables (Antsaklis *et al.*, 1998), where time is explicitly manipulated (e.g. to determine dates of events such as harvest actions). Instead of dealing directly with a set of non-linear equations for representing complex dynamics, the hybrid dynamical system approach uses simple equations (mostly linear) and switches among them.

After having developed specialized models dedicated to animal waste management (Guerrin, 2001; Guerrin, 2004), this approach was generalized at the farm-level in GAMEDE. This farm model, designed by the first author, comprises nearly 26,950 variables (including 2,980 constants) and 1,950 equations to represent both technical actions and biophysical processes. Like both previous models, GAMEDE has been implemented using the Vensim® modelling and simulation software in its DSS32 version 5.4a.

III.1.2 Stock-flow model

Conceptually, GAMEDE can be seen as a flow-stock model. Fig. 10 represents a dairy farm as made of four interconnected subsystems (i.e. forage crops, feeds, the herd, and fertilisers), each comprising several elementary stocks (a more detailed version of the diagram is presented in Vayssières *et al*., 2004). The main biomasses circulating within the system are forages, concentrate feeds, milk, animals, and manures.

Two types of flows are represented: i) those mainly driven by human agents: "actionable flows" (e.g. forage harvest, animal feeding, manure removal, manure spreading); ii) those mainly driven by natural causes: "biophysical flows"(e.g. grass growth, milk, animal biomass, manure production) and "leaks" to the environment (e.g. N volatilisation). Previous studies (Vayssières *et al*., 2004) have shown that most biomass flows in dairy production systems are actionable flows. 19 technical operations that generate these flows in the farm are represented in GAMEDE. The diagram in Fig. 10 underlines the cyclic aspect of biomass transfers within the farm. The biomass circulates along to two cycles. One is constituted by the flows: forage harvest-animal indoor feeding-manure removal and spreading. The second, much shorter, is constituted by the flows: grazing (outdoor feeding) and direct dejecta restitution to pastures.

Peripheral flows are of importance because they link the farm with its environment. The farm is an open system, subject to biomass imports and exports controlled by the farmer (e.g. milk, animals, feeds, fertilisers) or to "leaks" corresponding to specific biophysical processes (e.g. N gaseous emissions).

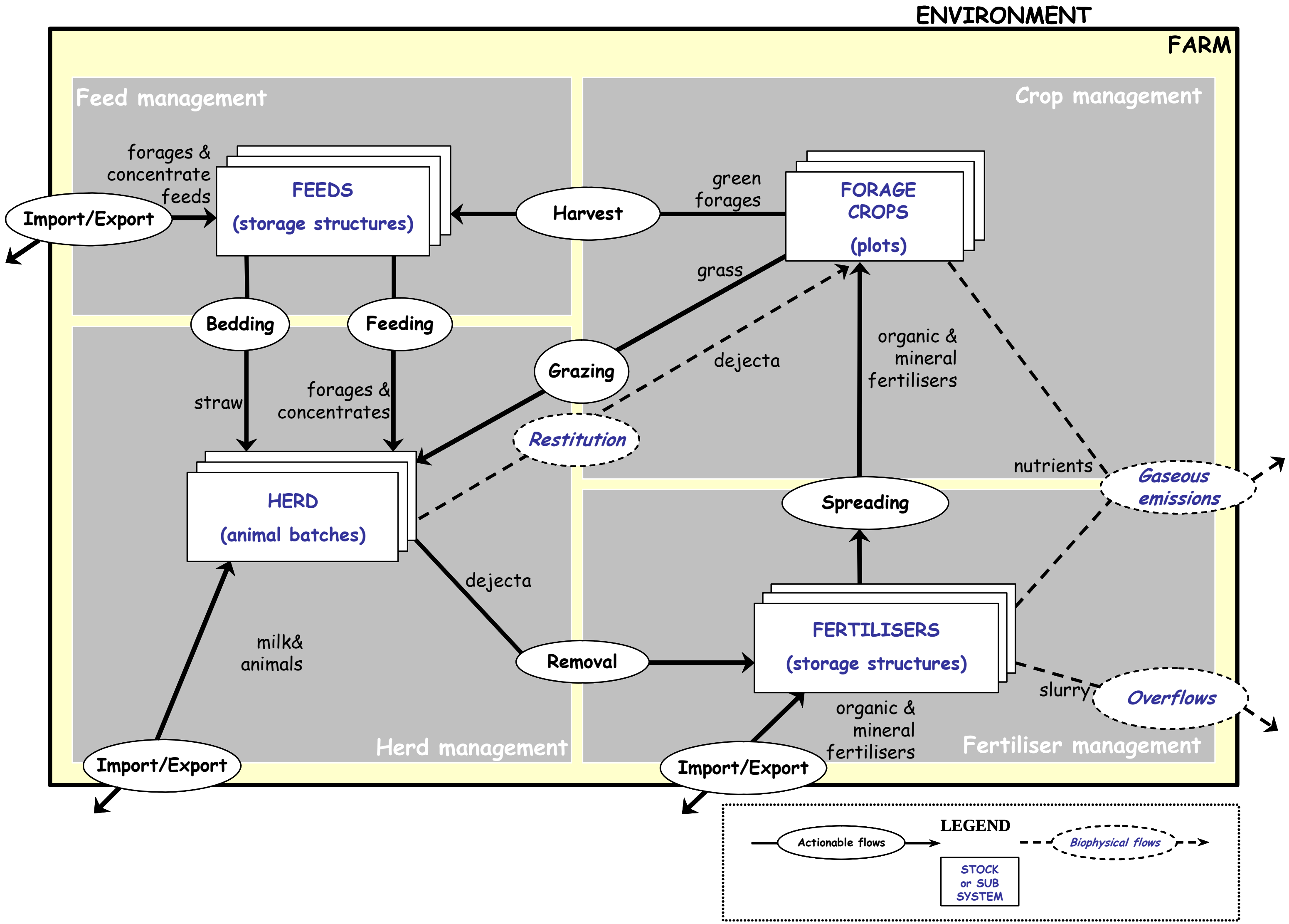

Figure 10. *Biomass stock-flow diagram illustrating the structure of GAMEDE made of four main subsystems among which circulate biomass flows.*

III.1.3 Model inputs and outputs

Simulations of GAMEDE are performed over temporal horizons of any length (possibly several years) using a time-step of one day. Over the whole simulation period, the farm's structure and the set of decision rules are assumed to be invariant with neither acquisition nor disposal of new durable assets (equipment, facilities, animals, land, etc.). As such, the model is a medium/short-term (1 to 3 years) and tactical/operational simulation tool. The spatial and material extension of the model is that of a dairy farm with (possibly many) forage crop plots and a herd of various sizes.

Model inputs

Five types of constant parameters have to be specified as input to GAMEDE: management (90 parameters), farm structure (15 ptrs.), herd (16 ptrs.), weather (9 ptrs.), and external resources (6 ptrs).

- The management parameters specify the strategy of the farmer: the action plan characteristics (e.g. composting or selling all the solid manure produced on the farm or composition of the feed ration, which depend on the season) and the technical decision rules (e.g. the quantity of concentrate distributed per cow, which depends on its lactating stage). Four management domains are distinguished according to the four interconnected subsystems: forage (harvest and fertilisation), feed stocks (concentrates and conserved forages), herd, and fertilisers (both mineral and organic).

- The structural parameters describe the number, size, and floristic composition of the forage plots, the initial herd size, the storage facilities for feeds, and manures available on the farm.

- The herd parameters are the reproduction parameters (e.g. the periods of calving) and the production parameters (e.g. the average milk protein content).

- A weather data file contains daily data at a particular location close to the simulated farm: rainfall, mean/max/min temperatures, evapotranspiration, and global solar radiation. The weather files for the four dairy farming areas of La Réunion are available with the model, and specific files may be created for other locations.

- The parameters accounting for external resources are the constraints or opportunities in the vicinity of the farm to buy or sell forages and organic fertilisers.

Model outputs

The aim of the model is to assess the sustainability of the simulated dairy farm according to technical, environmental, and social indicators.

The technical indicators concern both forage and animal productions as three synthetic indicators calculated on a yearly basis:

- silage productivity is the total number of round bales harvested on the total mowed field surfaces (in round bales ha^{-1} $year^{-1}$).

- forage crop productivity is the total energy harvested (in fodder unit for milk production: UF ha^{-1} $year^{-1}$) by ensiling, cut and carry, or directly grazed forages on the total utilised agricultural area (**UAA** in ha).

- milk productivity is the average amount of milk produced per cow (kgFM cow^{-1} $year^{-1}$)

The environmental indicators are currently limited to N dynamics aspect. N losses resulting from the slurry pit overflows and N gaseous emissions are computed on a daily basis and then summed over the whole year. Moreover, the model calculates annual N farm-gate balances. "Nin" is the sum of N in purchased biomasses: concentrate feeds, forages, and straw for bedding, animals, mineral fertilisers, and manure. "Nout" is the total amount of N in exported biomasses: milk, animals, and manure. The whole-farm N surplus is calculated as $\frac{\text{Nin-Nout}}{\text{UAA}}$ (in kgN ha^{-1}). The whole-farm N use efficiency is defined as the dimensionless ratio $\frac{\text{Nout}}{\text{Nin}}$. The N contents of the different types of biomass are dynamically calculated by the model. We are currently developing additional modules to evaluate the effects of management practices on the greenhouse gases emissions and the consumption of non-renewable energies, inspired by a life-cycle analysis approach.

The social indicators are the total and the repetitive work time. Both are expressed in hours per week to allow comparisons with the statutory working week. Repetitive work is substantial in dairy farming systems; it concerns daily mandatory tasks like milking, feeding, or slurry removal. Both these social indicators depend upon actual operation modalities (manually performed or mechanised) and the kind of biomass manipulated.

III.2 Integration of decisional and biophysical systems

III.2.1 Model architecture

Following Martin-Clouaire and Rellier (2000) we represent an agricultural production system as a DS, accounting for the farmer's objectives, decisions, and operations (either planned or reactive), coupled to a BS, accounting for purely biophysical processes. GAMEDE therefore explicitly represents the effects of operational decisions interacting with biophysical processes. Simulating human action at operations level is a novel feature of this model.

In GAMEDE, the technical actions are simulated by the DS based on the farmer's action plan and decision rules, the state of the production system, and the environmental conditions of the farm. The BS translates the technical actions into actionable flows and simulates the biophysical flows, both being influenced by the weather conditions. A synthesis translates the biomass in N flows and calculates the three types of sustainability indicators described above (cf. § III.1.3).

III.2.2 Model ontology

The variables in GAMEDE, either biophysical or decisional, may be grouped according to ten concepts constituting the model's ontology: four decisional concepts presented in § III.2.2.1, five biophysical concepts presented in § III.2.2.2, and an additional concept "action" defined in § III.2.2.1 The action concept is at the interface between the decisional and the biophysical systems.

III.2.2.1 Main decisional concepts

The four decisional concepts are practical season, management option, starting rule, characterisation rule (see their interrelationships in Fig. 11).

Practical season

A practical season is defined as a time period over which the farmer realises any kind of technical operation according to a specified mode (see the example of harvesting grasslands just below). It corresponds to the farmer's anticipation of seasonal variations of environmental conditions affecting mainly forage availability (for imported forages) and productivity (for on-farm-produced forages). Practical seasons may differ from one operation to another.

Management option

Discrete-valued parameters allow the user to specify management options. The values of these parameters may differ according to practical seasons. Some are binary, for example the choice of making compost (if 1) or not (if 0). Others are multi-valued, for example to specify the harvest mode of grasslands: no harvest (if 0), making silage (if 1), cut and carry (if 2), or grazing (if 3). These management options can be vectors relative to the plots (e.g. for harvest, fertilising operations) or the animal batches (e.g. for rationing, bedding operations).

Starting decision rules

The realisation of operations obeys two types of starting rules defining the operations schedule:

- the rhythms of operations advocated according to the current practical season (e.g. grassland harvest has to be performed every two months in summertime, animal rationing is done on a daily basis whatever the season);

- the sequencing of operations (e.g. slurry spreading is performed three days after harvest, slurry mixing is done the day before spreading).

Characterisation decision rules

This type of decision rules, which may also differ from one practical season to another, defines the descriptive variables of the technical operation realised:

- its modality and the corresponding speed of realisation (e.g. ration distribution is manual or mechanised using a feed mixer; the second modality is faster),

- the biomass quantity used, the store from which the biomass is taken and which store is replenished. These three biomass flow variables define the composition (i.e. the quantity of each feed types) of the anticipated ration of each animal batch.

Action

According to the modelling framework proposed by Guerrin (2005), actions related to the technical operations are represented by dynamic binary variables “action realisation” (**AR**). As the time step of the model is one day, 1 means that the action is done the current day, 0 that it is not. The precise time at which the action is performed within a day is thus not represented in GAMEDE in contrast with the MAGMA model (Guerrin, 2001). This choice was made for simplification purposes.

III.2.2.2 Biophysical concepts

The five biophysical concepts are flow and stock, biomass type, biomass composition, biophysical process, and category.

Flow and stock

Each stock accounting for each kind of biomass in the farm is the integration over time of the difference between (possibly many) inflows (e.g. manures collected in animal housing) and outflows (e.g. biomass used for manure spreading). These flows are generally piecewise continuous. As explained before we represent both actionable (i.e. man-driven) and biophysical (i.e. nature-driven) flows (cf. § III.1.2). All biomass flows are expressed as kg of the considered material expressed as fresh matter (**FM**).

Biomass composition

Other groups of variables describe for each biomass type both their dry matter (in kgDM $kgFM^{-1}$) and nitrogen (in kgN $kgFM^{-1}$) contents. More specific characteristics are also calculated by the model, for instance the nutritive value of feeds or the ammonia content of fertilisers.

Biophysical process

Some biophysical processes are represented as flows: grass growth, gaseous N emissions, production of milk or dejecta. Other biophysical evolutions are not represented as flows: the evolutions of the leaf area index, the weight of animals, the nutritive value of forages due to conditioning.

Category

In the Vensim® software, subscripted variables are used to denote vector variables. For example, the dry matter content of forages can be represented as only one vector variable: DMC_f (in kgDM $kgFM^{-1}$) where **f** is the "forage" subscript containing 21 elements corresponding to the various types of forages available (listed in appendix G). Subscripts thus differentiate between technical operations (19 elements), grasslands (20 elts.), sugar cane plots (10 elts.), animal cohorts (21 elts.), animal batches (6 elts.), fertilisers (11 elts.), concentrates (19 elts.), forages (21 elts.), and sub-stocks of round bales (20 elts.).

III.2.2.3 Main mathematical functions

A dairy farm is represented in GAMEDE by sets of ordinary differential equations (e.g. for representing stocks); queuing functions (e.g. for modelling the herd demography as successive cohorts); data tables (e.g. for describing food rations or animal batch composition); conditional sampling functions (e.g. for determining the nature of conserved forage); pulses (e.g. to account for the realization of actions); delay equations (e.g. to account for delays in action realization); If–Then–Else rules (for decision-making aspects as action modality choices); resource allocation functions (e.g. to allocate pastures to different animal batches according to priority ranking). A complete mathematical description of these functions, used in a model for manure management, is given in Guerrin (2001).

III.2.3 Decisional system

III.2.3.1 From strategy to management actions

The DS simulates the realisation of 19 technical operations in accordance with the production system's state (e.g. defining the feeding ration depends on the level of feed stocks). The concept of 'action model' (Duru *et al*., 1988) is a hierarchical structure that defines the DS of GAMEDE: "to each farmer's strategy corresponds a forecasted action plan (**AP**) as a schedule accounting for how the farmer hopes operations unfold, and to each stage of this plan corresponds a set of realisation and adjustment decision rules". Thus the management actions can have two origins: the AP or the realisation and adjustment decision rules (e.g. modifying the feeding ration according to the unavailability of some forage; delaying the date of harvest because of rain). In this version of GAMEDE, most simulated actions are planned and, as labour is assumed to be a non limiting resource, the competition between concurrent operations is not dealt with.

III.2.3.2 The action plan is a resource for action simulation

In the DS of GAMEDE, an AP is composed of management options, practical seasons, starting rules, and characterisation rules: realisation modalities, realisation speeds, and quantities manipulated per biomass type (concepts defined in § III.2.2.1). The action realisation simulated by the DS is completed by two additional variables: the flow the action generates and the action duration (see Fig. 11).

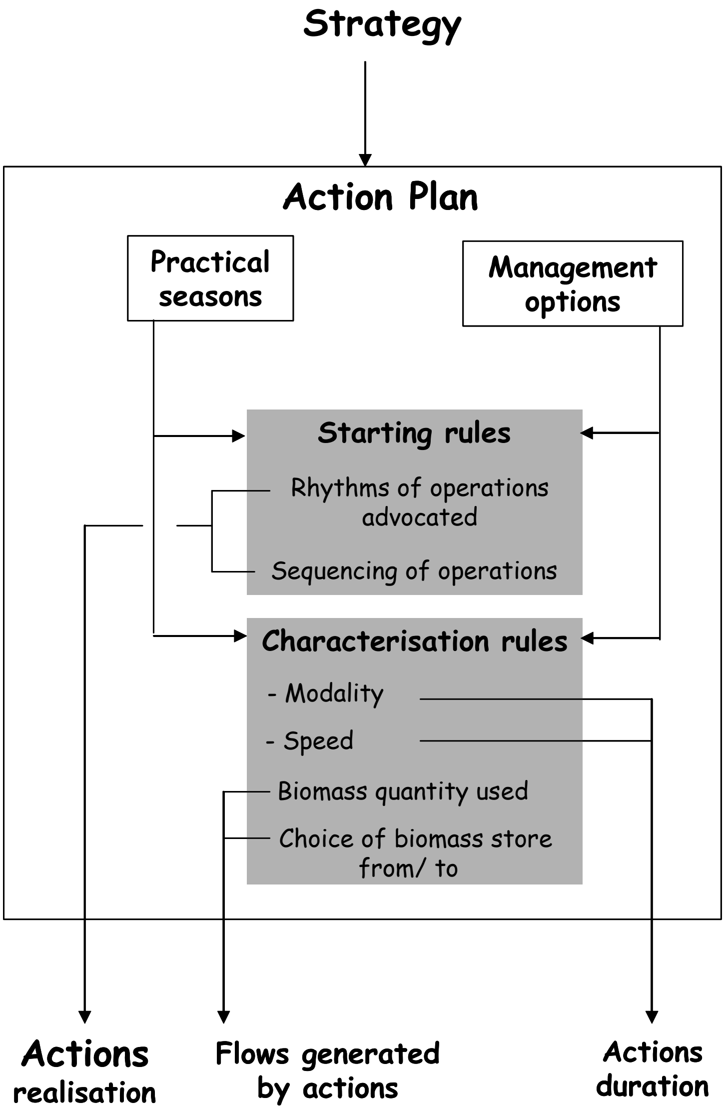

Figure 11. *Structure of the DS of GAMEDE.*

We take here the example of forage crop fertilising operations for farm 1 (one of the six farmers involved in the model construction). In this farmer's AP two practical seasons are defined: summer (PS_1) from 16 September to 15 May, and winter (PS_2) the rest of the year. To each season corresponds a management option: "slurry + 15-12-24 mineral fertiliser" (**MOP_1**) for summer and "slurry + 33-11-06 mineral fertiliser" (**MOP_2**) for winter.

Action realisation

Starting rules such as "slurry is spread two days after harvest" and "mineral fertiliser is spread five days after harvest" define the time interval between an event prior to action (e.g. here the end of harvest) and action realisation (**IEA_{fe}** in days) according to the fertiliser **fe**. Action realisation is calculated as follows:

$$\text{IF } TEA_{pl} \geq IEA_{pl,fe} \quad \text{THEN } AR_{pl,fe} = 1 \quad \text{ELSE } AR_{pl,fe} = 0 \qquad (01)$$

where **TEA_{pl}** (in days) is the time interval elapsed since the event prior to action, and **$AR_{pl,fe}$** is the dimensionless binary variable accounting for action realisation for each fertiliser fe and crop plot **pl**.

Flow generated by action

The quantity of fertiliser **fe** to be spread **Q_{fe}** (kgFM ha^{-1} day^{-1}) varies according to the management option, for example between a summer management option (MOP_1) and a winter management option (MOP_2). The resulting spreading flow is generated as follows:

$$\text{IF } MOP = MOP_1 \quad \text{THEN } Q_{fe} = Q_{1,fe} \quad \text{ELSE } Q_{fe} = Q_{2,fe} \qquad (02)$$

$$AF_{pl,fe} = AR_{pl,fe} * Q_{fe} * S_{pl} \qquad (03)$$

where **$AF_{pl,fe}$** (kgFM day^{-1}) is the flow the action generates for each plot pl and each fertiliser fe, **S_{pl}** (ha) is the surface of the plot, and AR_{pl} is the "action realisation" variable defined in Eq. 1.

Action duration

In the case of forage crops the modalities of fertiliser spreading do not depend upon the season but differ according to the farm and the fertiliser type fe. The speed of action realisation (**SPE_{fe}**) corresponding to the modality is expressed in kgFM hr^{-1}. Thus the action daily duration (**AD_{pl}** in hrs day^{-1}) is calculated as follows:

$$AD_{pl,fe} = AF_{pl,fe} / SPE_{fe} \qquad (04)$$

where the spreading flow $AF_{pl,fe}$ is defined in Eq. 3.

III.3 Integration of various soil, crop, and animal processes in the biophysical system

The BS in GAMEDE is composed of six modules based, when possible, on biophysical models in the literature (see Tab. 2).

Tableau 2. The six biophysical modules of GAMEDE based on models of the literature

Acronym	Biophysical domain	Main inspiring models	Main references used to build the module
MPF	Grassland and sugar cane forages production	MCP MOSICAS	Leteinturier *et al*., 2004; Martiné, 2003
MCF	Forage composition evolution during conditioning	-	Paillat, 1995
MD	Herd demography	GEDEMO	Coquil *et al*., 2005
MPA	Milk and dejecta productions, animal body weight variation	INRAtion CNCPS	Faverdin *et al*., 2007 Fox *et al*., 2004
MP	Animal intake during grazing	SEPATOU GRAZEIN	Cros *et al*., 2003 Delagarde *et al*., 2004
MEA	Fertilisers composition evolution and N emissions during handling	-	Dollé *et al*., 2000, Paillat *et al*., 2005, Morvan and Leterme, 2001, Whitehead, 1995

The biophysical modules of GAMEDE have been designed to interact with the DS. The relationships among the various modules and their control by the DS are shown in Fig. 12. These relations are gradually illustrated in this section.

The six biophysical modules are described with mathematical equations in three technical reports (Vayssières, 2005, 2006, and 2007). A brief description of the different modules is provided in the following paragraphs. As this paper's goal is to show the integration of different sub-models in a coherent whole, we give the same importance to describing the modules encompassing equations from the literature (MPF, MD, MPA, and MP) and original modules developed by ourselves (MCF and MEA). This description is organized to fit with the cycle of the biomass within the farm: soil → plants → forage stocks → herd →fertilisers stocks → soil.

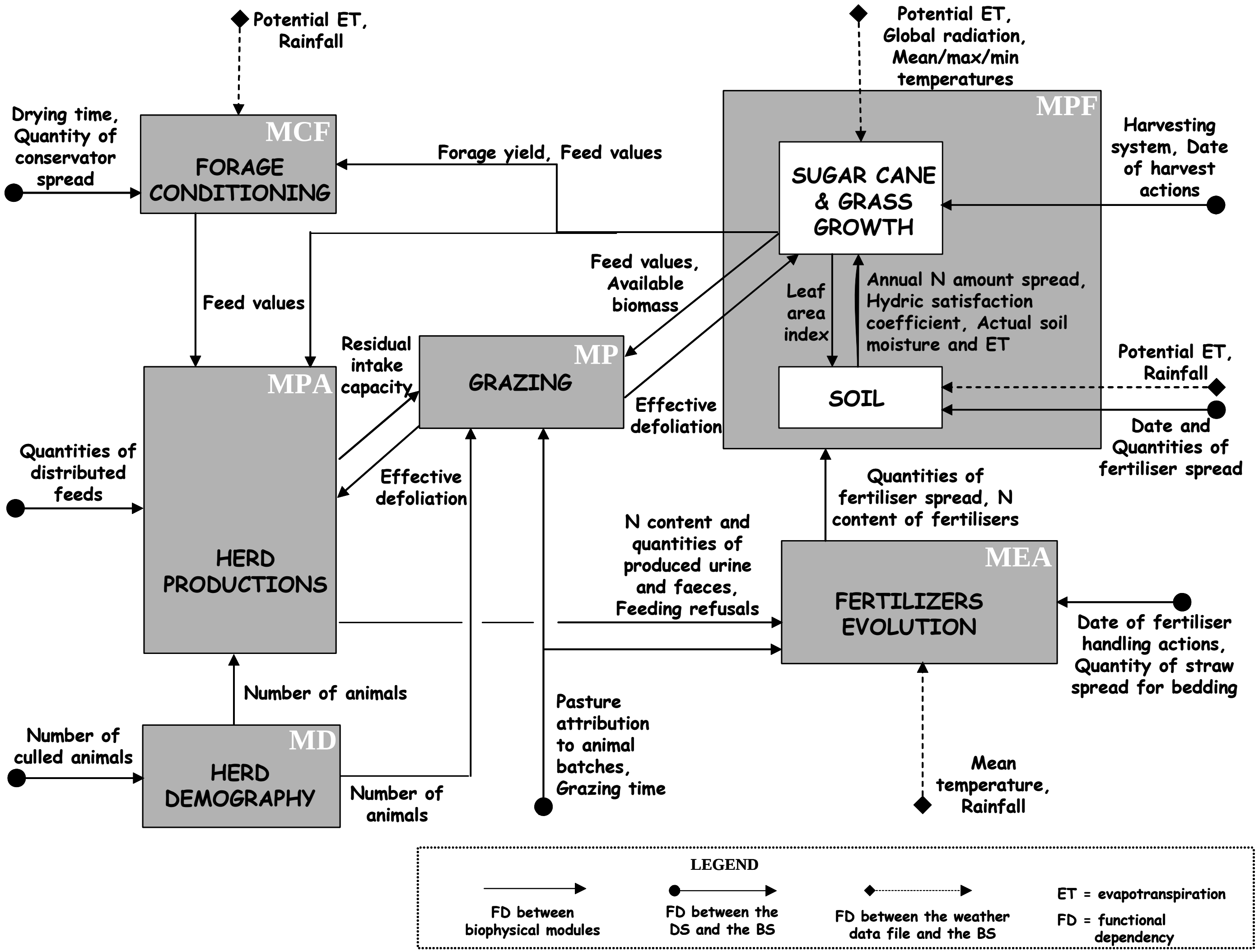

Figure 12. *Functional dependencies between the six different modules of the BS and their control by the DS in GAMEDE.*

III.3.1 The module of green forage production (MPF)

The MPF module describes the forage production according to harvesting and fertilising actions (defined by the DS) and climatic conditions including, among others, the soil water balance and the water stress effects on the phenological and crop growth processes.

III.3.1.1 The soil water balance sub-module

As in the first version of the MOSICAS model (Martiné, 2003), the hydrological model adapted in GAMEDE is a simplified three-layer model where soil surface evaporation and plant transpiration are not differentiated.

Net water content of soil layers

This sub-module considers three soil layers i (i =1, 2, 3) with differing depth (**h_i** in m) and field capacity (**FC**$_i$ in mm m^{-1}): i) the interception layer corresponds to the mulch interfacing the air and the soil, ii) the rooting layer, iii) the buffer layer corresponding to the remaining soil depth beyond the root layer.

In each layer the water mass-balance is calculated according to the soil and forage species characteristics. The amount of water available from rainfall (**Rf** in mm day^{-1}) is allocated everyday to the three soil layers, starting from the surface layer. The layers, in sequence, are charged up to their water retention capacity (**$Wcap_i$** in mm). Water in excess $Wcap_i$ of soil layer i percolates (**P_i** in mm day^{-1}) to the next layer. The process is continued until the third soil layer, where the remaining amount of water is assumed to feed the drainage flow (**D** in mm day^{-1}**)**. The rate of change in the soil water content for the second layer (**dW_2** in mm day^{-1}) is calculated as follows:

$$dW_2 = P_1 + U_3 - ETR_2 - P_2 \qquad (05)$$

where **U_3** (mm day-1) is the upward water flux from the third to the second layer calculated as the difference between the current soil moisture (**Th_i**) of the two layers. Th_i is the dimensionless ratio of the current soil water content (**W_i** in mm) and its water retention capacity $Wcap_i = FC_i \times h_i$.

Actual evapotranspiration

The actual evapotranspiration (**ETR**) is a function of the potential evapotranspiration (**ETP** in mm day^{-1}) limited by the soil water content W_i of the first two layers. It is determined as follows:

$$ETR = ETR_1 + ETR_2 \qquad (06)$$

$$ETR_1 = MIN(ETP, W_1) \qquad (07)$$

$$ETR_2 = Kc * Keag * (ETP - ETR_1) \qquad (08)$$

where ETR_1 is assumed to be the evaporation of W_1, ETR_2 is a positive function of the residual ETP (the 3rd layer is considered not to be concerned by ETR), and the cultural coefficient (**Kc**, dmnl) represents the crop capacity to pump water from the soil. It is a function of the leaf area index

(**LAI** in m^2 of limb m^{-2} of soil) calculated by the sugar cane and grass sub-modules. The Eagleman coefficient (**Keag**, dmnl) represents a curvilinear reduction of ETR due to the decrease in soil moisture Th (Eagleman, 1971).

Output to the crop growth calculation sub-modules

ETR, Th, and the hydric satisfaction coefficient (**Sh**, dmnl) are calculated to determine the plant hydric stress. Sh is determined by the equation of Slabbers (1980) as in the STICS model (Brisson *et al*., 1998).

III.3.1.2 The sugar cane and grass growth sub-modules

The plant growth sub-modules are organised around i) radiation interception and its utilisation by the Leaf Area Index of the plant, ii) conversion of this energy into biomass and, for sugar cane only, biomass partitioning between the different plant components: roots, leafs, and stalk.

Cultivated species characteristics

In the sugar cane growth sub-module, differentiation according to the cane cultivar is not considered. The grass growth sub-module simulates green forage production of the three grassland types in La Réunion:

- Two pure C4 tropical grassland types: chloris (*Chloris gayana*) encountered below 800 m of altitude; and kikuyu (*Pennisetum clandestinum*) encountered above this limit;
- A third, mixed grassland type, is encountered above the 800 m limit; it is mainly composed of C3 temperate species like cockfoot (*Dactylic glomerata*), raygrass (*Lolium multiflorum* and *Lolium hybridum*), and brome (*Bromus catharticus*). The kikuyu tropical *gramineae* is the minority and grows only during the summer above 1000 m.

Phenology and Plant development

In the major crop models, degree-days (i.e. the sum of the daily temperatures above a certain threshold) are used to represent the dynamics of plant development, such as for cane growth modelling. For grass growth modelling, a time scale has been specially defined (Leteinturier *et al*., 2004): the biological time calculated by integrating the ratio between the temperature stress index (**IT**) and the water stress index (**Iw**) (see definitions below). These thermal and biological times are used to define the phenological stages of sugar cane and grass.

Leaf area index and plant maturity

For the two crops (sugar cane and grass), modelling the leaf area index (LAI) dynamics is global, i.e. it does not differentiate development of aerial organ (leafs and stalks). Concerning sugar cane, the LAI is the difference between the daily leaf area production and the daily leaf area senescence. Concerning grass, leaf area production and senescence are not explicitly represented. In both cases different phenological stages are differentiated in the plant development. Four stages are distinguished over the plant cycle:

- emergence, where the LAI increases exponentially with the plant maturity (with strong control of temperature over the area formation);
- maximum development stage, where the LAI reaches its maximum and remains constant;
- the beginning senescence stage, where the LAI decreases linearly due to senescence;
- the equilibrium phase where the LAI stays very low.

Radiation interception

For both crops, the corrected photosynthetically active radiation (**PARc** in MJ ha^{-1} day^{-1}) is a function of the global solar radiation (**RG** in MJ ha^{-1} day^{-1}) and the LAI taking into account two-step radiation losses: reflection and extinction. A specific loss coefficient ($0 < k < 1$) is defined per step. The extinction loss coefficient is a function of the LAI.

Biomass production

The total (for sugar cane) or aerial (for grass) daily growth rate of the crop (**dB** in kgDM day^{-1}) is calculated as a function of the crop plot surface (S), the radiation conversion efficiency (**RCE**, dmnl), the PARc, and a crop specific coefficient, the maximum conversion rate (**MConv**, kgDM MJ^{-1}) as follows:

$$dB = MConv * RCE * PARc * S \qquad (09)$$

The RCE synthesises the effects of numerous abiotic stresses expressed by dimensionless indexes:

$$RCE = Iw * fT * IT * In \qquad (10)$$

where Iw is the water stress index, **fT** is the photosynthesis efficiency factor depending on temperatures, IT is the temperature stress index, and **In** is the nitrogen stress index

Water stress

Iw for sugar cane is calculated as the ratio of Th and Sh (both calculated by the soil sub-module, cf. § III.3.1.1). Considering grass, the water stress index Iw is an exponential function of the ratio $\frac{ETR}{ETP}$. In both cases the water stresses have a double effect:

- a positive effect on maturation. The water deficit decreases transpiration, raising the canopy temperature and consequently accelerating the rate of crop development (Idso *et al*., 1980).
- a negative effect on the growth speed (Eqs. 9 and 10): it reduces the radiation use efficiency. In the case of the sugar cane sub-module, water stresses also accelerate senescence and then can stop growth.

Effects of temperature on photosynthesis efficiency and plant development

Two plant-specific threshold temperatures are defined (see appendix C):

- **Tbase** (in °C) is the temperature below which the plant growth is stopped. This parameter is used to calculate the thermal time (for sugar cane development) and the photosynthesis efficiency fT (for grass). The periods when average temperature goes below this threshold, depending upon their duration, affect the biomass production. The calculation of fT is based on the average temperature of the last ten days to take account of plant response inertia.

- **Topt** (in°C) is the temperature above which the radiation conversion efficiency is optimum. This parameter is used to calculate the temperature stress index IT. IT is used to represent the negative influence of low temperatures on biomass production and plant development.

N fertilisation effect on growth

In more complex plant models like INFOCROP (Aggarwal *et al.*, 2006), the N stress calculation is based on the potential and actual levels of N in different plant parts. In GAMEDE this is not the case; N uptake and distribution are not represented. The N effect is synthesised in the In index. Empirical relations between the annual N fertilisation level (**AN** in kgN ha^{-1} $year^{-1}$) and the growth rate dW of the plant have been established from local long-term experiments on sugar cane (Chabalier *et al.*, 2006) and grasslands (Lecomte, unpublished) in diverse pedo-climatic areas of the island. In GAMEDE the annual N amount spread over a considered plot (AN) is the sum of the total N applied the last 366 days affected by an N efficiency coefficient (**Kn**, dmnl), taking into account the availability of the applied N for crop development as follows:

$$AN_{pl} = \sum_{fe=1}^{fe=11} (QSP_{pl,fe} * NC_{fe} * Kn_{fe}) / S_{pl} \qquad (11)$$

where $\mathbf{QSP}_{pl,fe}$ is the quantity of fertiliser fe spread on the plot pl, and $\mathbf{NC}_{fe}$ is the N content of the fertiliser fe. Please refer to appendix D to have the Kn and NC values of the 11 fertilisers considered in the model.

Biomass partitioning

For sugar cane growth, a constant part of the biomass production (= 0.1) is directly allocated to root renewal (Martiné, 2003). The rest (= 0.9) is allocated between the under-mulch bud biomass and the aerial biomass (leafs and stalk). The allocation rate of the non-root biomass production to aerial biomass production is an increasing function of the aerial biomass. Concerning grass, the aerial biomass production is directly determined, and thus the partitioning of the biomass is not represented.

Green forage feeding value

Green forage feeding value is an important output of the MPF used by the MCF (forage composition evolution) and the MPA (animal production) modules (Fig. 12).

Feeding values are defined according to the UF/PDI feeding value system (Jarrige, 1989). The energy value of feeds is expressed in **UF** kgDM^{-1}. Protein truly digestible in the small intestine (PDI) has two origins: dietary (**PDIA)** and microbial (**PDIN** and **PDIE)**. The last two are synthesised in the rumen respectively from degraded dietary N and dietary energy. For estimating N excretions from the animals (in the MPA module) we refer to the total protein (**MAT**) and digestible crude protein (**MAD**) feed value units (where 1gN = 6.25 MAT). A fill unit (**FU**) is used to predict animal intake.

In the current version of GAMEDE, feeding value variables for sugar cane are determined by empirical linear functions of plant maturity derived from the feeding tables of Aumont *et al.* (1991). Regarding green grass feeding values, more complex empirical regressions have been established using the data from the long-term fertilisation experiments cited above (Lecomte, unpublished). These values are functions of grass maturity, field biomass and season.

III.3.2 The forage conditioning module (MCF)

The MCF module dynamically simulates the quantity and quality of wrapped bale silage. Quality is determined mainly by weather conditions during forage drying, the forage yield, and the nature of the raw grass (the last two being determined by the MPF module) along with the quantity of conservator spread over the grass swaths, as defined by the DS.

Forage drying

Forage drying models are often based on evapotranspiration ETP (Thompson, 1981; McGechan, 1990). We have chosen an “empirical ETP class model” based on ETP and rainfall (Rf). Farmers define six weather classes (from heavy rain to persisting sunny weather) that are linked to ETP classes. From local experimental data (Paillat, 1995), a relation was defined between these ETP classes and the drying intensities (**DI** in kgDM kgFM^{-1} hr^{-1}). Moreover the DS (denoting the farmer) reacts differently to these weather classes by adapting the drying time (**DT**: 0.5 to 6 hrs). The gain of dry mater content (**GDMC** in kgDM kgFM^{-1}) is given as the product of these variables corrected by an empirical forage yield index (**Ir**, dmnl) as follows:

$$GDMC = DT * DI * Ir \qquad (12)$$

where Ir is a linear function of the forage yield (**FY** in kgDM ha^{-1}): the more biomass is available on the field, the less drying is efficient (Paillat, 1995).

Quality of conservation

From experiments by Barbet-Massin *et al*. (2004) we have defined a four-class abacus (given in appendix E) in which the silage quality is a function of the DMC of the dried forage and the quantity of conservator spread (**QCons** in kgFM round bale^{-1}).

Silage feeding value and refusals

The quality of conservation of the silage influences the intake, the protein value, and the proportion of forage refusals. Badly conserved, silage is largely refused by the animals. The energy (UF) and total protein (MAT) values of the silage forage remain the same as in the fresh forage (Andrieu and Demarquilly, 1987). However, poorly conserved silages are characterised by a higher proportion of rapidly degradable N that leads to an increased MAD value and a higher imbalance between PDIN and PDIE values. It leads to more N excretions and favours N urinary way (MPA module). The correction factors of FU, MAD, PDIN, and PDIE feeding values used in GAMEDE are based on the equations given by Andrieu and Demarquilly (1987) adapted according to Paillat (1995).

III.3.3 The herd demography module (MD)

The MD module dynamically simulates the herd composition and animal culling according the reproduction/mortality parameters of the herd and the farmer's culling/replacement actions (defined by the DS). The herd demography is a key element to estimate the variation in forage and feed consumption and in production of milk and manure (simulated by the MPA module).

Animal cohorts

The initial herd size must be set at the start of a simulation. Conceptually, the herd is composed of 21 cohorts: 1 cohort for calves, 11 for heifers, 6 for lactating cows, and 3 for dry cows. Animals pass through the various cohorts depending on their age and physiological stages.

Calving

The herd is composed only of females. The number of female calves kept to breed calving heifers for recruitment is based on the average herd mortality in order to respect the herd growth rate and the cow culling rate (**CCR**, dmnl), two objectives that are defined by the farmer.

Cohort transitions

Transitions are governed by a queuing function of the transit time (**TT** in days) of the corresponding cohort. TT is the number of days the animal stays within a cohort before moving to the next cohort. TTs of the different cohorts are given in appendix F. In GEDEMO (Coquil *et al*., 2005), all TTs are constant and the duration of lactation is standardised (9 months): a cow is assumed to calve one time per year. In GAMEDE the TT of the cows ending their lactation is variable and calculated depending on the average calving interval (**ICC** in day).

Animal export

Two animal types are exported: i) mortality, including culling for accidental causes, is determined by rates fixed for each animal cohort; ii) voluntary culling concerns only male calves and dry cows. All male calves are sold at birth and cow culling is determined by the cow culling rate (CRR).

III.3.4 The herd productions module (MPA)

The MPA module simulates the weight variations and the milk and dejecta productions of animals according to the feeding rations defined by the DS and the animal intake during grazing (MP module). As in the DM, animals are grouped in the same 21 cohorts. Thus the calculation of variables relative to the animals (weight, milk, dejecta, etc.) refers, for each cohort, to an average animal. Calves and heifers are only concerned by growth. Conversely, cows are mainly concerned by milk production (except during drying), which controls their weight variations. For all cohorts, the calculation of both milk production and weight variation is based on the UF/PDI feeding unit system (§ III.3.1.2) and the principles defined by Jarrige (1989).

Feed characteristics

In GAMEDE, 21 forage and 19 concentrate types are distinguished; all are characterised by their feeding values (see appendix G and H). Most of the forages are produced on farm. In this case, their feeding values are dynamically determined by the MPF and the MCF modules of GAMEDE. The feeding values of the imported feeds are constant and given by feed tables (Aumont *et al.*, 1991; Hassoun and Latchimy, 2001) or by the local food industries for concentrates.

Intake capacity and refusals

Intake capacity (**IC** in FU Al^{-1}) limits the ingested quantity (**QI** in kgDM Al^{-1} d^{-1}). The basic hypothesis is that offered concentrates are totally ingested. The remaining ingestion capacity affects ingestion only if forage is distributed indoor *ad libitum* and/or pasture is offered (see the MP module). The IC of calves and heifers is a function of their live weight (Troccon, 1987); while the IC of dairy cows is a function of both their live weight and potential production (Faverdin *et al.*, 1987).

Milk production

Milk production allowed by the ration (**MPAR** in kgFM Al^{-1} Day^{-1}) and potential milk production (**PMP** in kgFM Al^{-1} Day^{-1}) determine the effective milk production (**EMP** in kgFM Al^{-1} Day^{-1}), taking into account the animal capacity to mobilise its own body reserves. According to Wood (1967), the PMP is a function of the lactation day number. Two curves are differentiated, depending on the cow parity (Faverdin *et al.*, 2007). The MPAR is the minimum between i) the milk allowed by the available energy (**MPAE** in kgFM Al^{-1} Day^{-1}), calculated from the UF values of the ingested concentrates (**c**) and forage (f), and ii) the milk allowed by the proteins, calculated from the PDI values. In both cases (energy and proteins) the milk allowed is the difference between the supply and the requirements for maintenance, growth, and moving (Jarrige, 1989; Hassoun and Latchimy, 2001).

In GAMEDE the calculation of energy supply via the **CorUF** variable (in UF Al^{-1} day^{-1}) takes into account the depressive effects of concentrate-forage interactions in the rumen (Vermorel *et al.*, 1987). When MPAR is higher than PMP, the EMP is equal to the PMP, and the cow can gain body score (often the case in ending lactation and drying phases). Otherwise, the EMP is the sum of MPAR and the milk production allowed by the loss of body reserves (**MPAB**, in kgFM Al^{-1} Day^{-1}). The latter case is often encountered in early lactation because the feeding requirements increase more rapidly than the feed intake capacity.

Animal weight variation

The capacity of cows to mobilise their body reserves, resulting in a weight loss, is represented in GAMEDE as a positive sigmoid function of the body score. Body score is a continuous 0-5 scale that represents the body reserves status of the cows.

Daily live-weight gains (**LWG** in kgFM Al^{-1} day^{-1}) of calves or heifers are function of energy supply and current live-weight (**LW** in kgFM Al^{-1}) (Troccon, 1987).

Nitrogen excretions and dejecta production

Empirical (Castillo, 1999) or mechanistic (Fox *et al.*, 2004) calculation methods exist to predict N excretions. In GAMEDE, we chose an intermediate method used in the INRAtion model (INRA, 2003). In this model, the total excreted N is the difference between the total ingested N and the total fixed N for milk and meat productions and gestation. Two ways of excretion are distinguished. The faeces part is the indigestible part of the total uptake N. The rest of the total N excreted constitutes the urine part. Consequently, N urine excretion depends strongly on the N:energy equilibrium in the ration, in contrast with the N faeces excretion as described in (Broderick, 2003).

The diet plays a key role in dejecta production (Whitehead, 1995). Fox *et al.* (2004) proposed the empirical models used in GAMEDE. Urine production (**UP** in kgFM Al^{-1} day^{-1}) is a function of total dry matter and N intakes and the effective milk production (EMP). Calculation of faeces production (**FP** in KgFM A^{-1} day^{-1}) is similar, but total N intake is replaced by total energy intake (in UF Al^{-1} day^{-1}) in the formula.

III.3.5 The grazing module (MP)

The MP module simulates the daily defoliation generated by the herd on the forage biomass, depending on the attribution (by the DS) over time of the different plots to the different animal batches. In GAMEDE, several plots can be grazed independently and simultaneously by different batches. The actual defoliation is limited both by the animals' intake capacity, the biomass available on the plots, and the grazing time.

Remaining intake capacity of animals

As in the SEPATOU model (Cros *et al*., 2003), grazing is considered as the least priority intake for animals. The remaining intake capacity available for grazing (**RIC** in FU AI^{-1} day^{-1}) is the difference between the intake capacity (IC) and the fill of indoor-ingested feeds (concentrates and conserved forages). The RIC multiplied by the number of grazing animals is translated into the potential defoliation (**PD** in kgDM day^{-1}) (= potential intake by the animals) according to the fill value of green grass (in FU $kgDM^{-1}$).

Biomass available

Grass growth is simulated by the MPF module. Delagarde *et al*. (2001) propose a 2-cm height limit below which the grass is not available for cattle. This corresponds to a residual biomass (**RB**) of 800 kgDM ha^{-1} (Cros *et al*., 2003). An abundance indicator of offered grass, the **AOG** (in kgDM LU^{-1}) is calculated as the ratio between the available biomass (**AB** in kgDM) and the livestock unit number (**NbLU** in LU) grazing the considered plot.

Corrected potential defoliation

As proposed by Cros *et al*. (2003), the potential defoliation (PD) is corrected as **PDc** (in kgDM day^{-1}) according to the grazing time (**Tg** in hrs day^{-1}) and offered grass (AOG) as follows:

IF AOG > 20

THEN PDc = CorTg * PD (13)

ELSE PDc = CorTg * [PD – 0.3 * (20-AOG)]

The SEPATOU model considers only two management options (diurnal: 12 hrs day^{-1}, or all-day grazing: 24 hrs day^{-1}). Because management options are more diverse in practice, we used the corrected factor (**CorTg**, dmnl) defined by Delagarde *et al*. (2004) that considers four Tg classes: 0-5, 5-8, 8-20, 20-24 hrs day^{-1}. The effective defoliation (**ED** in kgDM day^{-1}) is the minimum between the corrected potential defoliation (PDc) and the available biomass (AB).

III.3.6 The module of fertiliser evolution (MEA)

The MEA module simulates the evolution of organic fertilisers during handling (evacuation from barns, conditioning, and spreading to crops) and storage controlled by the DS. This module also calculates the N gaseous emissions, which occur mainly during organic fertiliser handling. Imported fertilisers, mainly mineral, are concerned only by N emissions after spreading.

Mixed handling systems

Four possible effluent handling systems (**EHS**) are distinguished: i) direct restitution during grazing, ii) liquid manure, iii) raw solid manure, and iv) composted solid manure. All these EHS are used in the same farm in practice because farmers differently manage the effluents of animal batches; moreover, the same batch may daily contribute to different EHS. The total dejecta production of each animal batch (determined by the MPA module) is shared between all the possible EHS in proportion of the grazing time (Tg, also used by the MP module) and according to bedding practices (defined by the DS for each batch).

Each EHS is conceptually a *succession of handling steps* represented as a *chain of flows and stocks* of variable length: the shorter chain corresponds to restitutions during grazing, and the longer to producing composted solid manure. Whatever the EHS, the first flow of the chain is raw effluent production and the last one spreading on crops. To each fertiliser handling flow corresponds an N emission flow (Fig. 13).

Various composting practices exist and can significantly influence N emissions (Parkinson *et al*., 2004). GAMEDE simulates a technique tested in La Réunion by Lepetit and Paillat (2005) and based on two 15-day periods spaced by one turning. Non-N losses during composting (corresponding to water and carbon losses) are also simulated by the MEA.

Effluent production

The *type of raw effluent* produced indoor is determined by the quantity of bedding material spread indoor and mixed each day with urine and faeces. In GAMEDE, bedding materials are forage refusals and sugar cane straw. The quantities spread in the barn (defined by the DS) are converted into cane straw equivalents and corrected by the duration the animals are kept indoor to determine the corrected quantity of straw spread for bedding (**QSc** in kgFM LU^{-1} day^{-1}). This variable determines the raw effluent produced indoor. Four types of manure are differentiated: slurry (if $0 \leq QSc \leq 1$), soft solid manure (if $1 < QSc \leq 3$), strawy solid manure (if $3 < QSc \leq 6$) and very strawy solid manure (if $QSc > 6$). The quantity of raw effluents produced (**Qpe** in kgFM day^{-1}) is the sum of urine, faeces, and bedding materials. Outdoor dejecta are not mixed, and thus urine and faeces are considered on their own.

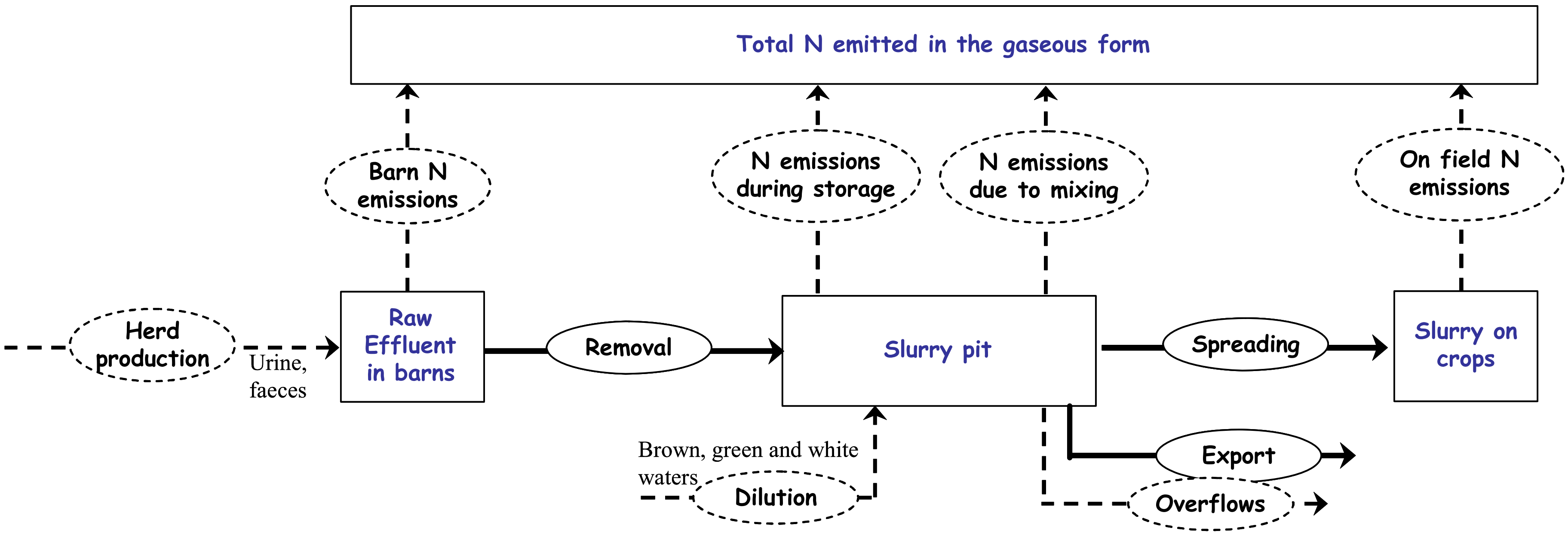

Figure 13. *Formalisation of the "liquid manure" effluent handling system (EHS) in* GAMEDE *(same legend as Fig. 10).*

Effluent composition

The nitrogen content (NC) of raw effluents is calculated as the total N introduced by its three constituents (urine, faeces, and bedding materials) divided by the total mass of raw effluent. The ammonia and dry matter contents are calculated the same way. In the case of solid manure, mixing dejecta with bedding material induces warming and water evaporation. The effluent drying intensity depends on the quantity of bedding straw (QSc).

Along the handling chain, the N and DM contents of the effluents are daily updated according to the feeding and bedding actions (varying from one day to the next) performed by the DS. These updates take into account the nature and the level of the stock the day before, and the nature and the quantity of the produced and used effluents, N emissions and, possibly, the dilution of effluent at the current day. Dilution concerns only liquid manure; it occurs through the collection of rain by the roofs and the farmyard (brown water) as well as washing the milking machine (green water) and the milk tank (white water). Brown water production can vary widely depending on the rainfall and the collecting surfaces, while green and white water production is constant and determined by the milking parlour type.

Gaseous emissions

Three N gaseous emissions are considered: ammonia (NH_3 an acidifying gas), nitrous oxide (N_2O a greenhouse gas), and N_2 (a main component of the atmosphere). The literature provides no general model to predict N emissions dynamically; it proposes instead emission factors (**EF**, dmnl), i.e. the part of total N globally emitted during the entire handling step considered. In GAMEDE, we assume that emissions occur on the day manure is handled. This simplification is acceptable because N_2O and N_2 emissions are usually low, and NH_3 volatilisation occurs mainly during a few hours after handling, for example when spreading (Génermont *et al.*, 2003) or composting (Paillat *et al.*, 2005; Abd El Kader *et al.*, 2007).

Emissions (**E** in kgN day^{-1}) of each handling step **st** are calculated as follows:

$$E_{st} = \sum_{fe=1}^{11} [HF_{fe,st} * NC_{fe,st} * (Ith_{fe} * Irf_{fe} * EF\_NH3_{fe,st} + EF\_N2O_{fe,st} + EF\_N2_{fe,st})] \quad (14)$$

where **HF** is the handled flow (in kgFM day^{-1}) and **EF_NH3, EF_N2O, EF_N2** are the emission factors (listed in appendix I). As the EF in the literature are measured in temperate climates, **Ith** (dmnl) and **Irf** (dmnl) are respectively thermal and rainfall correction indices of NH_3 volatilisation necessary for taking into account the climate variability and tropical conditions in La Réunion. As N_2O and N_2 emissions are far less sensitive to climatic variations, no correction is required.

The calculation of Ith depends on the fertiliser type. For urine, faeces, slurry, soft solid manure, and mineral fertilisers (whatever the handling step) a linear increasing function of daily average temperature was established from measures by Amon *et al*. (1998) and Génermont and Cellier

(1997). For strawy and very strawy solid manures (whatever the handling step, composting included) a second similar function was defined based on the observations of Amon *et al*. (1998), Denmead *et al*. (1982), and Parkinson *et al*. (2004).

There is a lack of references describing the effect of rainfall on N emissions. For this study, we defined Irf as a linear decreasing function of daily rainfall on the basis of the ammonia emissions simulated by the mechanistic model of Génermont and Cellier (1997). In a second step, this function was satisfactorily validated on the data observed by Misselbrook *et al*. (2004) for solid manure and by Moal *et al*. (1995), Pain and Misselbrook (1997), and Misselbrook *et al*. (2005) for liquid manure. This function is valid for outdoor storage and spreading of organic and mineral fertilisers. Wind can also significantly influence NH_3 volatilisation but it is not considered in the MEA module, as the data are rarely available.

III.4 Model evaluation

Partial biophysical models from the literature have been widely validated in different contexts. But it was not certain that integrating them into a single model and coupling them with a DS would lead to a reliable simulator. This section discusses briefly how the farm model was validated and how the realism of simulations can be improved.

III.4.1 Quantitative validation of the model

Classically, validation of biophysical models involves experiments checking the model behaviour against actual measurements (Rykiel, 1996). In our study case, six “actual” farming systems were simulated to evaluate GAMEDE. These six typical farms, extensively described in the companion article, were selected to cover our intended application domain according to

- the diversity of decision profiles and management practices in reference to a typology of practice combinations,

- the pedo-climatic characteristics of the areas where dairy farms are encountered in La Réunion with reference to an expertise-based zoning.

The six farms were surveyed on a bimonthly basis during three years (2004-2006), offering data to be compared with the model outputs. As usual, the data used for validation were independent of those used for calibrating the biophysical modules. The model was quantitatively validated by comparing simulated and observed sustainability indicators (described below in § III.4.1.1) at the year-scale and dynamical evolutions of some biomass flows (cf. § III.4.1.2).

III.4.1.1 Validation of GAMEDE according to sustainability indicators

The results in Tab. 3 show that GAMEDE is able to simulate the inter-farm variability of the sustainability indicators (defined in § III.1.3): silage productivity, milk productivity, N efficiency, N surplus, total and repetitive work times. For example the observed N efficiency varied from 0.15 to

0.44 (dmnl) in the farms. N surpluses in these farms also showed a large variation: 270-970 kgN ha^{-1}. These variations are well represented by the model.

Tableau 3. *Variation domains and root mean squared errors (RMSE) of six sustainability indicators calculated by GAMEDE (farm 1 to 6, 2004)*

Indicator	unit	Variation		Mean of observations (n = 6)	RMSE
		observed	simulated		
Nitrogen efficiency	dmnl	0.15-0.44	0.17-0.33	0.26	0.04 ± 0.04
Nitrogen surplus	kgN ha^{-1} $year^{-1}$	270-970	270-1020	445	70 ± 45
Total work time	hrs $week^{-1}$	45-98	51-118	68	12 ± 8
Repetitive work time		43-84	49-105	62	12 ± 6
Milk productivity	kgFM cow^{-1} $year^{-1}$	4880-7615	4020-8140	6100	410 ± 290
Grasslands productivity	round bales ha^{-1} $year^{-1}$	54-108	53-90	68	7 ± 7

In Tab. 3, root mean-squared errors (**RMSE**) were calculated from the data observed in 2004. For the six farms, the simulated sustainability indicators are close to the observed values. GAMEDE particularly well simulates the technical performances (silage and milk productivities) and the N surpluses (mean errors = about 10%). The model has a slight tendency to over-valuate N surpluses and the total and repetitive work times (mean errors < 20%).

III.4.1.2 Validation of GAMEDE according to dynamical evolutions of biomass flows

We illustrate the quantitative validation of GAMEDE by comparison with dynamical evolutions of biomass flow, taking the example of milk production. Milk constitutes a major N output and thus is determinant for the environmental impact of the farm (N efficiency and surplus). Milk production cannot be ignored from a technico-economic point of view as it is the major source of income for dairy farmers (in particular in La Réunion where subsidies are linked to production). Observed data are milk quantities sold to the cooperative. The results show that GAMEDE satisfactorily simulates the monthly flow of milk production (Fig. 14).

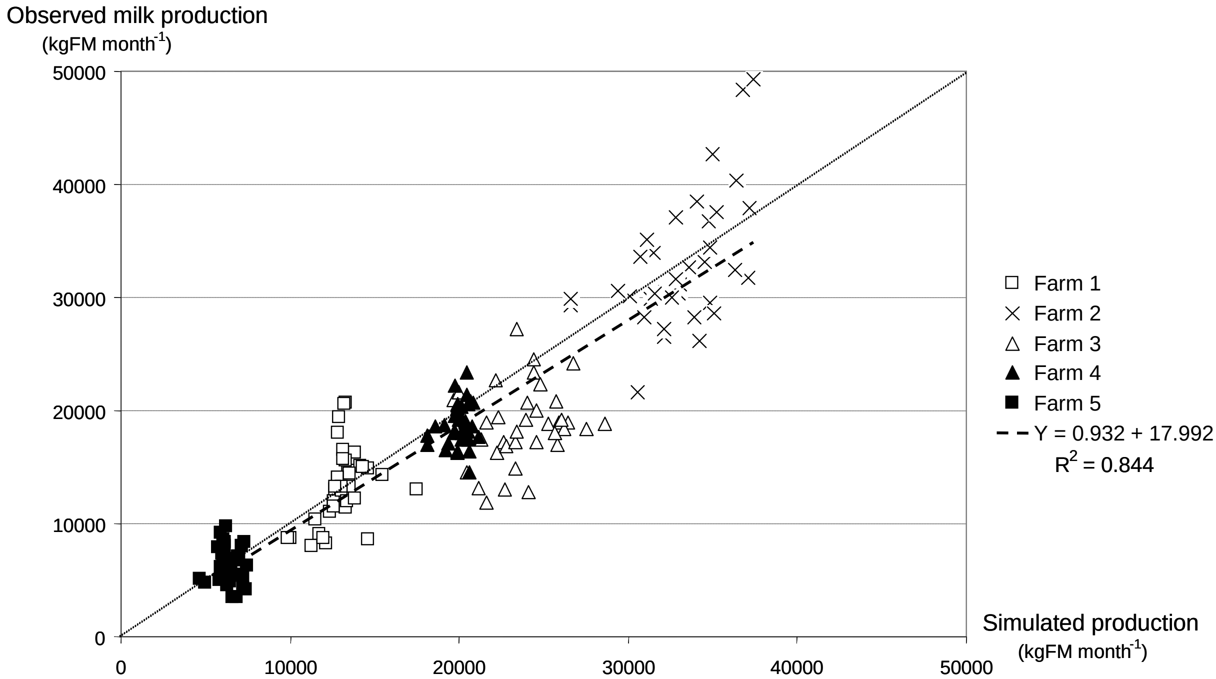

Figure 14. *Observed and simulated milk production sold (data from farms 1 to 5 for the years 2004-2006).*

Taking the example of farm 1, Fig. 15 shows that intra-year variations are well represented. The variations are due to changes in feeding rations (controlled by the DS), variability in the forage quality (determined by the MPF module) and, above all, demographic dynamics of the herd (MD module). In effect, calving is not uniformly distributed over the year, and the beginning of lactations is characterised by larger milk production. As lactating cows are grouped in cohorts represented by an average animal, GAMEDE generally underestimates the fluctuation amplitudes. In other cases not represented in Fig. 15, some time-shift between the simulated and observed production peaks appears during the third simulated year for some farms. This shift is due to inter-annual variations in the herd reproductive performances. Hence this explains the discrepancy between observed and simulated productions because, in GAMEDE, the herd reproduction performances are kept constant. To improve the model accuracy, based on the data from Tillard *et al.* (2007), a mathematical function could be designed to allow the calving interval (ICC) to be dynamically calculated, depending on energy feeding of cows, for instance.

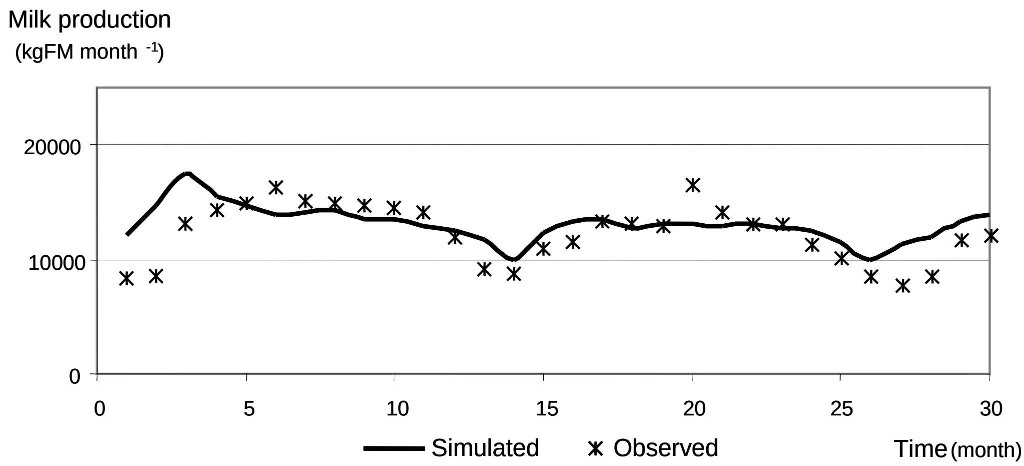

Figure 15. *Observed and GAMEDE simulated milk production sold (farm 1, 2004-2006).*

Other main biomass flows and stocks have also been quantitatively confronted with observed data: forage production, stocks of imported and on-farm produced forages, and effluent stocks (liquid manure in particular). Dynamical simulations were also globally satisfactory but time-shifts were often noted between simulated and observed stocks filling and emptying. In practice, management action adjustments due to unforeseen events, weather in particular, are frequent and have important consequences on farm flow dynamics.

III.4.2 The DS as a central way to improve the model realism

Let us recall that, in this version of GAMEDE, the DS simulates few adjustments in action capable of dealing with unexpected events. Integrating within the DS the capability of dealing with competing resources, e.g. labour (as in the MAGMA model; Guerrin, 2001) and adjustment decision rules (all already available) appears the best way to improve the realism of GAMEDE's simulations. A conceptual "Structure for Action Modelling" (**SAM**) has been especially designed to explore this way. This adaptation of the DS allows us to assess the importance of action adjustments on the farm's functioning and performances. This comparison has already been made for specific operations (animal feeding and silage making), showing marked improvement of the realism of flows' evolutions (Vayssières *et al.*, 2007b).

III.4.3 Interest of subjective and qualitative validations

It has not been possible to quantitatively validate all the aspects of dynamical representations because the records of observed data from the six dairy farms are incomplete with respect to many hard-to-measure aspects that are dealt with in the model: N emissions, slurry pit overflows, quantity of dejecta daily produced, evolution of effluent N content, etc. This difficulty to validate all the outputs of farm models was also noted by Cros *et al.* (2003). Obviously, complete quantitative validation is feasible only if models involve a relatively small number of easy-to-measure variables and parameters.

For the whole-farm model, quantitative validation becomes increasingly difficult. Expertise-based validation is often the only one alternative for validating farm models developed by economists (Crosson *et al*., 2006) or agronomists (Cros *et al*., 2003; Andrieu *et al*., 2007).

In our study case, subjective and qualitative validations were used in addition to quantitative validations. Numerous experts were provided with simulations of cases familiar to them. Scientists and technical advisers were asked if the model behaviour was consistent and reasonably accurate on hypothetical farm-type scenarios. The main outputs examined were N flows and emissions. The farmers of the six reference farms were also asked if the model outputs were realistic to account for the real functioning of their own farm. Here the main outputs considered were actions dates, biomass flows, and work time. After a number of such group meetings in addition to numerous individual meetings, researchers, advisers, and farmers were satisfied that GAMEDE correctly replicates the system processes and the farm functioning. Both quantitative and qualitative validations were part of the modelling process because the feedback was continuously integrated to improve the model accuracy.

The sensitivity analysis of the model is described in the companion paper. It reveals the strong influence of management variables on the sustainability of the farm, showing that farmers can improve the performances of their farm by modifying their practices.

Conclusion

The main goal was to develop a farm model that can meet the needs expressed by a variety of rural development actors (farmers, extension agents, and scientists) to estimate the sustainability of dairy production systems, forage crop and animal productivity, farm biomass/N flows and emissions, and work time. Modelling such a complex system required the integration of diverse factors (decisional, structural, biophysical, and environmental). GAMEDE integrates a decisional system (DS = the farmer as a decision-maker and performer) interacting dynamically with a biophysical system (BS = the material farming system). GAMEDE is not the simplistic sum of the two systems. The DS simulates the realisation of 19 technical operations according to the BS state, which is determined by the actions performed by the DS.

The BS of GAMEDE is partitioned into six modules accounting for forage production, forage conditioning, animal productions and demography, grazing and fertiliser evolution during handling. Many partial biophysical models are available in the literature. The stake was thus to integrate these models to serve a common goal: representing globally the dynamical evolution of a farming system interactively with a DS. For this, some of these models had to be reshaped and others invented to link the different modules and allow their control by the DS in a single integrated model.

Our studies have shown that through its simplified decision-making system, the model performs well for dairy farms of La Réunion, although these farms have very contrasted characteristics in terms of climatic conditions, forage crop varieties, herd size, buildings, agricultural land area, and above all, management action plans. We show, in the companion paper, how to use GAMEDE to represent the functioning of these farms and to identify improvement options tailored to each farm.

The structure of the model, focused on *technical actions and biomass flow* representations, offers numerous opportunities to develop other options in GAMEDE: i) The biomass flows can easily be assessed in terms other than nitrogen: e.g. phosphorus, carbon, water, energy. ii) As the work time is linked to each technical operation, the costs and benefits of each operation can also be calculated according to various management strategies. An economic module for GAMEDE has already been conceptually designed. The costs/ benefits of each operation are calculated depending on actions' duration and the quantity of biomass manipulated. The costs/ benefits are added up to represent the influence of practices on the annual gross margin. Moreover, the daily financial flows offer a dynamical representation of the cash-flow of the farm. In the future, the cash-flow will be additional information to be considered by the DS simulating the management actions (e.g. mineral fertiliser spreading can be cancelled if the cash-flow is insufficient) and will also serve as the new sustainability indicator demanded by farmers.

Acknowledgements

The authors thank the six farmers committed to our research, three extension agents, and eight researchers for model development and evaluation of the whole model. Some biophysical modules were conceptualised or validated thanks to student works of M. Châtelet, J. Teyssier, M. Herrou, and S. Rouam.

Conclusions intermédiaires et transition

Ce chapitre de description du modèle GAMEDE souligne l'importance des interactions entre les différents modules du système biophysique (BS) et le système décisionnel (DS). Il conclut sur la proposition d'une voie d'amélioration du réalisme des simulations.

Cette voie comprend le développement d'un DS plus élaboré, permettant davantage d'ajustements dans l'action en réponse à des contraintes de disponibilité des ressources (e.g. la main d'œuvre) et à l'aléa climatique.

Cette voie d'amélioration et ses conséquences sont explorées dans le chapitre suivant. Différentes formes du DS y sont comparées sur la base d'un BS invariant : celui du modèle GAMEDE décrit dans le chapitre III.

Chapitre IV. MODELLING FARMERS' ACTION: DECISION RULES CAPTURE METHODOLOGY AND FORMALISATION STRUCTURE[6]

Abstract

Studies on decision making processes are generally aimed at identifying farmer's needs and predict farmers' reactions to technical innovations. In the present paper we study these decision making processes, with reference to dairy farms, to build a whole farm computer model, called GAMEDE, which simulates farmers' actions. In this study, (i) a multi-tool and multi-step methodology is proposed, which can also be qualified as an iterative and interactive methodology to revel decision rules and (ii) a generic structure to formalise how action is conducted, termed 'structure for action modelling' (**SAM**). In the case of forage crop-dairy cattle system, we have tested the current methodology to capture the decision rules and the SAM to represent action concerning the farm management. 'Immersion' approach, inspired by the ethnographic approach has been adapted to access operational technical decisions (taken on a daily basis). This study helped to understand how detailed and large approaches can be complementary and can facilitate to identify what can be generalised in a conceptual model. To define the generic structure (SAM), a set of descriptive variables concerning technical operations have been selected. The conceptual model generated is composed of decision rules reconstructed by researchers with farmer's committed participation. The validation method is based on participatory approaches and on comparing of actions simulated by the model to practices on ground. Not contesting the fact that farmers plan their action, this study also revealed the importance of adjustments in action. For example, 20 to 55% of the time the planned food ration is not distributed to the milking cows because of forage unavailability. We also discuss how this structure can facilitate integration of decision mechanisms in biophysical models and how such an integration of adjustment decision rules can produce more realistic simulations of technical actions. Error of dynamic biotechnical representations done by GAMEDE is reduced from about 25% to about 10% with the application of the proposed method.

Keywords: dairy farm management, decision rules, practices, simulation model, technical operations.

[6] **Basé sur** : Vayssières, J., Lecomte, P., Guerrin, F., Nidumolu, U.B., 2007b. Modelling farmers' action: decision rules capture methodology and formalisation structure: a case of biomass flow operations in dairy farms of a tropical island. Animal 1, 716-733.

Introduction

During the second part of the last century, a number of studies have been undertaken to define techniques or models to improve technical and economical performances of farms. However it is often seen that farmers do not follow the technical advice of the extensions services. For example, Sumberg (2002), cites the case of livestock nutrition, and underlines that African producers have shown little interest in improved food technologies. Aubry *et al.* (1998) and Aubry (2000) cites similar cases studies on crop systems (Spedding, 1975; Ruthenberg, 1980; Collinson, 1983). It is now widely acknowledged that such poor application of advice is not simply due to the technical failings of the farmers. Farmer's practices reflect their particular aims and constraints (Sebillotte, 1979; Capillon, 1986). Understanding the reasons of these practices is now regarded as a necessary step towards designing new agronomic production techniques (Sebillotte, 1987; Gibbon, 1994). According to Thornton and Herrero (2001), the likely trends of smallholders crop-livestock systems development within the next 20-30 years will require models to enable analysis of those complex systems, assess their impact, and help farmers improve their performances. These observations justify farming systems and decision making process research (Aubry *et al.*, 1998; Aubry, 2000).

It is now widely assumed that computer models can be used to support farmer's decisions. However, most of these decision support systems are optimisation based models which are mainly used as recommendation and prescriptive models: responding to "How-to questions?" (McCown, 2002b). Computer models can be constructed with other objectives such as: representing farmers' practices and simulating technical alternatives with participation of farmers (Attonaty *et al.*, 1999). These simulation models respond to "What if?" questions (McCown, 2002b). The authors argue that this approach is more likely to foster interactive reflection and discussions among stakeholders about their own practices.

As discussed by Cros *et al.* (2001), one way to represent effective practices can be developing a decision system linked to the biophysical system (composed by purely biophysical models). But the basic question is how can the decisional system (**DS**) be structured to link it to the biophysical system (**BS**)? Farmer's actions constitute the material and conceptual link between their decisional processes and their control on the biophysical processes. Hence, technical operation could be considered as a central concept of models that have to represent farmers' practices. A technical operation constitutes an elementary action or a group of elementary actions (always performed together), realised by the workforce of the farm, that have well defined effects on the different production processes of the farm.

A dairy farm system can be represented as a biomass cycle and within such system, two types of material flows are distinguished: those mainly driven by human agents: actionable flows, and those mainly driven by natural causes: biophysical flows. Previous studies by the authors (Vayssières *et al.*, 2003; Vayssières *et al.*, 2004) have shown that most of biomass flows in dairy production systems are actionable flows. 19 technical operations that generate biomass flows in the farm are listed in Tab. 4.

This type of flow is called 'biomass flow operations'. All these operations have been considered in this study (Vayssières, 2004). Hence, a dairy farm system can be defined as the management of temporal variability of biomass stores and flows to improve economic returns, to reduce labour stress and environmental impact. Moreover, the term of 'farm management' is used here to describe the ways in which a farmer obtains, stores, uses and distributes, the biomass, originating from his own farm or other farms, over time and space.

The aim of this paper is to propose a method to study and represent technical decisions for action modelling. The first hypothesis is that the action plan is not sufficient to simulate the realism of management actions. The second hypothesis is that one methodological approach will not be sufficient to capture the decision rules. We take an example of the dairy farm management and illustrate our approach on two management operations in the scope of responding to these resulting questions: "Do the dates of ensiling works and the ration composition correspond to the action plan or supplementary decision rules have to be captured to simulate more realistic management actions?" and "How to access farmers' reasoning about farm management and to capture their decision rules while not being limited to a basic action plan description by farmers?".

IV.1 Literature Review

IV.1.1 General concepts to define the domain of the present study

Researches on production systems are based on two principles. The first considers a farm as a complex system with many components which interact. The second is the farmer's rationality principle. Farm functioning and farming practices are seen as the result of a farmer's direct intentions. To analyse them, one must look at the underlying decision-making processes, which acts as 'a sort of driving force for the practices' (Papy, 1994).

Strategic, tactical and operational decisions are classically distinguished (Fountas *et al.*, 2006). The distinction is based on the temporal horizon of the decision. Strategic decisions have a multi-year horizon (long-term), the horizon of tactical decisions is limited to the yearly campaign (medium term) and the operational decisions are made on a daily basis (short-term).

Structural and technical decisions are also classically differentiated. Structural decisions are strategic decisions. They represent production choices (e.g. dairy or meat cattle) and productive resources gathering (land, workforce, equipments, buildings, etc.) that constitute the production system. Technical decisions are taken to manage the production system. They concern resource allocation to technical operations (Papy and Mousset, 1992).

In this article we consider only technical decisions in general and operational decisions in particular.

IV.1.2 Conceptual decision models resulting from the concept of action model

An 'action model' is a conceptual representation of a farmer's practices, composed of (i) one or several general objectives that guide the farmer's technical decision making, (ii) an anticipated action plan including a forward planning schedule organising these decisions in time and the way it is hoped operations will unfold; and (iii) a set of decision rules (holding for each stage of the plan) and indicators designed to make sure the desired plan is adhered to (Duru *et al*., 1988; Sebillotte and Soler, 1988 and 1990; Papy, 1994). This conceptual representation proposes to distinguish two types of operational decision rules: the realisation decision rules that determine how action is usually made, and adjustment decision rules that facilitate alternative actions.

This approach has been used successfully for representing the management of annual crops (Aubry *et al*., 1998; Dounias *et al*., 2002), perennial crops (Bellon *et al*., 2001), grazing (Duru *et al*., 1990; Cerf *et al*., 1990), animal waste (Aubry *et al*., 2006) and resources such as labour (Attonaty *et al*., 1993) or irrigated water (Le Gal and Papy, 1998). In the present study, we apply this concept at the whole farm level, considering both crop and livestock production sub-units, with special consideration to animal management operations.

Most of those previous studies have shown that farmers plan their cyclical (recurrent) technical operations and that one can model this planning process (Aubry *et al*., 1998; Le Gal and Papy, 1998; Dounias *et al*., 2002). These studies propose a conceptual decision model explaining how farmers define and decide their planning schedules. We propose here to generalise it to decisions behind actions. We shall therefore propose building a model including:

- descriptive variables of the technical operations, i.e. the elements the farmer must decide upon in order to do action;

- decision rules that lead to these variables.

IV.1.3 Agricultural production systems ontology

An ontology is a modelling framework. As in industrial systems (Uschold *et al*., 1997), agricultural production systems can be divided in three subsystems: the manager, the operating system and the BS (Martin-Clouaire and Rellier, 2000).

The BS formalises global farm structure and is the place of production processes. It is composed of biophysical entities that have usually their own processes (e.g. plant development, animal productions like milk or faeces). Some of these processes are biomass flows. Among the events controlling these processes are those resulting from the operations executed by the operating system (Martin-Clouaire and Rellier, 2000).

The manager who is typically the farmer is the system responsible of achieving the overall production system objectives. To this end it possesses a management strategy that drives the behaviours of the operating system and indirectly of the BS. In the ontology, strategy does not hold the same significance for the agronomists, as it corresponds to their action model. The management strategy specifies the flexible organisation of the intended operations (nominal plan), their implementation requirements and the conditional self adaptations that should take place when particular events occur. This subsystem generates, among others, the candidate sets of operations that are feasible (= to be considered).

The operating system is in charge of transforming the manager's advocated sets of operations (all or a part of the operations) into an executable set of operations in compliance with the requirements communicated by the manager. Its unique component is the resources pool. The operating system has then to execute the operations in compliance with the requirements communicated by the manager, the resources availability and the state of the production system environment. Resources (e.g. labour, biomass stores, etc.) are elements of the production system that are necessary and mobilised for the operations realisation (Martin-Clouaire and Rellier, 2000). In this study, we consider that the DS contains both the manager and the operating system.

Martin-Clouaire and Rellier (2003) have defined an ontology for managed systems applied to agricultural productions. Relevant terms to represent the DS of our model have been selected from this ontology and these terms are presented in this section.

In accordance with the subdivisions of the production system, the operations are in the first instance advocated (= suggested) by the DS, then the operating system specifies each operation, i.e. it activates and characterises them regarding the state of the BS and its environment. It happens that conditions are not favourable and that, in consequence, some advocated operations are not realised.

(1) Advocating process: the operations advocating obeys to starting rules. Those rules are elements of the manager. They are associated with two information types:

- Alarms informing on the production system state in reference to an indicator. For example a level of slurry pit exceeding 90% of the storage capacity puts the operation 'slurry spreading' in the set of feasible operations.

- Operations schedule defining directly the rhythms and the periods of advocating. For example the milking has to be performed two times per day. This schedule corresponds to the timing part of the action plan of the model for action.

(2) Specification elements: one operation is characterised by two resources among others: the performer, the author of the operation and the operated object, object of the operation as its name indicates.

(3) Specification rules: the strategy also contains a set of specification rules for management operations:

- Some priority rules. Those priorities concerns resources or operations. The operations priority rules guide the operating system for the constitution of the set of operations to be realised. The resources priority rules attribute to operations one resource more than others when a choice is possible.

- Some constraints of operation realisation.

This ontology has been conceived from the survey of indoor tomato cropping. This production system is specific and is not so far from industrial systems. Indeed, this production is relatively free from climatic risks and it supposes an abundant labour with different hierarchic decision levels.

We propose here to venture outdoors, to use this conceptual model to represent the way farmers manage a whole farm, and to transfer those approaches to represent action in an animal dominant production system.

IV.2 Study area description

La Réunion is a volcanic island of 2500 km2, with 40% of its area located above 1000 m of altitude and 2/3 with slopes above 10%. The general agricultural context of the island has been described by Aubry *et al*. (2006). Sugar cane is the main crop (59% of the agricultural land) and is located in the lowlands. Dairy farms are distributed in the highlands (between 500 and 1600 m of altitude). Pedo-climatic conditions are very variable over the island linked to relief and altitude, producing important vegetation diversity. The main forage crops cultivated are chloris (Chloris gayana), sugar cane (Saccaharum officinarum), forage cane (Pennisetum purpureum) under 800 m of altitude. Over this limit kikuyu (Pennisetum clandestinum), dactyle (Dactylic glomerata), ray-grass (Lolium multiflorum and Lolium hybridum), brome (Bromus catharticus) are cultivated (Barbet-Massin *et al*., 2004). La Réunion climate is tropical with oceanic influence due to exposure to trade the winds. The eastern part of the island is exposed to trade wind and is humid (3000 to 6000 mm per year), whereas the western part, protected by the central mountains, receives less than 1000 mm per year. Two main seasons can be distinguished (with short transitions) (i) a rainy and hot period: the summer from October to May, and (ii) a dry and cold period: the winter season from June to September.

The dairy sector in La Réunion is recent and has seen significant development since the end of the 1980's. This development responds to the local demand with the increased purchasing power, the changing consumption patterns, and the population growth. In 2003, the total local production was 22 millions litres (135 farms). This production is largely under the production allowed by the global quotas attributed to the island (40 millions litters). The milk is produced by about 4000 cows. The farm surveyed by the 'milk control' had an average cow productivity of 5750 kg per year per cow in 2003. The milk control is a service (partially financed by the Regional Authority) giving periodically (each 45 days) technical characteristics of the dairy cattle (milk production, reproduction performances, milk composition, etc.) to help farmers manage their farm. All the 135 farms are members of the only Dairy Co-operative in the island. The milk locally collected represents 30% of the consumption of the island. The rest of the demand is covered by powder and cheese imports. La Réunion agricultural policy has developed its dairy farming sector in order to increase its self-sufficiency in milk, to preserve agricultural employment and rural population in highlands.

IV.3 Methodology: an iterative combination of approaches to revel decision rules

Real-world cases are studied, building up a methodology based on three complementary types of inquiries per farm: immersion, visits and meetings. A special group of six farmers called the 'working group' was involved in those three types of inquiry.

IV.3.1 Immersion

Detailed research was conducted by sociologists, like Becker (1963) and Dodier (1995), by living the life of their subjects. In agreement with Lawas and Luning works (1996), immersion was retained with the aim of revealing operational decisions taken on a daily basis. Immersion is an original method for technical data gathering. It is based on one-week work-cum-training periods including open discussions with the farmer (Vayssières, 2004). The researcher directly participates in the technical operations of the farm under the direction of the farmer. This particular rapprochement creates a confident atmosphere and offers many opportunities for action observations. About eight weeks was spent by the first author of this paper in immersion in dairy farms.

This study on dairy farmers' technical decisions at farm's scale is new in La Réunion island. Living farmers' lives was also a good opportunity to realise the questions and constraints of farmers on a daily basis and to improved definition of the hypothesis of this study.

The main result of this type of inquiry was six monographs and action models (of these six farm cases included in the working group). The household and farm chief's objectives, the production objectives and the action plan were identified well; however, adjustment rules were incomplete. It was realised later that only more common operational decision rules were expressed by farmers. It was difficult for them to consider all the cases as the inquiries were localised in time. Farmers could have forgotten some adjustment rules, hence bimonthly visits were organised.

IV.3.2 Inquiries and observations within the scope of bimonthly visits

In tune with the experiences of Aubry *et al.* (1998) and Dounias *et al.* (2002), we organised regular visits to the farmer's about the planning of their technical operations, their effective practices and the technical results of their actions (to quantify biomass flows). We have collected those data on a bimonthly basis during two years. The first author of this paper continued to participate in the farm works to maintain the especially confident relationship.

The principal objective of this second type of inquiry was to regularly (six times per year) compare with farmers their action plan to their effective actions (plan versus reality). We used farm management schedules as discussion supports. Environmental conditions (weather, fodder market, etc.) were recorded and some observations were made on the grass fields and the cattle, so as to be able to describe operating conditions. Many complementary operational rules, adjustment rules in particular, were identified.

IV.3.3 Individual and collective validation from farmers themselves

Three types of validation contexts have been coupled: individual feed-backs in the scene of the bimonthly visits, collective feed-backs and collective work during meetings. These meetings were organised three times per year in each of the farms of the working group. It was an occasion for the farmers to present their farm and their practices to the others. This idea came from a particularly active farmer. The reason expressed was “we do not like to be in offices and it is an opportunity to see farms from other areas”. It was a sort of ‘spontaneous farm field school’.

Each individual model for action was individually and collectively presented (both by farmers and a researcher) and discussed. The experience has shown that it is difficult to speak about operational rules during a meeting, and that individual feed-backs are more adapted to validate this type of decision rules. Most corrections have resulted from individual feed-backs. But it was important to verify if the farmers’ discourses changed from private talk to public expression and it was realised that there was no significant change and it is seen as a sign of validation in the current study.

A brainstorming session was organised, with the working group consisting of the six farmers, to select the key management points. Topics such as “to produce liquid manure, solid manure or compost?”, “to feed cows with bought or on farm produce food?”, “pasture, cut and carry or ensilage?” were discussed and this led to improved understanding of reasons of the technical choices.

The method presented above was applied for three years consequently on each of the chosen farms. Working during three years with only six farmers needed to have careful consideration on the definition of this working group.

IV.3.4 Definition of the working group based on an iterative process

The definition of the working group has been an important question. The objective was to select less than ten farmers – a small number dictated by the time consuming nature of our methodology - to represent the diversity of the management strategies. One technical-economical typology had been carried out earlier in the same region (Alary *et al*., 2002). The first sample was composed of six farms chosen to have one farm per type and per dairy cattle-rearing area. For this occasion, four areas were defined with agricultural technicians (Vayssières, 2004). We also requested the agricultural technicians to validate this first sample of six farms to represent the diversity of management styles (Fig. 17).

A first series of immersions (-1-) was conducted in the six farms producing six action models. During individual feed-backs many discussions were stimulated on the content of the action models (farmer’s objectives, action plan, adjustment rules). Therefore we identified a series of management key points concerning key technical operations (described below). These points later helped in the formulation of a rapid appraisal which was administered on a larger sample of farmers to evaluate the first sample of six farmers.

The farmers of the first limited sample were mobilised in the definition of the large sample. "From your point of view, which farms have to be visited to cover the different way of farm management?" have been asked to the first six farmers. They decided to introduce to five to seven farms in each of their area. A total of 36 farmers were selected and were interviewed about their management practices and their household objectives (-2-). A typology (five types for the 36 farmers) which was defined by a combination of practices of farm management was developed (Vayssières *et al.*, 2006). It was then possible to re-evaluate the first limited sample of six farmers. Four of the five types of 36 farmers were represented in the first limited sample of six farmers. Hence, a complementary immersion (-3-) was conducted with a farmer (falling in the fifth type) in the sample of 36 farmers.

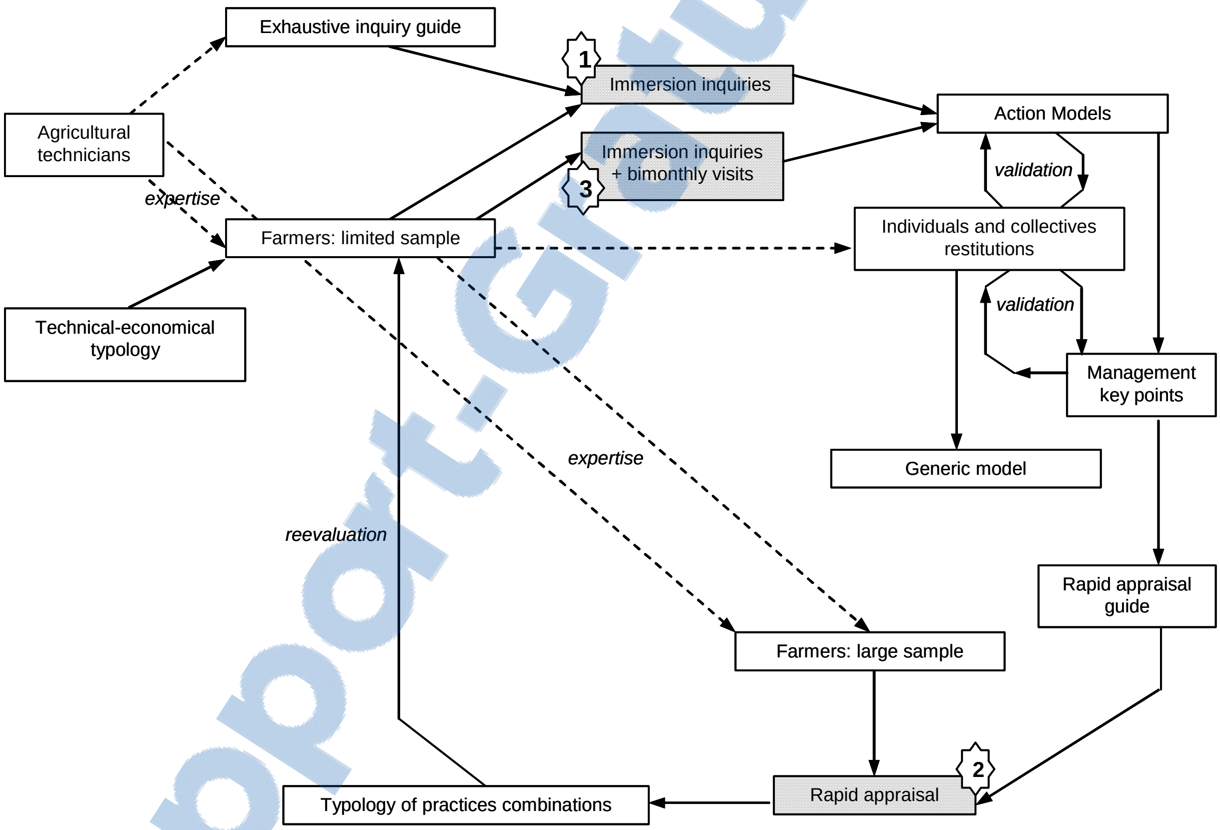

Figure 16. *The multi-approaches methodology to capture decision rules represented as an information gathering cycle.*

IV.3.5 Complementarities of immersion and rapid appraisal

The methodology presented above should not be considered as rigid and flexibility in use is required.

We argue that immersion and rapid appraisal are complementary. Immersions provide insights into intricacies of farming systems and it is essential to understand such complex systems such as crop-livestock production systems. But its specificity and illustrative nature mean that generalisation may be limited. Outputs from detailed studies have been important pre-requisites for the larger approaches (covering more than 30 farms) and should therefore be used in conjunction with other larger analysis.

Rapid appraisal was not only conducted to evaluate the representativeness of the real cases studied but also to compare the results of the methodology proposed in this paper (including immersion) to the results of a more classical rapid appraisal. Rapid appraisal is adapted to define the action plan of the farmer. The detailed studies offer the opportunity to define the operational decision rules presented in the general structure (the SAM) proposed below.

IV.3.6 Validation by simulating farmers' actions

A whole farm model, called GAMEDE, has been developed using Vensim® to dynamically represent the functioning of the farm. Based on the studies of Cros *et al.* (2001), this computer model comprises of two sub-systems: the whole-farm BS and the whole-farm DS. The BS is constructed by merging different functions or parts of the existing biophysical models of the literature (e.g. Jarrige, 1988; Fox *et al.*, 2004 for the milk production sub-model). The DS is relevant to the current article while BS is beyond the scope of this paper.

The DS construction is based on the SAM and the decision rules identified with the chosen methodology. Two options have been simulated with GAMEDE: (i) simulation of the 'planned actions': this simulation is based on the action plan of the farmer; (ii) simulation of the 'SAM actions': this simulation is based on the operational rules: both realisation and adjustment rules are structured in the SAM. To validate the chosen approach 'planned actions' and 'SAM actions' have been compared to 'effective actions' observed in the scope of the bimonthly visits to the farms. Deviation from reality can be quantified for the actions of the six farmers of the working group.

IV.4 Results

IV.4.1 From study of dairy farm management constraints: adjustments to be made to decision approaches

The models we have for understanding and representing farmer's action processes apply to situations where there is a single decision maker per holding. In the case of dairy farms of La Réunion island, the single decision maker manages multiple and quickly accomplished technical operations. Each operation takes a short time and is performed in a day.

Previous conceptual models focused on farming systems making extensive use of machinery. In the dairy farms of La Réunion island, though technical operations are also mainly mechanised, farms where the technical operations are mostly manual are also seen; the diversity of farm practices is particularly important in this island. In all the cases, the main part of the work is done by the farmer, while some assistance is provided by household members and occasionally by trainees. Since hired labour is expensive, it is not preferred (like in many developed countries).

Tab. 4 presents the main constraints, concerning the realisation of biomass flow operations, expressed by the 36 farmers interviewed in the scope of the large-scale approach. These constraints are presented in priority order and they essentially concern (i) climate, (ii) forage availability and (iii) workforce.

Tableau 4. *Main realisation constraints expressed by farmers to realise the nineteen technical operations that generate biomass flows.*

Action domain	Technical operations	Main constraints	Priority N°
Forage surface management	Silage making in wrapped bales	Rain, equipment downtime and breakdown, high cost	7
	Green grass harvest	Workforce insufficiency, daily mandatory work, variability of grass growing speed, rain	3
	Green canes harvest (sugar and forage cane)	Workforce insufficiency, work onerousness, daily mandatory work, rain	4
	Changing of pasture (rotation)	Rain, heat	8
Feed management	Concentrated feed buying (concentrate, molasses, milk powder, etc.)	High cost	13
	Forage buying (cane straw, bagasse, hay, etc.)	Low availability, storage difficulties, high cost	15
Herd management	Feeding of different animal batches (calves, heifers, dried up cows, producing cows)	Variability of forage availability, acidosis risks	2
	Heifers buying	High cost, sanitary risks	16
	Calves sale	-	17
	Voluntary culling of animals (DC or heifers)	Lack of heifers, to much sustained scrapping, demand variability	18
	Milking	Daily mandatory work	1
	Mulching	Low availability and high cost of sugar cane	5
Fertiliser management	Slurry removal	Work onerousness	6
	Solid manure removal	Work onerousness	12
	Mineral fertiliser buying	High cost	14
	Mineral fertiliser spreading	High cost	11
	Slurry spreading	Rain, field impracticability, workforce insufficiency	9
	Solid manure spreading	Rain, field impracticability, workforce insufficiency	19
	Solid manure sale	High offer and low price	10

IV.4.1.1 Climatic constraints: importance of adjustments rules

Some dairy cattle-rearing areas which are located roughly between the 2000 and 4000 mm isohyets are particularly wet. There is a single rainy season spread over about eight months, between September and May. Farmers are under the constraint of rainfall patterns. Rains activate weed growth in the fields and limit harvest possibilities. Therefore for the farmers "it is difficult to foresee dates of silage making". Owing to this fact it is not surprising to observe divergences of practices from action plans. In such cases, alternative solutions have to be activated by farmers. Date adjustments for action by farmers owing to climatic constraints have been particularly focused in this study (e.g. Fig. 20).

IV.4.1.2 Variability in forage resources availability: adjustments to jungle with different feeds

An action plan does not consider only time characteristics of action but also includes the descriptive variables of technical operations (which stores have to be mobilised? What is the usual modality?). For example, the plan provides different types of food rations to different animal batches, according to different practical seasons (Vayssières and Lecomte, 2006). The definition of the practical seasons by farmers is expressed as their anticipation of intra-year variations of forage availability. Forage production and supply is seasonal (sugarcane campaign for cane straw and bagasse, summer for Chloris gayana hay). Also, forage production varies also widely from year to year. It is a result of inter-year climatic variations because of the island and mountainous character of the environment. These factors make it difficult for the farmers to follow their planned rations. Adjustments of type and quantity of biomass using (e.g. feed) are also important concerns of this study (e.g. Fig. 21).

IV.4.1.3 Time is the scarce factor: importance of arbitration rules between competing operations

During favourable weather windows, farmers have to both harvest forage and spread manure (on different fields). Hence, these technical operations can be concomitant at the farm scale. Furthermore, in these production systems, available time as the scarce factor is appreciated because of its cost and limited availability at certain periods.

Given this available time limitation, work organisation on the farms must be taken into account in technical management models for dairy farms management. We define work organisation as a farmer’s plans for distribution of labour and equipment to carry out the technical operations determined by the technical management decisions taken for present on the farm (Aubry and Chatelin, 1997). Equipment constraint appears only when it is shared between farmers. Regarding the whole farm management and in view of the severe time constraints on these farms at certain seasons, special emphasis is given on how the labour is divided among technical operations (mainly through priority rules).

IV.4.1.4 Priority between technical operations: a meta-rule

Study of labour competition reveals that priority rules between technical operations are very similar from one farm to an other. It can be considered as a meta-rule (Dounias *et al*., 2002). We propose to synthesise this priority rule in three groups of technical operations classified in priority order:

(1) ‘Non deferrable and routine technical operations’ are performed daily, generally at specified times in the day. It is essentially herd management operations: milking, animal feeding, green harvest, mulching, slurry removal.

(2) 'Urgent and contextual technical operations' are performed in the day. It is all the operations that need very specific climatic conditions, cultural stage, and material availability. These are essentially forage culture management operations: ensiling, changing of pasture, manure spreading, mineral fertiliser spreading.

(3) 'Non priority technical operations' are realised in a two week planning horizon and these can generally be anticipated by the farmers. These include solid manure removal, buying of concentrate feed, mineral fertiliser and forage, buying and selling of animals and selling of solid manure.

To have the precise hierarchy between technical operations priority numbers in Tab. 4 may be referred. The precise hierarchy could be defined as: 'milking > animal feeding > green harvest > mulching, etc.'. It illustrates, the priority rule found in the conceptual structure on the dairy farm management case, proposed in following section.

IV.4.2 The conceptual structure: convergence between the action model and the agricultural production systems ontology

The structure for action modelling (SAM), proposed in Fig. 17, is based on the ontology of Martin-Clouaire and Rellier (2003). Three sub-systems (the manager, the operating system and the BS) are defined. The technical operations are advocated first, then activated and finally characterised, and the characterised operations generate biomass flows in the BS.

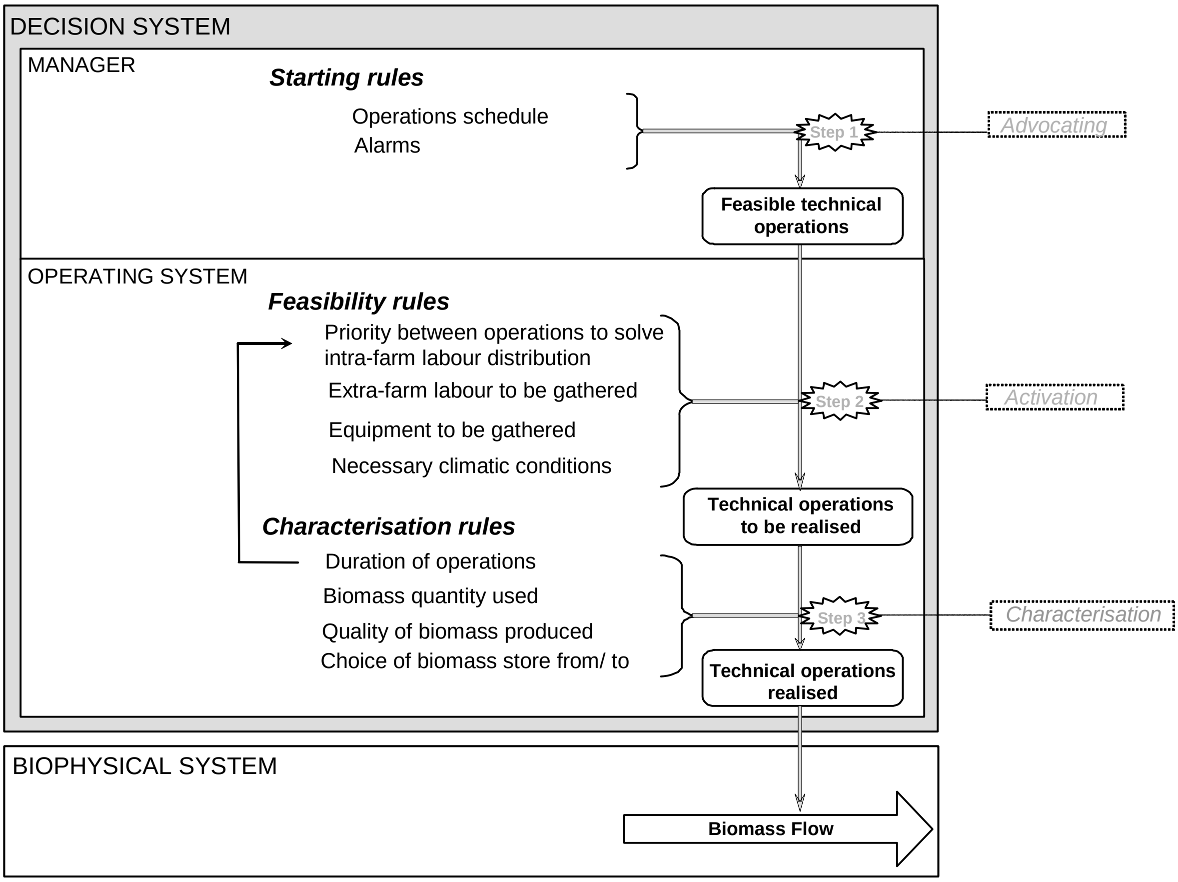

Figure 17. Representation of the structure for action modelling (SAM) applied to biomass flow operations.

This structure is also composed of:

(1) Starting rules relative to both alarms and operations schedule.

(2) Feasibility rules are composed of:

- A priority rule that concerns solely of technical operations. It solves labour distribution when concurrence occurs. This priority rule has been dealt in the previous section.

- Feasibility conditions rules that specify if extra farm labour and equipment have to be gathered and what climatic conditions are necessary to realise the technical operation.

(3) Characterisation rules define the specification elements of the ontology, i.e. the descriptive variables of the technical operation realised: its modality and duration, the biomass quantity used, store from which it is taken, the quality of the biomass produced (if there is transformation during manipulation), and which store is replenished.

These descriptive variables of operations are the link between the DS and the BS. They specify the biotechnical characteristics of the biomass flows generated by operations.

The SAM, proposed in this study, also incorporates the concept of action model. Effectively, for each three types of decision rules (starting, feasibility and characterisation rules) we find both realisation and adjustment rules (see examples proposed in next section), as defined by the action model. Moreover, as discussed by Aubry *et al*. (1998) and Dounias *et al*. (2002), the structure consists of descriptive variables and decision rules. Some types of rules are common such as activation rules, arbitration rules, rules for establishing mode. Operations sequencing and fields grouping rules are not necessary in our structure because we do not model how the action plan is defined. But we model here how the action plan is put into practice or not.

IV.4.3 A generic structure offering a pertinent way of interpreting farmer's actions: illustration by examples

It is a generic structure in a way that it is available for all the technical operations at the origin of biomass flows identified in dairy farms.

We illustrate here the generic nature of the SAM and its application to two operation domains that have significant consequence on biomass flows: forage harvest and animal rationing. Practices of the farmer 2 (one of the six farmers of the working group) are formally described with the conceptual structure to represent action. In Tab. 5 and 6, we list and classify the different operational decision rules.

Forage harvest

The first example is ensiling operation (Tab. 5). It is relative to a grassland field (= the operated object). This operation is exclusively advocated by alarms about the state of the grass land. The grass height is generally the indicator used by farmer 2, but in winter the percentage of plants at ear-emergence stage is more often used. The growth rate of grass is also evaluated by visual assessment of grass height about two months after previous harvest, if the farmer judges it insufficient the field is harvested earlier. This second type of adjustment generally occurs during a severe dry period or when a strong rain occurs just after fertilisation (leaching of mineral nutrients).

Tableau 5. Translation of discourse and practices of farmer 2 into decision rules for ensiling works

Decision rules categories		Descriptive variables	Realisation decision rules	Adjustment decision rules
Starting rules	Operations schedule		Ø	
	Alarms (operation a priori selected)		**If** grass height > 35 cm (in summer)	**Or if** percentage of plants at ear emergence stage > 30% (in winter) **Or if** time from the last harvest > 2 month and if grass height < 25 cm
Feasibility rules	Hierarchy between operations		Feeding > ensiling > spreading	
	Extra-farm labour to be gathered		**If** one or two extra-farmers (his brothers) are free	
	Equipment to be gathered		**If** two tractors (from the farm preferentially) are fi **And if** the common ensiling chain is free	
	Necessary climatic conditions		**If** the beginning of the morning is sunny **And if** two last days without rain (not humid grass and dried soil)	
Characterisation rules		'Modality' and Duration	Generally 'with two extra-farmers': speed S = 40 round bales/h	**If** not the two extra-farmers are free: 'with one extra-farmers': S = 10 round bales/h
		Biomass quantity used	All the biomass present on the field at the beginning of the action	**If** interruption by rain: all the biomass present on the harvested part
		Quality of biomass produced	Depending of the weather: **If** fine rain: dry mater percentage (DM) = 15-20% **If** cloudy weather: DM = 20-30% **If** mixed sunny/ cloudy weather: DM = 30-40% **If** persisting sunny weather: DM = 40-60%	
		Choice of biomass store from	The field at the origin of the action	**If** interruption by rain: a part of the field at the origin of the action
		Choice of biomass store to	A new store of round bales on the field border	

When climatic conditions and realisation constraints are satisfied the ensiling operation is directly carried out. The concurrence with other operations does not affect its activation, because it is slotted in a high level of hierarchy. In Tab. 5 and 6 the priority rule defining this hierarchy is simplified from the one described above: it is applied to only three operations. The ensiling works suppose extra-farm labour, generally represented by two brothers of farmer 2, but only one brother could be adequate. They hold their own ensiling chain they share to harvest the grasslands in each of their farms. It is less restricting than renting it to an enterprise. Farmer 2 explains that the main constraint is climatic: two days without rain are necessary to harvest a non-humid grass and to have relatively dried soils (to avoid grassland degradation). The following day, if the morning is sunny, the work can be done.

The ensiling modality and its duration are determined by the number of farmers ready to work. Generally the three brothers are present. The biomass harvested is generally all the grass present on the field at the origin of the operation. But rain can interrupt his work. In this case, the harvested area of the field is reduced. From a flow point of view, the 'store from' is the harvested field (or a part of it) and the 'store to' is a new store of round bales constituted on the field border.

Animal rationing

The second example is the feeding operation of the producing cows (Tab. 6). Contrary to the previous example, this operation is advocated by the operations schedule. Farmer 2 plans to feed his cows one time per day to avoid silage degradation (occurring if he would distribute once in two or three days as done by other farmers). Feeding is one of the priority operations (with milking). No realisation constraints and no climatic conditions exist; this operation is effectively undertaken on a daily basis.

Tableau 6. ***Translation of the discourse and the practices of farmer 2 into decision rules for feeding of producing dairy cows***

Decision rules categories		Descriptive variables	Realisation decision rules	Adjustment decision rules
Starting rules	Operations schedule (operation a priori selected)		one time per day	
	Alarms			
Feasibility rules	Hierarchy between operations		Feeding>ensiling>spreading	
	Extra-farm labour to be gathered		Ø	
	Equipment to be gathered		Ø	
	Necessary climatic conditions		Ø	
Characterisation rules		'Modality' and Duration	**Generally** 'Main part with the mixer… - silage: speed S = 3 round bales/h - cane straw: S = 4 sheaves/h - molasses: S = 200 l/h - concentrated feed: S = 1200 kg/h and the rest manually' - hay and concentrated feed: S = 400 kg/h	**If** the mixer is out of order 'all manually' - silage: S = 2 round bales/h - cane straw: S = 2 sheaves/h - molasses: S = 120 l/h, etc.
		Biomass quantity used	**Generally** For 50 animals and per day: - 'dry' silage: 1.5 round bale - cane straw: 1/3 sheaf - bagasse: 0 kg - molasses: 30 l Per animal and per day: - hay: 1 kg - concentrated feed: 14 kg (B 80: 55%, M 45: 30%, Pulco: 15%)	For all the herd **If** no hay in store: improve cane straw to 1/2 sheaf and bagasse to 50 kg (hay: 0 kg) **If** no hay and no cane straw in store: improve bagasse to 75 kg (hay and cane straw: 0 kg) **If** no cane straw: improve bagasse to 50 kg (cane straw: 0 kg) **If** no cane straw and no bagasse in store: improve hay to 1.5 kg/ animal (cane straw and bagasse: 0 kg) Individually **If** animal have diarrhoea: improve hay to 1.5 kg/ animal **If** individual milk production (IMP) excess 30 l/day: improve concentrated feed to 15 kg/ animal (increasing Pulco's proportion) **If** 20 < IMP < 25 l/day: reduce concentrated feed to 12 kg (keeping the proportion) **If** 15 < IMP <= 20 l/ day: reduce concentrated feed to 10 kg (keeping the proportion) **If** IMP <=15 l/ day: reduce concentrated feed to 8 kg (keeping the proportion)
		Quality of biomass produced	Ø	
		Choice of biomass store from	The feed store corresponding to the feed category (e.g. hay)	
		Choice of biomass store to	The trough of producing cows	

Ration distribution is generally done with a ration mixer: the silage, the cane straw, the molasses and the bigger part of the concentrate (60%) is incorporated in the mixer. The rest of the concentrate and the hay are distributed manually. On farm observations, during the immersion, permit us to evaluate the speed at which this operation is performed. Even if some feeds are mixed and simultaneously distributed, we differentiate distribution speed for each feed, for modelling needs. It could happen that the mixer goes out of order, and then the entire ration is manually given. Concerning the quantity of biomass used, farmer 2 has one planned food ration for all the year and any adjustments are done according to forage store levels. The part generally distributed with the mixer is defined for the entire producing cows' batch (about 50 animals). The rest is individually distributed, so adjustments can be done about (i) hay if an animal has diarrhoea by improving quantities (ii) and concentrate corresponding to individual milk production (**IMP**). For example an animal starting its lactation with an IMP higher than 30 kg/day receives 15 kg/day, and an animal ending its lactation with an IMP lower than 15 kg/day receives 8 kg/day of concentrated feed. Adjustments are also realised by farmer 2 at the herd-scale if the hay store or the cane straw store is empty. If the farmer is short of hay he compensates with the cane quantities and vice versa. From a flow point of view, the stores-from are the stores of the corresponding feeds. Silage represents a particular case, where the farmer tries to reserve better quality (= 'dry' silage) to producing cows in giving less quality (= 'humid' silage) to heifers' batch. But sometimes, when humid silage stores proportion is too important, it is used in cows ration. In this case half a round bale of humid silage is given to producing cows (replacing half a round bale of dry silage). The store-to of the biomass flow is the trough of the animal batch considered (producing cows in this case).

IV.4.4 From operational decision rules to simulation of farmer's actions

The different operational decision rules listed in the SAM can be converted to mathematical functions and introduced into a computer model. The SAM's pertinence to build the DS of a computer model that simulates farmer's actions is here illustrated with the two operations described in the previous section.

The two operation descriptions of the previous section illustrate the importance of adjustments in the farm management. The adjustments mainly affect:

- the realisation date for outdoor operations subject to climatic uncertainty (e.g. forage harvest),

- the quantity of matter manipulated for indoor operations subject to biomass availability (e.g. animal rationing).

Therefore, we propose here to focus the attention on two particular outputs of the DS: the dates of the ensiling works and the composition of the producing cows' ration. We continue to discuss the practices of farmer 2 in 2005 to present the entire process of converting the discourse of farmer 2 into a computer model that simulates his management actions.

From a mathematical point of view, actions and conditions are represented as a dynamic process by a binary function of time. For actions: 1 value represents that the action is in course, 0 it is not. For conditions: 1 value signifies that the condition is verified; 0 it is not. Only the conditions that have effective influence on the realisation of actions for the 2005 year are presented in Fig. 18.

(1) Concerning the ensiling operation, starting and feasibility rules of Tab. 5 can be converted into conditions used in a mathematical function that determinates if the ensiling works are done or not:

IF (C1 = 1 OR C2 = 1 OR C3 = 1) AND C4 = 1 AND C5 = 1 AND C6 = 1 AND C7 = 1

THEN Ensiling action = 1 (15)

ELSE Ensiling action = 0

where:

C1 is ‘Grass height > 35 cm’.

C2 is ‘Percentage of plants at ear emergence stage > 30%’.

C3 is ‘Time from the last harvest > 2 months and grass height < 25 cm’.

C7 is ‘The beginning of the morning is sunny and two last days without rain’.

The outputs of the model are presented in Fig. 18. The model represents that the indicator used by farmer 2 to start ensiling works depends on the season: the grass height in summer (ensiling works 1 to 3) and the plant maturity in winter (ensiling works 4 and 5). It also represents that climatic conditions are responsible for any delay in ensiling works (ensiling works 2 and 5).

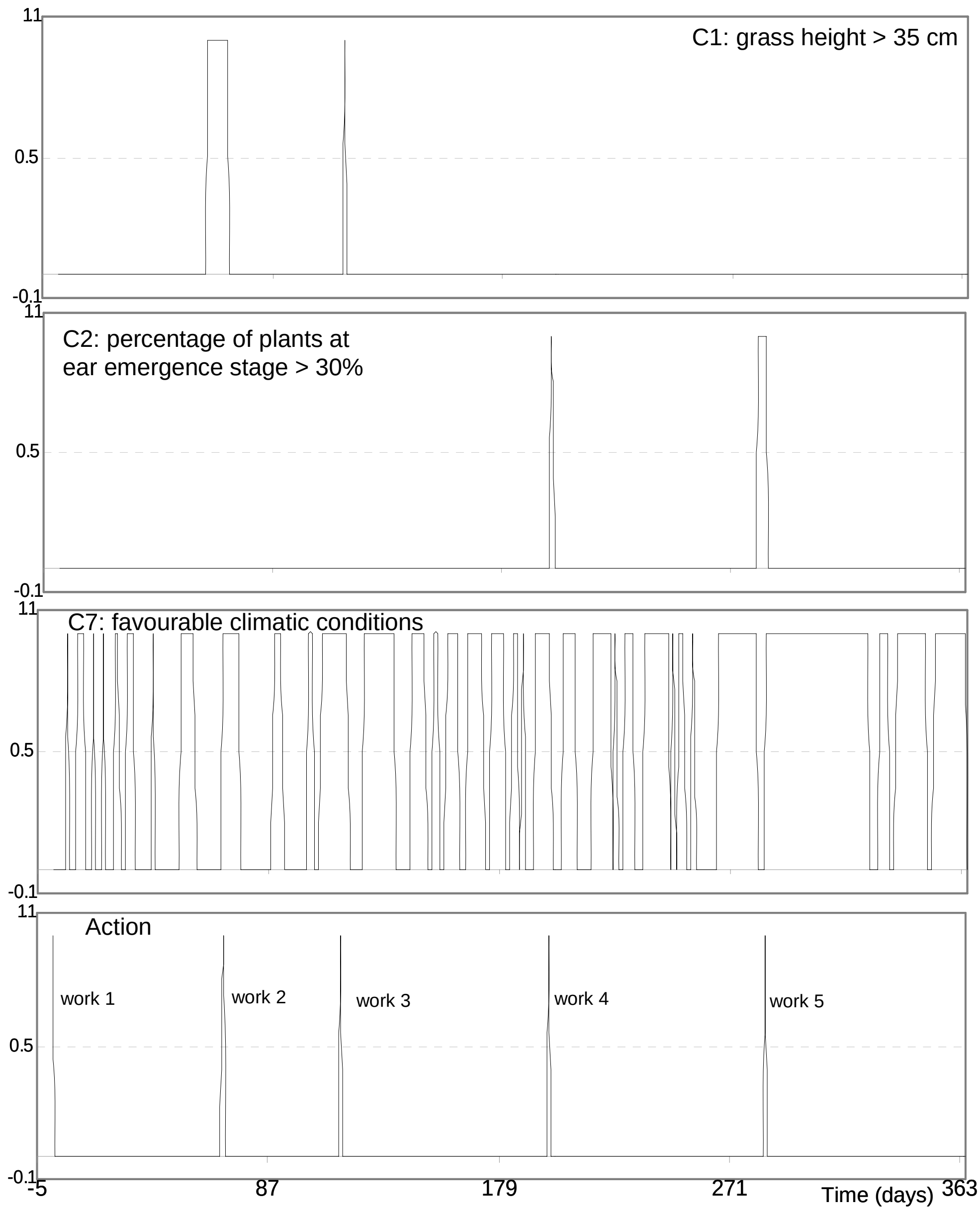

Figure 18. *Ensiling works: conditions status and action dates simulated by* GAMEDE *- ('SAM actions', field 2, farm 2 for 2005).*

(2) Concerning the feeding operation, characterisation rules of Tab. 6 have also been converted into mathematical functions. For example, the hay quantity distributed to cows (HQ) is calculated as the following equation:

IF HS = 0
    THEN HQ = 0
    ELSE, IF CS > 0
        THEN HQ = 42 (16)
        ELSE, IF BGS > 0
            THEN HQ = 42
            ELSE HQ = 75

where:

HS, CS and BGS are the levels of the hay store, the sugar cane straw store and the bagasse store (in kg) respectively.

HQ, CQ and BQ are the quantities of hay, sugar cane straw and bagasse distributed to producing cows respectively (in kg/day or in sheaves per day).

The outputs of the model are presented in Fig. 19. The model illustrates the big variability of forages stores levels over the year and its consequences on the ration composition. For example, for farmer 2, hay unavailability (days 1 to 152, 247 to 258, and 280 to 285) is represented as an important source of variation of the ration composition. Only the forage part of the ration is presented here. The transition period, just before the beginning of the sugarcane campaign, is also critical. This example shows that in some years cane straw stores are insufficient to continue with the normal rations until the provisioning of the sugar cane straw after just the transition period. Therefore, a ration composition adjustment becomes necessary (days 236 to 239).

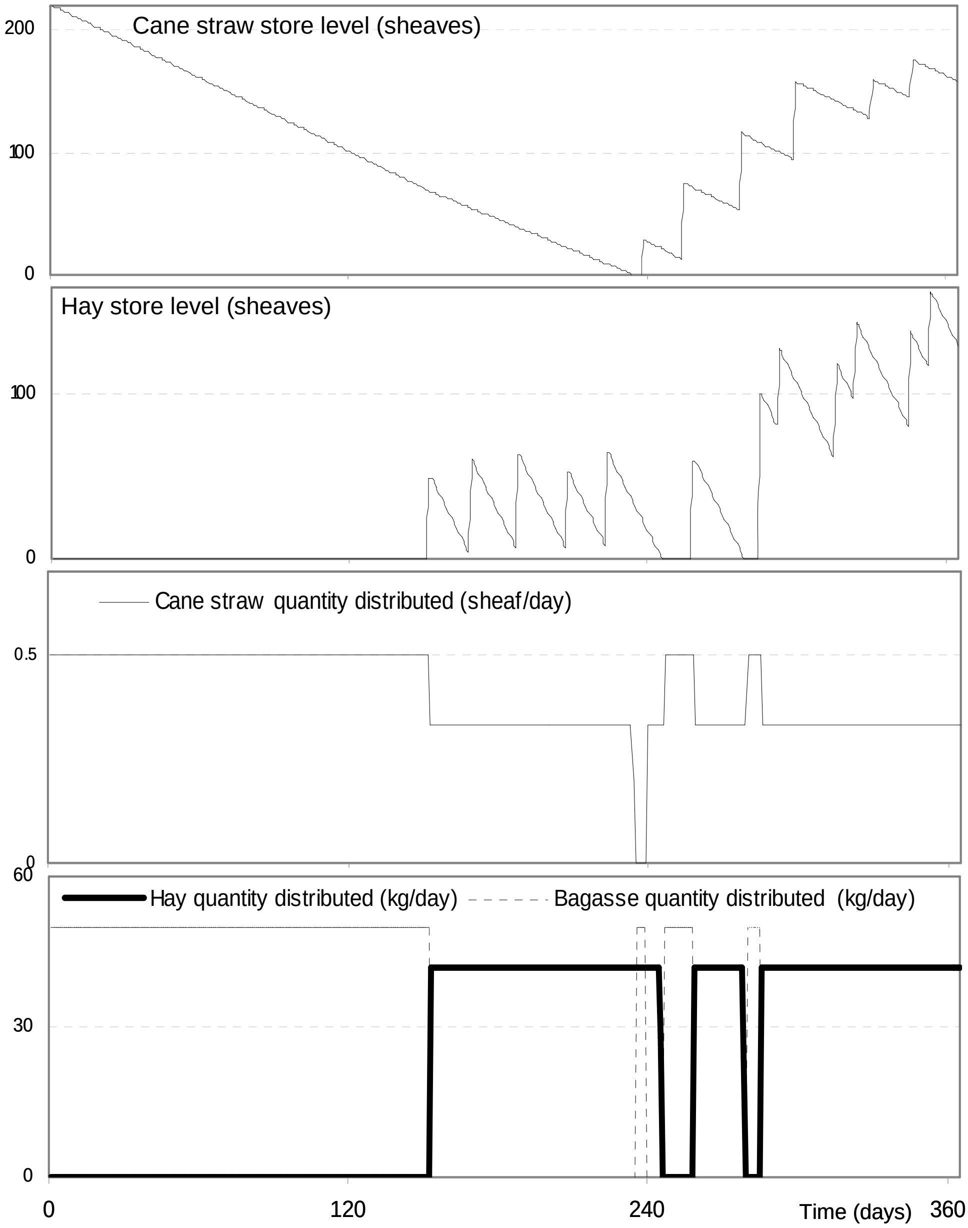

Figure 19. *Forage stores level and ration composition of producing cows simulated by GAMEDE ('SAM actions', farm 2 for 2005).*

IV.5 Discussion: validation and co-products of the action modelling

IV.5.1 Quantitative validation of the methodology

As discussed above, this section compares the outputs of two simulation options of GAMEDE: (i) if actions are derived from the action plan they are called 'planned actions', (ii) if from the operation decision rules listed in the SAM, they are called 'SAM actions'. The two types of simulated actions are compared to 'effective actions' observed in the scope of the bimonthly visits to the farms. Continuing with the two illustrations of operations in the results section, we propose here to compare (a) the dates of simulated ensiling works to the effective dates (Fig. 20) and (b) the nature of the food ration simulated to rations effectively distributed to dairy cows (Fig. 21). Schedules within a week time-step are used for this comparison. Two error indicators can be derived from these simplified representations: (a) the percentage of ensiling works if the simulated date differs by more than two weeks from the effective date and (b) the percentage of weeks if the simulated ration is different to the effective ration. Fig. 20 and 21 illustrate that SAM actions are more realistic than planned actions. For example, the error on ensiling dates is reduced from 14.8 days (+/-11) to 6.2 days (+/-6).

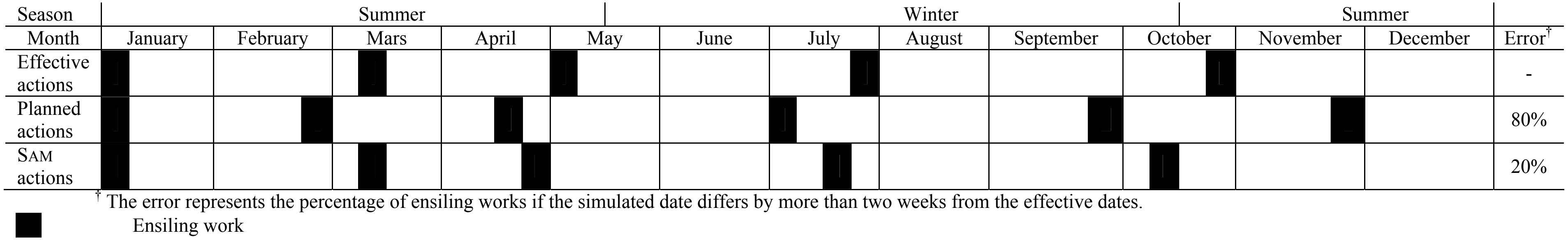

Figure 20. *Temporal repartition of the ensiling works: simulated actions compared with effective actions (field 2, farm 2 for 2005)*

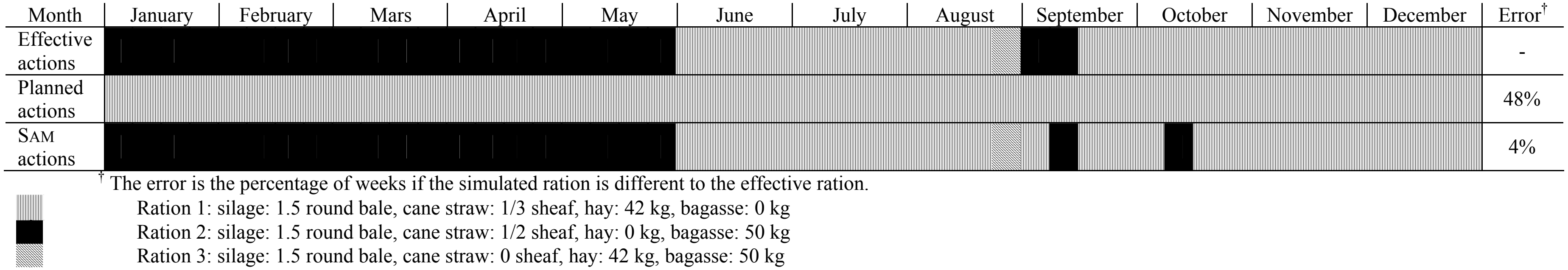

Figure 21. *Composition of the food ration (forage part): simulated actions compared with effective actions (50 producing cows, farm 2 for 2005)*

Improving the realism of the action increases the precision of the dynamic biotechnical representations calculated by GAMEDE. To illustrate this point Fig. 22 shows the biomass of green forage present on a field in farm 2 as a result of two harvest practices (planned and SAM harvests). The action plan simulation generates early harvest of the forage (meaning under estimating the quantity harvested per ensiling works) and over estimates the annual yields (6 harvests per year versus 5 harvests per year for the SAM and the effective practices). The error due to the simulation (over estimates and under estimates) on quantity harvested per ensiling works is reduced with the SAM actions: the error is reduced from 28.5 to 12%.

Fig. 23 represents dynamically the store level of sugar cane straw as a result of two rationing practices (planned and SAM rationing). The action plan tendency is an overvaluation of store levels because of an undervaluation of the use of co-products of sugar cane to feed animals. Using the SAM to simulate actions decreases the error of stores management models from 20.5 to 7.5%.

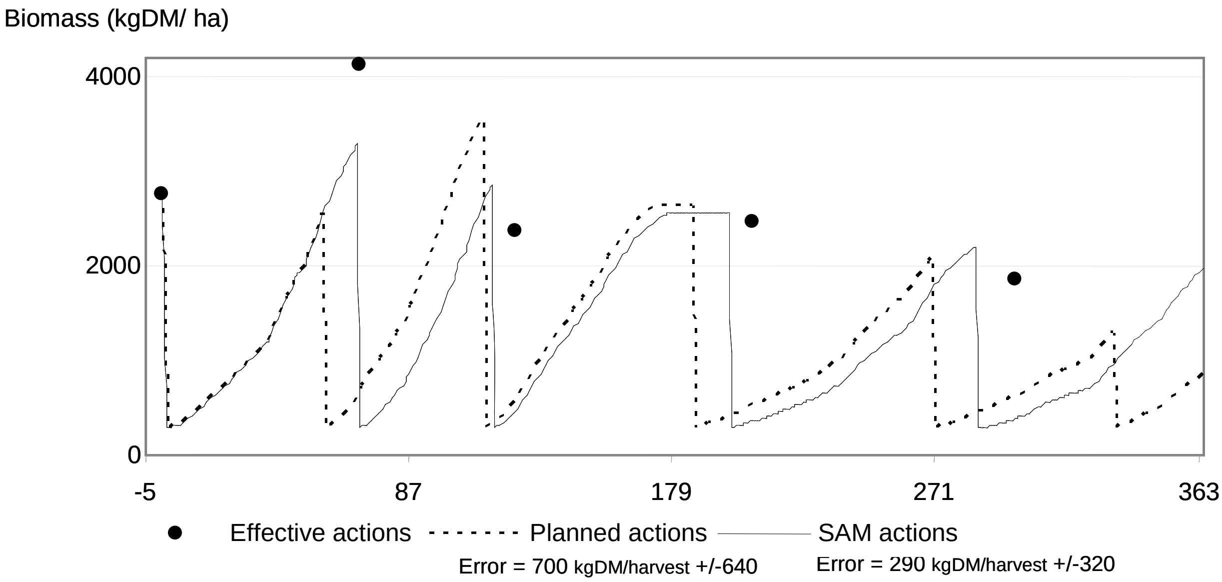

Figure 22. Green forage on field simulated by GAMEDE: compared with biomass simulated from 'planned actions' and from 'SAM actions' to 'effective actions' (field 2, farm 2 for 2005).

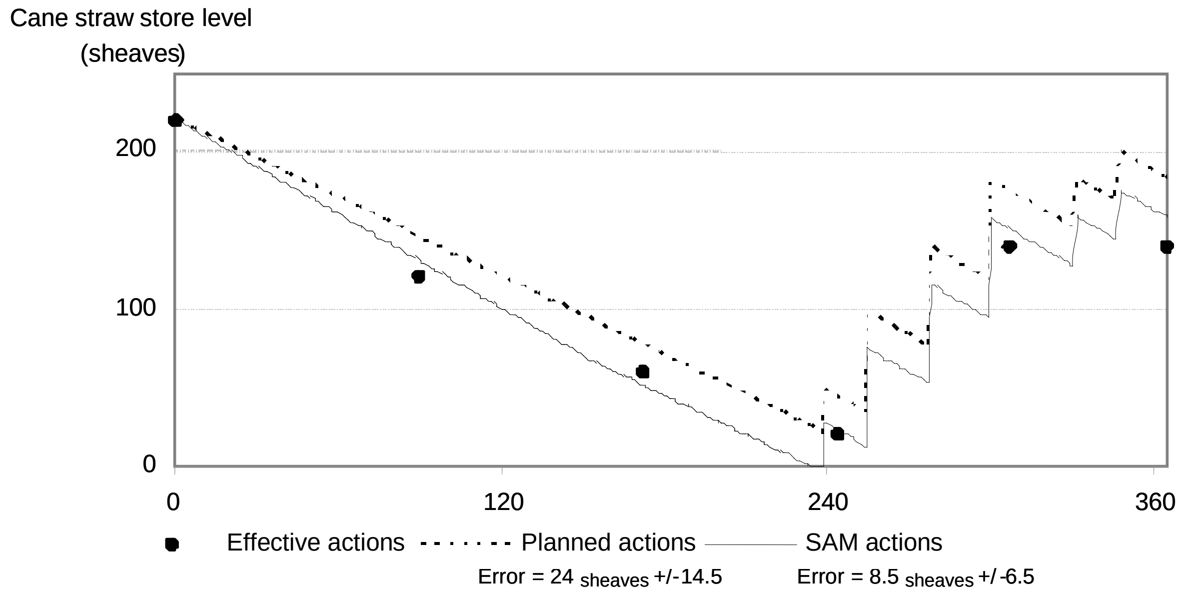

Figure 23. *Forage store level simulated by GAMEDE: compared with biomass simulated from 'planned actions' and from 'SAM actions' to 'effective actions' (sugar cane straw store, farm 2 for 2005).*

To summarise the SAM and the corresponding methodology (including immersion) increase the realism in comparison to more classical methodologies (rapid appraisals) and resulting models that simulate actions from the action plan.

IV.5.2 Qualitative validation of the SAM

Three forms of validation have been combined.

(1) Validation at the farm level. We used the SAM to formalise and represent various actions: all the 19 technical operations that generate biomass flows were studied. Hence this could be considered as a generic structure. Two radically different operations have been taken as illustrative cases for the study, and the validation approach that can be extended to the remaining operations.

(2) Validation at the working group level. As discussed by Fountas *et al*. (2006), we notice that the participatory method offers certain form of validation by leading to refinement and modifications of the SAM. As explained above, farmers of the working group were involved in individual and collective validations. Since decision rules are researchers' mental constructions, it became important for us to validate them from farmers' expertise. We have coupled three types of validation contexts: individual feed-backs in the scene of the bimonthly visits, collective feed-backs and collective work during meetings. The SAM was presented to the six farmers under the form of a question series corresponding to the different decision rules. The farmers' reactions were "all the questions that we have to consider are listed… some of them are momentary… but those questions do not come up all the time…". Discussions with farmers about this conceptual model have shown that

this three steps structure (the SAM) has a certain similarity with real decisional processes of farmers. The farmer, starting his days' work, lists the technical operations he has to perform in the day, he selects those he can realise considering his means of action (= resources), then he carries out the operations that have been selected.

(3) Validation done at the regional level. It concerned the 36 farms of the typology group: 27% of the farms of the dairy sector. It was necessary to test the SAM with farmers not involved in the conceptualisation of the structure. The SAM has been applied to formalise the 36 dairy farmers' actions of farm management, their work organisation and to understand their strategies. This application has constituted the base of the typology of practices combination (Vayssières *et al*., 2006). Additional research is required to test the validity of the SAM proposed in this study in dairy farms of other countries or moreover to study other production systems.

IV.5.3 Crossing planned action and situated action theories

We have already seen that conceptual elements of both the action model concept and the ontology of agricultural production systems are combined in the structure proposed. Several previous studies applying the action model insist on planning of decisions and actions. However, as this study has shown, the action plan is scarcely followed because of diverse reasons (constraints listed in Tab. 4) and that adjustment rules are numerous.

An other theory exists, generally presented in opposition to 'planned action' and called 'situated action'. This theory presents action as a result of decisions mainly guided by contextual aspects of the farmer's environment and not only oriented by general objectives. In situated action (Suchman, 1987), the emphasis is on interaction between the agents and their environment. The notions of 'plan' and 'objective', which are the bases of the planned action theory (the problem-solving approach), are deemed irrelevant to simulate action in people's practice. A plan is viewed as a resource for action, not as its mere determinant, and 'motive' is substituted for 'objective' (Suchman, 1987; Clancey, 2002).

This second theory can explain observations of Fountas *et al*., (2006), noting that some farmers are more instinctive than others which is also noted in dairy farmers of La Réunion. In certain cases, it was difficult to construct the action plan of the farmers with them, as they did not have a plan of their farm management at a yearly time horizon but at a two weeks time horizon. In spite of this drawback, the way they manage their farms was also successfully developed with the SAM. For those 'intuitive farmers', the majority of technical operations are initiated by alarms contrary to 'planning farmers', in which technical operations are more often initiated by operation schedules. The SAM approach has the advantage to consider both planned action and situated action theories. Studies on operational decisions, like the one presented in this article, seem to offer a bridge between those two theories and could help to define a modelling ontology of action (Guerrin, 2005).

IV.5.4 Co-products of action modelling: a better comprehension of farmers' logic of farm management

Other results of this study have not been reported in this article and will appear as separate publications. However, we list here some co-products of action modelling.

The primary aim of this study was to explain (with simulation) farming practices and difference of achievements between years for the same farmer to identify realisation and adjustment rules. As discussed by Aubry *et al*. (1998) and Dounias *et al*. (2002), this study focused on identifying key management factors and to understanding variability of practices between different farmers in a same year. We have represented the strategy diversity of dairy farmers as the typology of practices combination (Vayssières *et al*., 2006). We have also identified the indicators used by farmers to manage their farm and we have observed that they are not the same as the ones proposed by researchers. Taking the grasslands management example was the occasion to defend search of common indicators (Vayssières *et al*., 2005).

These studies on technical operations were also an opportunity to synthesise knowledge about complex agricultural production systems and to move to other decision levels: tactical (the action plan) and strategic decisions. In particular, we have identified numerous factors that determine farmer's strategy definition: biophysical (climate, soil characteristics) and socio-economic (degree of geographical isolation, concentration of dairy farms) environmental factors, exploitation structure (equipment, land), technical references of the farmer and the objectives of the household. These two last components appear particularly important in our study case (Vayssières, 2004). They are based on a set of experiences, level of training, education and cultural aspects. They have important consequences on time that the farmer is ready to invest in the management of his farm (between 35 and 75 hours per week), and on the strategic technical choices. In the DS derived from the SAM factors which are not purely technical (e.g. cultural) are taken account via the available time to realise technical operations. For example, farmers participating in religious/cultural events loose a part of their available time at certain periods. The SAM offers the possibility to also consider current life events, like death in the family/friends, sickness or wedding, by decreasing momentarily the available time, and to represent their consequences on technical actions. The effect on actions is indirect (via the available time) and consequently beyond the scope of this article.

Moreover, the methodology proposed in this study presents an opportunity to determine the nature of technical references and to point lack of information and knowledge. Those two observations are respectively supported by Sebillotte and Soler (1988), Barbier and Mouret (2000) and Fountas *et al*. (2006). A better learning of farmer's knowledge could help to define more adapted management indicators, and to predict innovation adoption or rejection.

To synthesise, action modelling gave us a larger expertise of the production system than expected.

Conclusion

The results of this study are twofold. First, a multi-step and multi-tool methodology has been developed for systematically collecting information from farmers to describe their action-making process. The methodology combines detailed and large approaches (36 farms). The detailed approach concerns a work group of six farmers involved in the whole farm model construction. These real case studies are based on three complementary methods of inquiry: immersion, visits and meetings.

Second, a three steps structure for action modelling, the SAM, has been presented. It describes the successive intervention of different types of operational decision rules and it solves competition for resources between technical operations. The importance of this competition would not be revealed if the whole farm management was not considered. The SAM also helps to define the guidelines of the inquiries, making sure factors that could influence decisions are not forgotten. The methodology and the conceptual structure to represent action are thus particularly linked.

The hypothesis that farmers plan their decisions is verified as regards the technical management of forage crops and dairy cattle. But regarding how action plan is executed or not has shown the importance of necessary adjustments with reference to climatic uncertainty, forage abundance, labour and equipment availability. This whole farm study shows that technical management of dairy farms is not the sum of the technical decisions taken for each field, for each animal batch or for each technical operation. The farmer manages the farm shift as a whole and it is the decisions made at this level that determine how each individual field or animal batch is managed and how each technical operation is conducted.

To approach the research objectives by technical operations was not only a way to better understand managing interactions within the agricultural system but, technical operations and their descriptive variables, specifying the biophysical effects of operations (flows nature and stores level in this case), are the link between the DS and the BS.

The methodology and representation structure presented in this paper could possibly be extrapolated to study other agricultural production systems because, firstly the structure has been applied in dairy farms from concepts developed and mainly applied to crop farms. Secondly, the dairy farm is a particularly complex system, comprising both animal and crop management. Thirdly, we have studied a very large range of technical operations: crop fertilising and harvest, cattle feeding, replacement and culling, manure conversion and spreading. Finally, the strategies observed are diverse: we encounter strategies existing as in developing countries (e.g. based on manual green harvest of forage), as in developed countries (e.g. based on mechanised grass ensiling in wrapped bales). Therefore, this 'action modelling approach' has to be tested on other crop-livestock systems to build computer simulators of practices and to better understand Research-Development programs failures and successes.

Acknowledgements

We express our gratitude to Jean-Pascal Deurveilher, Etienne Vitry, Jeannick Marianne, Jean-Luxène Padre, Pierre-André Gérard and Gervais Hoarau, farmers of the working group, for their cooperation during the three years of the study, and their involvement in the practices study. They have generously allocated a significant amount of time to describe their practices and validate the proposed structure on their farms. We are also grateful to Roger Martin-Clouaire and Jean-Pierre Rellier for their training about their ontology.

Conclusions intermédiaires et transition

Sans remettre en cause le fait que les agriculteurs planifient la conduite de leur exploitation, ce chapitre montre l'importance des ajustements dans l'action au quotidien et l'intérêt de développer un DS sur la base de la « Structure for Action Modelling » (**SAM**).

En effet, la SAM permet ici d'organiser 300 règles opérationnelles : à la fois des règles de réalisation et des règles d'ajustement.

Ayant ainsi décrit et formalisé de façon approfondie les pratiques décisionnelles des éleveurs nous proposons dans le chapitre suivant de montrer en quoi l'utilisation de GAMEDE avec différents acteurs de la filière laitière peut les aider à prendre des décisions pour améliorer la durabilité de leur élevage.

Chapitre V. INTERACTIVE SIMULATION OF VARIOUS MANAGEMENT STRATEGIES[7]

Abstract

GAMEDE is a dynamic simulation model designed to represent dairy farm functioning and the consequences of the farmer's management choices on the sustainability of the farm. The sustainability is evaluated according its three pillars: technical viability, environmental respect, and social liveability. This paper illustrates typical applications of the model. Results show that GAMEDE can help scientists i) to compare existing systems, ii) to explore the farm functioning and constraints, and iii) to better understand the origin of sustainability.

Moreover, the model is a useful tool for farmers to improve farm sustainability by i) making explicit the underlying control levers and interrelated effects of decisions on the indicators and ii) simulating prospective scenarios defined by farmers and extension agents. Our experience has shown that interactive visual simulations using GAMEDE with the farmer are particularly relevant to generate knowledge exchange and to define improved ways to reach farmers' objectives. While certain authors have noted that decision support systems (**DSS**) are poorly adopted by farmers, we observed that our model responded particularly well to issues of the dairy farmers, who were actively involved in the design of the model. Moreover, GAMEDE permits dynamic assessment of the production system and represents the farm as a whole, increasing the interest of farmers in the model outputs.

Keywords: Whole-farm management; Visual interactive simulations; Real and prospective strategies; Dairy farming; Tropical island

[7] **Basé sur**: Vayssières J., Bocquier F., Lecomte P. GAMEDE: a Global Activity Model for Evaluating the sustainability of Dairy Enterprises. Part II – Interactive simulation of various management strategies. Agricultural Systems, in review.

Introduction

In many developed countries, dairy farms have grown more dependent upon commercial fertilizers and supplemental feeds. Their use has increased forage crop yields and milk production. With heavy import of nutrients, however, there is greater opportunity for build-up of nutrients in the soil and loss of excess nutrients (e.g. nitrogen: **N**) to ground and surface waters.

In this context, dairy farms that are more sustainable must increase the whole efficiency of the farms while maintaining or reducing the negative impacts on the environment and keeping the workload of the farm at an acceptable level. Many alternative management options are available to today's farmers. These include i) strategic choices in the number of animals to keep, crop harvesting systems, manure handling systems and ii) tactical and operational choices in the forage stage for harvest, the fertiliser dose and frequency, the quantity of concentrate distributed per cow, and much more. Changes in one component of the farm often affect other components, and their interactions can cause changes in the productivity, environmental impact, and workload of the farm.

It is not easy to quantify and compare the sustainability of management strategies and tactical decisions. A farm that performs well under one set of practices and weather conditions may not perform well under other conditions. Field studies of this type are costly, impractical, and sometimes impossible. Another approach is to use computer simulation models to study such complex systems and to compare results over several years. Models testing management options should be relevant for farmers to gain expedient and risk-free experience (Carberry, 2002).

The need for a research tool that integrates the major decisional processes in technical management and the many biophysical processes on a dairy farm has led to the development of the GAMEDE simulation model. This model was designed (and is currently being used) as advocated by Chau (1993), following a participatory approach involving six dairy farmers. The model, to be used as a DSS, has been conceived as a reflexive exploratory tool for users to check for their ideas (e.g. tentative farm management strategies), to assess their consequences, and, by performing "what-if" simulations, to understand how the whole system behaves. The same philosophy underlies CSIRO's FARMSCAPE project (Carberry *et al.*, 2002). In accordance with McCown (2002b), we thus do not follow the mainstream of operations research, from which many agricultural DSS have been derived based on optimisation models (e.g. linear or dynamic programming). As these DSS are, in essence, mainly prescriptive (they tell the user what to do) they have often been judged useless in many practical decision situations, namely in agriculture (see McCown's 'implementation problem'). In our opinion, such simulation models should be taken as tools (among others) to accompany a decisional process, not as a surrogate of the decision-maker.

GAMEDE has been described and validated in the companion paper. We propose here a concrete application of the model. The first section of this article describes the context of dairy farming in La Réunion and the methodology of GAMEDE implementation with different stakeholders.

The second, results section, illustrates GAMEDE i) by comparing "actual" production systems on the basis of sustainability indicators and along dynamic graphic representations of flows and stocks; ii) by simulating "hypothetical" options applied to actual farms to quantify progress margins. The discussion section compares this experience to other uses of DSS in a farm improved-management perspective. From stakeholders' viewpoint the model appears clearly as a useful tool to support farmers' decisions; possible reasons for this success are retrospectively evaluated.

V.1 Materials and method: from a model to interactive simulations

V.1.1 GAMEDE: the material support of simulations

Input parameters of GAMEDE relate to management, structure, herd, weather, and external resources. Action is a central concept in the model. The decisional system of GAMEDE simulates technical actions according to the farmer's action plan and operational decision rules and to the state of the production and the environment of the farm. The biophysical system of GAMEDE translates the technical actions into biomass flows depending on weather conditions. A synthesis translates the biomass flows (expressed in kg of fresh matter: **FM**) into N flows and calculates three types of sustainability indicators:

- Environmental indicators are the N efficiency (dmnl) and N surplus (in kgN ha^{-1} $year^{-1}$),

- Technical indicators are the milk productivity (in kgFM cow^{-1} $year^{-1}$) and the forage crop productivity (in UF ha^{-1} $year^{-1}$) all harvesting systems included (silage, cut and carry, or grazing). The UF is the forage unit defined by the UF/PDI feeding unit system (Jarrige, 1989) characterising the energy value of a considered feed to allow milk production or weight gain.

- Social indicators are the total and the repetitive work time (in hrs $week^{-1}$).

V.1.2 Dairy production areas and typical cases of farming systems

In this article, GAMEDE is illustrated by simulating six actual farming systems. These typical commercial farms were selected to cover

- the diversity of the decision profiles and management practices with reference to a typology of practice combination (Vayssières *et al*., 2006),

- the pedo-climatic characteristics of the four areas with dairy farms in La Réunion (Vayssières, 2004).

Tableau 7. *Description of the four dairy farming areas in La Réunion*

Dairy farming area	Altitude	Temperature			Rainfall		
		Summer	Winter	Year	Summer	Winter	Year
(code)	(m)	(°C)	(°C)	(°C)	(mm month^{-1})	(mm month^{-1})	(mm year^{-1})
1	950	20.4	17.2	19.2	95	35	915
2	1400	14.7	10.7	13.4	190	45	1700
3	1200	17.4	14.1	16.3	415	135	3855
4	700	18.6	14.4	17.2	225	265	2840

Average values observed from 1997 to 2006.

In the austral, tropical, and mountainous island of La Réunion, climatic conditions are contrasted according to altitude and exposure to trade winds. Two main seasons with short transitions can be distinguished: the summer (from 16 September to 15 May) and the winter (from 16 May to 15 September). In most areas winter is cold and dry, and summer is hot and rainy except for area 4 where rain falls all year (Tab. 7).

Increased milk production is encouraged in La Réunion by subsidies linked to production. The milk locally collected represents 30% of the local consumption. Due to severe land constraints, production performances depend largely on external inputs (concentrate feeds and mineral fertilisers). Due to its high cost, salaried labour is scarcely used and family labour is dominant. More details on the dairy sector are given in Vayssières *et al*. (2007b). The general agricultural context of the island has been reported by Aubry *et al*. (2006).

V.1.3 Definition of "actual" scenarios based on farms survey

To build the decisional system of GAMEDE and to capture operational decision rules of farmers, an iterative and multiple-tool methodology has been conceived (detailed in Vayssières *et al*., 2007b). This multiple-year survey was also dedicated to collecting the management, structure, and external resources characteristics of the farms necessary to parameter GAMEDE.

An interactive and iterative methodology

This methodology was applied for three years on each of the six farms and it was based on three types of inquiries per farm: immersions (1 week per farm in 2004), individual visits (on a bimonthly basis in 2005-2006), and meetings (thrice a year in 2005-2006).

- Immersion is based on one-week work-*cum*-training periods including open discussions with the farmer (Vayssières, 2004). The researcher (first author of the paper) participated in all the technical operations on the farm under the supervision of the farmer. This rapprochement created a trusting relationship and offered many opportunities for observations. Living farmers' lives was also a good opportunity to discover the questions and constraints of farmers.

- Regular visits to farmers were organised to investigate their action plans and effective realisation. Continued occasional participation in the farm works maintained the relationship.

- Individual (within bimonthly visits) and collective (during meetings) evaluations of our research results by farmers is a key aspect of our modelling approach. Farmers provided inputs, comments, recommendations, and criticisms on the partial prototype models and then on the global model.

The trusting relationship between the farmers and the researcher, the observations, and the critical feed-backs contributed to the *reliability of results* presented in this article.

Management, structure, and external resources characteristics of the farm

It is no longer necessary today to collect all these data because the model is built. To simulate a new farm with GAMEDE in the local context, it is sufficient to conduct a rapid appraisal based on a 2-hr semi-directive interview of the farmer using the inputs data grid of GAMEDE as a guide. This rapid appraisal has been successfully tested on about thirty other farms.

Herd characteristics of the farm were provided by the “milk board recording scheme”. This service provides, every 45 days, the technical characteristics of the dairy herd (e.g. milk productivity and composition, reproduction performances) to support farmers in managing their farm.

Weather data were provided by the GESMET software. It allows extraction of data collected on a daily basis by the dense network of meteorological stations of Météo France and CIRAD.

V.1.4 Identification of “hypothetical” options from different sources

GAMEDE has been designed to simulate a wide range of technical options, but the central question is which option to simulate. Three main entries are considered: computer-based options proposed by scientists, expert-based options proposed by extension agents, and practical options proposed by farmers.

Sensitivity analysis

Saltelli (2000) defines sensitivity analysis as “the study of the relationship between information flowing in and out of the model”. Brugnach (2005) proposes a general approach for building a process-level sensitivity analysis starting with defining the scope and the question of the analysis. Sensitivity analysis is generally used to characterise and understand model behaviour or to ensure that the way in which the model operates resembles the phenomena being modelled. In contrast we use it here to respond to an operational question: “what are the most important control levers on farm sustainability? Are they structural or management aspects?”

As reference scenarios for sensitivity analysis we used the same data sets corresponding to the six dairy farms used for validation in the companion paper. Simulation was done using three years of weather data (2004-2006), but only the mean results are shown (appendix J). Sensitivity analysis was performed with the PayOff function of Vensim®. The model’s response to changes was studied on the six sustainability indicators. The test ranged from -10% to +10% around each of the reference parameters considered for each of the six farms. In the first step the sensitivity was analysed for all the input parameters to identify their relative influences on the sustainability indicators. In the second step, to keep the analysis results to a manageable level, the model's response was tested along a subset of the 50 most influential inputs. Sensitivity results are presented in § V.2.3.1.

Questions raised by extension agents

Extension agents were mobilised to criticize the model's outputs. They were keenly interested in the representations proposed by the model. They already knew the six farms cases well and they had technical proposals to improve their performances. Numerous questions about consequences of these technical options were raised during simulations; we respond to some of them in § V.2.3.2.

Questions revealed during interactive modelling with farmers

Turban (1988) emphasizes the importance of user involvement in the design of DSS: "The requirement stems from a need for user expertise in the design effort, and also recognises that successful implementation will be more easily achieved with active involvement." GAMEDE was designed to support La Réunion farmers' decisions. A close interaction with the six farmers was maintained during the entire model designing process (Vayssières *et al*., 2007a). In the final stage of model evaluation, farmers spontaneously proposed hypothetical scenarios to be tested with GAMEDE. An example of scenarios proposed and analysed by farmers is presented in § V.2.3.3.

V.2 Results: from external assessments to co-constructed solutions

In this part, the first two sections demonstrate the model's ability to represent real production systems. The last two sections show that GAMEDE can represent the incidences of a wide variety of hypothetical management options, such as technical innovations, on the sustainability of existing farms.

V.2.1 Learning from diversity

The list of inputs constitutes a guide for inquiries describing farms. GAMEDE also calculates biomass and N flows and some sustainability indicators of the production systems. GAMEDE's inputs parameterisation and calculations allow farms to be compared.

Farm structure and location

The six study cases are all family-farm systems with limited workforce, which explains why the herds range from 20 to 90 cows (Tab. 8). Land availability is strongly limited by mountainous constraints and urbanisation pressure except in area 1. Hence, in areas 2 to 4, cattle stocking rates are generally high (> 3.5 LU ha^{-1}). Because straw is scarce, slurry is the dominant effluent handling system. In the six cases, slurry pits are uncovered and their capacity is paradoxically smaller in rainy areas where dilution by rainfall is potentially higher (farms 1, 3 and 5).

Tableau 8. The six farms' structure and location

Farm (code)	Dairy farming area (code)	Cows (Al)	UAA (ha)	Stocking rate (LU ha^{-1})	Slurry pit capacity (10^3 kgFM)	Workforce (AWU)
1	4	25	9	2.8	55	1.8
2	2	71	26	3.2	330	1.5
3	3	57	16.5	4.1	200	1.2
4	2	34	4.5	7.1	240	1.0
5	4	19	6.4	3.2	36 (0)	1.1
6	1	90	67.5	1.5	260	2.2

Data observed in 2004, which served as inputs for GAMEDE simulations
Al: Animal, UAA: Utilised Agricultural Area, LU: Livestock Unit, FM: Fresh Matter, AWU: Agricultural Workforce Unit.

Farmers' practices and social liveability

Four management domains with strong influences on N flows were identified by the sensitivity analysis (see § V.2.3.1): forage harvesting, animal feeding, effluent handling, and fertilising practices. In Fig. 24 technical options encountered in dairy farms of La Réunion are classified along a work-time intensity gradient (represented by the grey arrows). Two extreme strategies are encountered. i) A strategy based on continuous grazing was defined by farmer 5 to save work time. This farmer handles low quantities of effluents and forages. The feeds he distributes are mainly imported feeds already conditioned. In the barns, solid manure production is dominant and totally given to market gardeners who, in exchange, clean the barns for free. ii) A strategy centred on cut and carry foraging was defined by farmer 1 to attain a high feeding self-sufficiency; work time is set in second priority. Cut and carry is time consuming; it is a repetitive task requiring daily harvest of forage. In contrast, ensiling is based on high workloads localised in time. In this strategy, effluents are valorised by fertilising forage crops and by selling matured solid manure. To sell solid manure farmer 1 has to transport it. Forage crop fertilisation combines organic and mineral fertilisers. All these options are particularly time consuming but they improve farm N efficiency (Tab. 9 to 11).

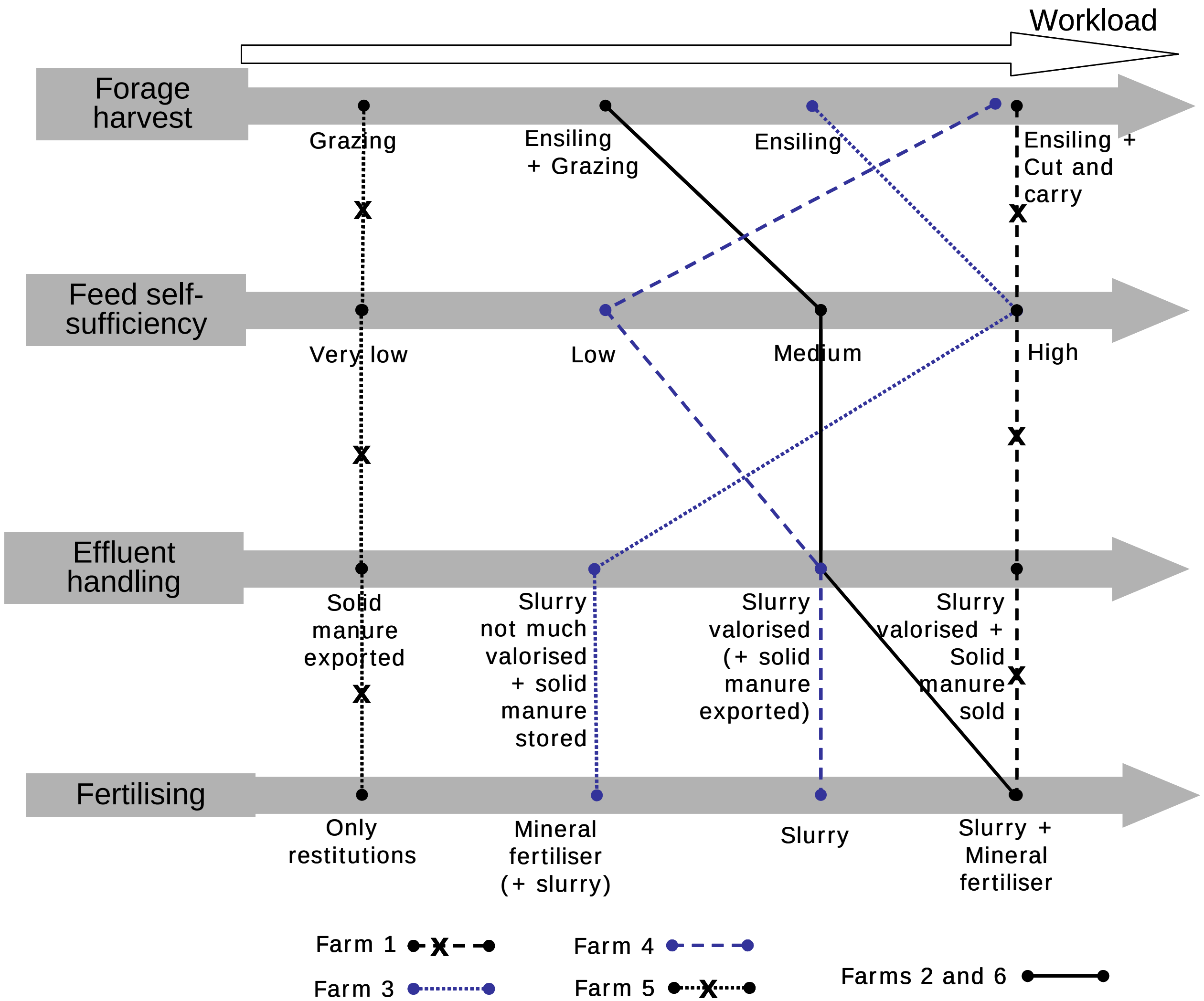

Figure 24. *Synthetic representation of the six dairy farmers' practices (data observed in 2004-2006).*

Technical results

Milk production of La Réunion dairy farms, with an average of 6 10^3 kgFM cow^{-1} $year^{-1}$, are not so far from productions of European farms. In La Réunion, however, they rely on large use of concentrates (> 10 kgFM cow^{-1} day^{-1}).

The silage yield depends on climatic constraints. Areas where *chloris gayana* (a C4 tropical grass) can be cultivated allow larger yields (farm 1). Harvesting at a sustained pace can lead to larger yields (farm 4 in comparison to farm 2 located in the same area, Tab. 9 and 11). Due to climate intra-annual variations, all-the-year grazing on the same surfaces leads to unexploited areas (see § V.2.2) and then to lower forage crop productivities (farms 5 and 6, Tab. 9 and 11).

Tableau 9. The six farmers' practices concerning forage crop and feed management

Farm (code)	Forage crop management				Feed management			
	Harvesting system: part of the UAA (dmnl)			Harvest interval in summer	Sugar cane straw import	Chloris hay import	Quantity of distributed concentrate	Feed self sufficiency
	Ensiling	Cut and carry	Grazing	(days)	(kgFM LU^{-1} $year^{-1}$)	(kgFM LU^{-1} $year^{-1}$)	(kgFM cow^{-1} day^{-1})	(dmnl)
1	0.48	0.52	0	65	507	0	13.5	0.4
2	0.5	0	0.5	60	915	558	12.6	0.25
3	1.0	0	0	62	760	0	12	0.38
4	0.72	0.15	0.13	50	472	0	15.5	0.16
5	0	0	1.0	-	1230	682	12	0.1
6	0.32	0	0.68	55	430	0	15	0.24
Average	0.50	0.11	0.38	58	719	206.7	13.4	0.26

These values are the means of observations collected for the 2004-2006 period.
UAA: Utilised Agricultural Area, dmnl: dimensionless.

Tableau 10. The six farmers' practices concerning herd and fertilisers management

Farm (code)	Herd management		Fertiliser management							
	Objective culling rate	Objective growing rate	Effluent handling system : destination of dejecta productions (dmnl)			Mineral N quantity spread on cut grasslands	Part of organic N spread or returned to farm crops	Part of organic N exported	Part of organic N not valorised	
	(dmnl)	(dmnl)	Slurry	Solid manure	Direct restitution	(kgN ha^{-1} $year^{-1}$)	(dmnl)	(dmnl)	Emitted before spreading (dmnl)	Others (e.g. slurry pit overflows) (dmnl)
1	0	0.25	0.82	0.18	0	162	0.42	0.17	0.32	0.09
2	0.1	0.10	0.30	0.05	0.65	369	0.84	0.05	0.11	0
3	0	0.20	0.35	0.15	0.50	265	0.58	0.03	0.15	0.24
4	0	0.10	0.48	0	0.52	0	0.86	0	0.13	0.01
5	0	0.20	0.19	0.06	0.75	0	0.72	0.20	0.08	0
6	0	0.30	0.17	0.10	0.73	898	0.75	0.07	0.09	0.09
Average	0.0	0.19	0.39	0.09	0.53	282	0.70	0.09	0.15	0.07

These values are the means of observations collected for the 2004-2006 period.

Tableau 11. Technical and social results of the six farms calculated with GAMEDE

Farm (code)	Technical results					Social results	
	Milk productivity	Silage productivity	Forage crop productivity	Feed self sufficiency	Work efficiency	Total working time	Part of repetitive work
	(10^3 kgFM cow^{-1} year^{-1})	(Round bales ha^{-1} year^{-1})	(10^3 UF ha^{-1} year^{-1})	(dmnl)	(kg of milk hr^{-1})	(hrs weak^{-1})	(dmnl)
1	6.6	81	8.6	0.40	48	62	0.88
2	5.9	49	4.6	0.25	93	85	0.94
3	5.8	69	10.2	0.38	79	73	0.91
4	8.1	73	9.4	0.16	66	70	0.97
5	4.0	-	2.0	0.10	32	51	0.97
6	5.5	64	2.8	0.24	73	119	0.88
Average	6.0	67	6.3	0.26	65	77	0.93

These values are the means for the 2004-2006 period.

Flow characteristics

In manual systems (farms 1, 4 and 5), farmers manipulate less biomass (about 7.5 10^3 kgFM day^{-1}) while in mechanised systems they manipulate more than 11.5 10^3 kgFM day^{-1}. The simulations show that internal N flows are substantial in all the studied systems. They represent 60% (55-64%) of the total N flows of the farm, justifying detailed modelling of all farm flows. These results are similar to the ones found for phosphorus in an experimental farm (Modin-Edman *et al*., 2007).

Controlled N flows (i.e. human driven) are also substantial: 83 % (74-91%). This reveals that farmers' decisions highly influence N flows. These controlled flows are greater in the most self-sufficient systems (farms 1 and 3) and lesser in the grazing systems (farms 5 and 6).

GAMEDE also calculates N allocation to main flows. Taking the example of farm 2, among the 10 tons of N imported per year, about 2.5 are exported, 2.0 are emitted in gaseous form, and 5.5 are stocked at the farm scale (within the 28 ha of grasslands).

Tableau 12. The six farms' environmental results and flow characteristics calculated with GAMEDE

Farm (code)	Environmental results		Flows characteristics		
	N efficiency	N surplus	Part of Internal N flows	Part of Controlled N flows	Average quantity of daily manipulated Biomass
	(dmnl)	(kgN ha^{-1} year^{-1})	(dmnl)	(dmnl)	(10^3 kgFM day^{-1})
1	0.32	329	0.60	0.91	7.3
2	0.26	330	0.64	0.83	11.9
3	0.18	547	0.63	0.86	11.6
4	0.23	1220	0.62	0.84	7.2
5	0.33	318	0.55	0.74	2.0
6	0.17	267	0.57	0.82	15.2
Average	0.25	502	0.60	0.83	9.2

These values are the means for the 2004-2006 period.

Environmental results

With reference to Tab. 12, two systems (farms 1 and 5) have a high N efficiency based on two environmentally friendly alternatives: the valorisation of on-farm-produced forages (farm 1) and the export of solid manure (farm 1 and 5).

Farms' N surpluses are generally about 300 kgN ha^{-1} $year^{-1}$ except for two systems with higher surpluses: farm 3 has a very low N efficiency due to limited on-farm valorisation of the organic fertilisers it produces; farm 4 strongly intensifies the land factor with a high stocking rate and a high use of imported concentrate feeds.

Fig. 25 is a synthetic graphic representation based on annual sustainability indicators calculated by GAMEDE that allows an overview and comparison of farming systems.

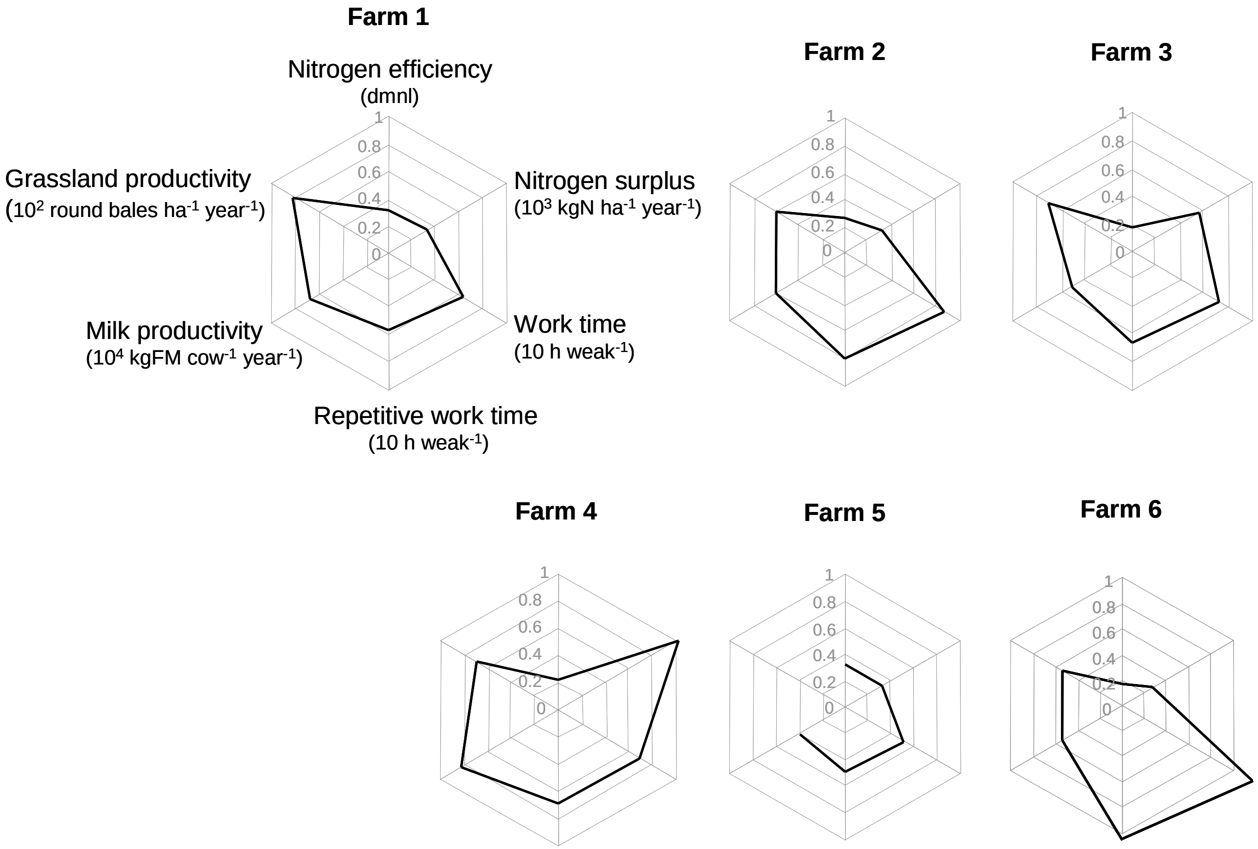

Figure 25. *Sustainability of the six farms' actual strategies (data simulated with GAMEDE, 2004-2006).*

V.2.2 Learning from dynamical graphic representations

The idea is now to keep three farms (1, 2 and 5) to illustrate GAMEDE's relevancy to isolate management difficulties encountered by farmers. Farms 1 and 5 have the same climatic constraints/assets (hot and rainy climate) but they differ strongly in farmers' practices (Fig. 24). This facilitates comprehension of how management practices influence on-farm results. Farm 2, which is in a very different area (fresh and dry climate), can be considered as an average dairy farm in terms of local practices (Fig. 24) and in terms of environmental and technical results (Tab. 11 and 12). This is why this farm is taken as an example to illustrate GAMEDE in this section and also in § V.2.3.

Periodical work peaks

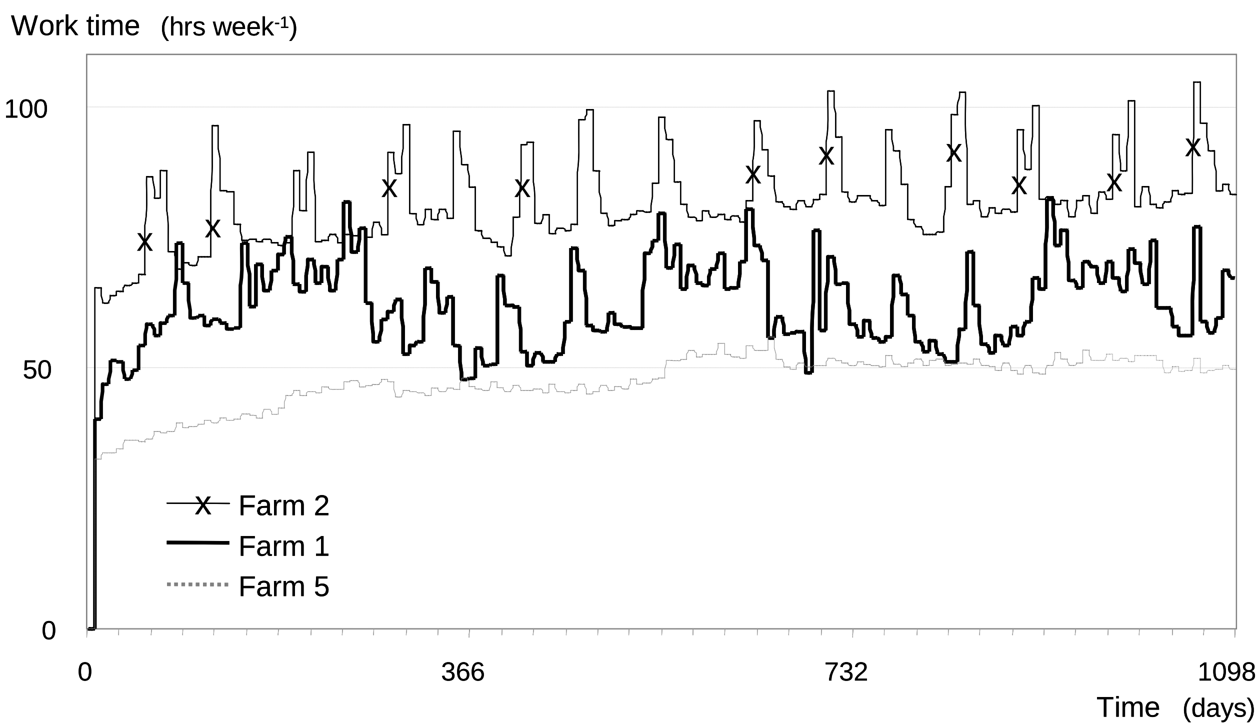

Figure 26. *Work time dynamical representation of three farms (data simulated with GAMEDE, 2004-2006).*

GAMEDE can be used to identify work peaks. In Fig. 26, periodical peaks of farms 1 and 2 correspond to ensiling and fertiliser spreading works. For farm 2 there are fewer peaks during winter because the grass growth rate is reduced by low temperatures and dryness. For farm 1 there is more workload during winter due to manual cut and carry of sugar cane *vs* mechanised cut and carry of grass during summer. In farm 5 the workload is more uniform over the year (no ensiling and fertiliser spreading works).

Periodical risk of forage deficit

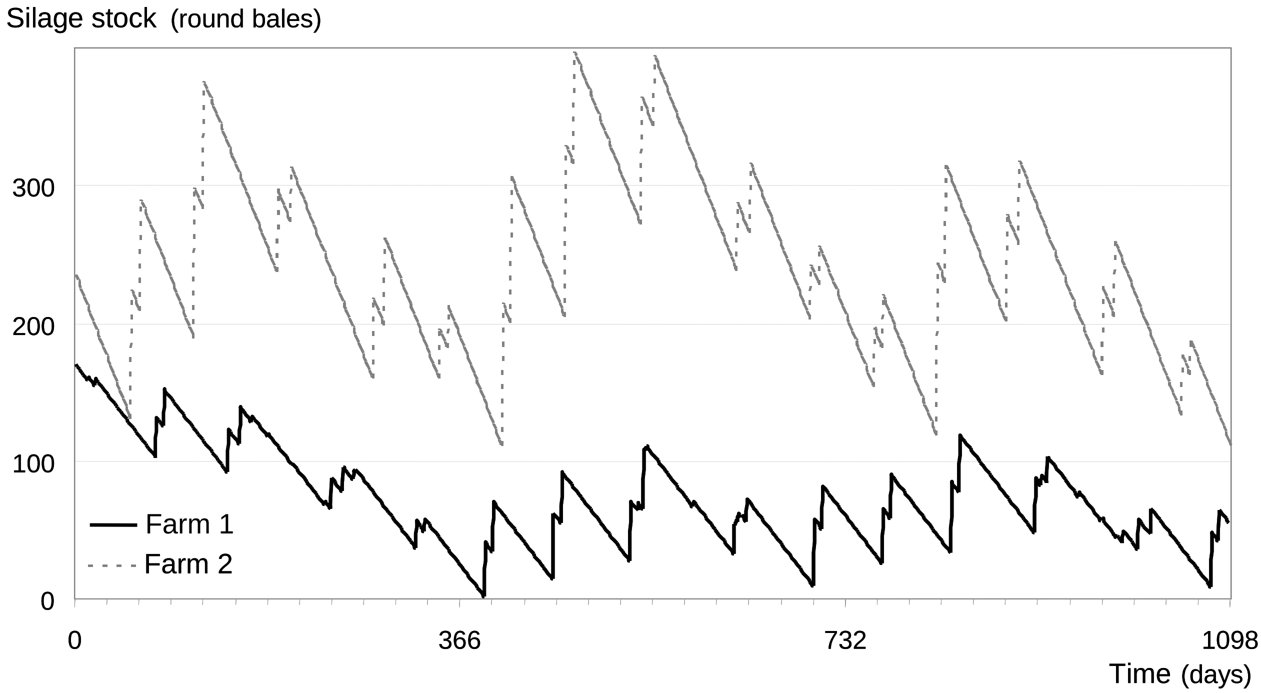

Figure 27. Dynamical representation of three farms' silage stocks (data simulated with GAMEDE, 2004-2006).

GAMEDE dynamically calculates the stocks of all feeds used by farmers. We take here the example of silage stocks. Farmer 5 does not make silage. For farms 1 and 2, stock increases correspond to harvests and decreases correspond to animal foraging. In both cases (farms 1 and 2) stocks are the lowest in mid-summer. There is a time-lag between growth restart in early summer and first harvests that occur later in summer. Fig. 27 illustrates that farmers can have two *decisional profile*s facing the risk of being out of stock. Farmer 2 is particularly cautious: he never goes below a minimum stock of 1.25 round bales per LU, whereas farmer 1 is more audacious: his stock is sometimes close to 0.

Unequal exploitation of grass areas

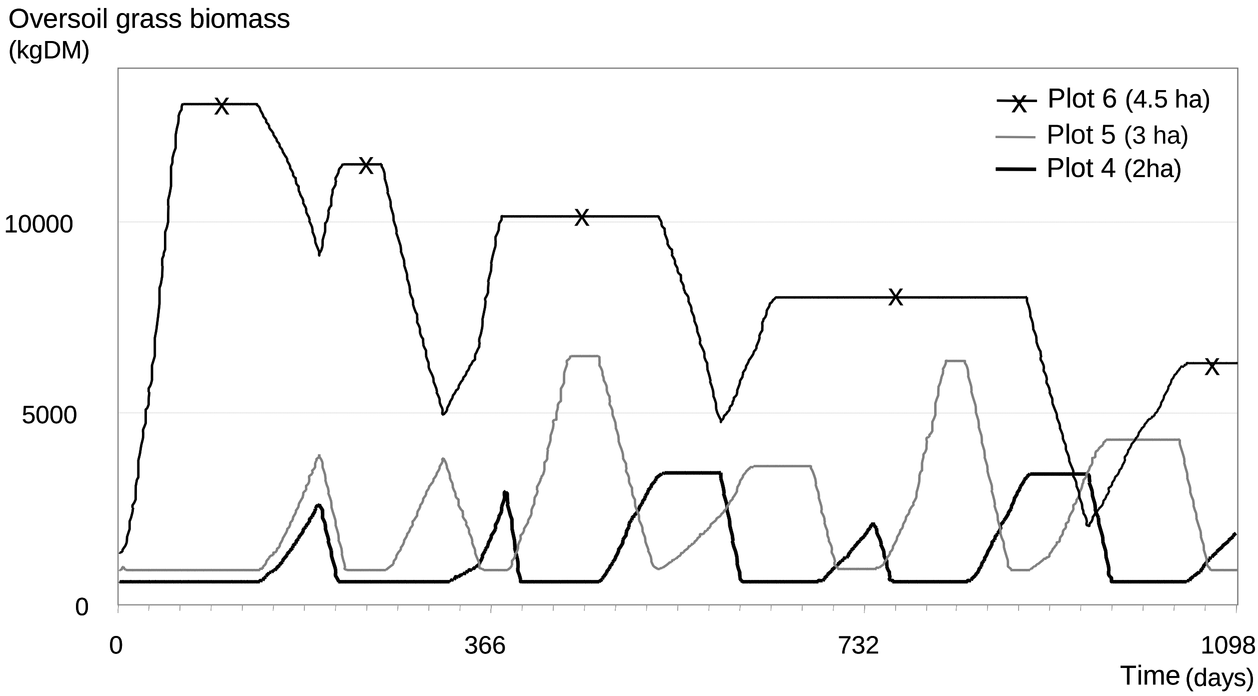

Figure 28. *Dynamical representation of the biomass available on three pastures of farm 2 (data simulated with GAMEDE, 2004-2006).*

GAMEDE can be used to represent any disequilibrium in forage area exploitation, as in the example of farm 2 in Fig. 28. The biomass increases correspond to grass growth and decreases correspond to defoliation generated by grazing cows. Cows transit between three pastures (plots 4 to 6) according to grass abundance. Plot 6 is the farthest and plot 4 the closest pasture from buildings. Grass of plot 6 often reaches maximum maturity (equilibrium between plant development and senescence), confirming that this plot is often underexploited, whereas plot 4 appears to be overexploited since its biomass often stays at the residual biomass level.

Variability in concentration of the slurry

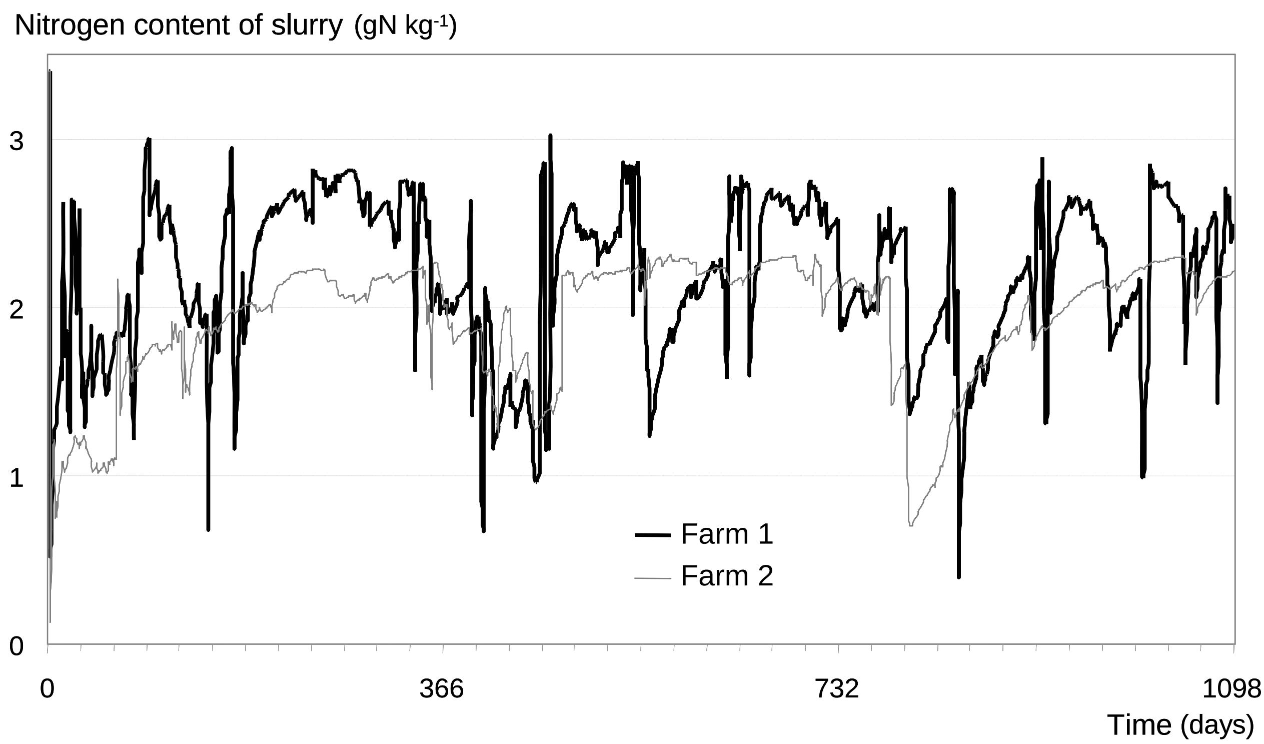

Figure 29. *Dynamical representation of the N content of stocked slurry of two farms (data simulated in 2005-2006).*

N content of slurry is strongly sensitive to dilution by rainfall. Taking the example of farm 1, located in a wet area, N contents can quadruple (varying from 0.75 to 3.0 10^{-3} kgN $kgFM^{-1}$). Low concentrations are encountered all year long because in area 4 it also rains in winter (Fig. 29 and Tab. 7). Variations are lesser for farm 2 and dilutions are observed only at the end of summer: the tropical storm period. These substantial variations complicate the reasoning behind crop fertilisation with slurry and call for adjustments of the quantity of fertilisers spread per hectare according to slurry concentration. In addition, the huge variations in stored slurry may oblige farmers to spread it out of agronomical considerations.

Periods of more important environmental risks

Environmental risks are represented in GAMEDE by potential N leaks to the environment due to slurry pit overflows and gaseous emissions.

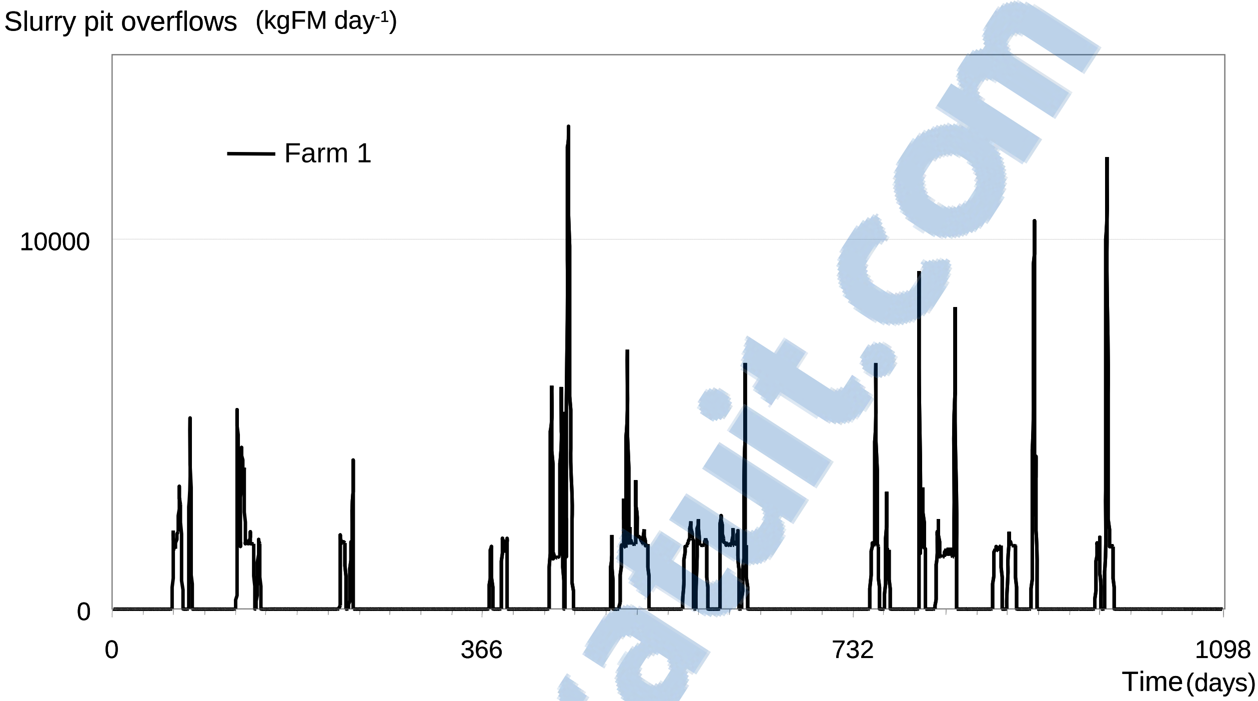

Figure 30. *Dynamical representation of N overflows from the slurry pit of farm 1 (data simulated with GAMEDE, 2004-2006).*

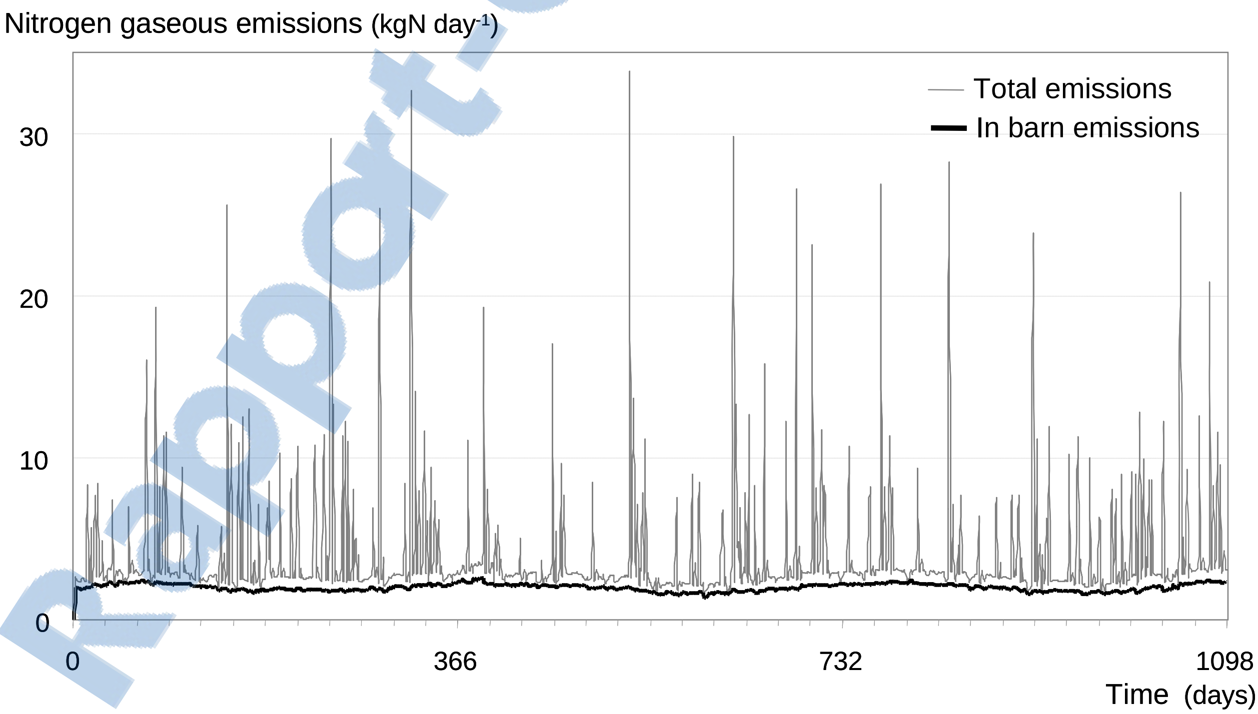

Figure 31. *Dynamical representation of N gaseous emissions of farm 1 (data simulated with GAMEDE, 2004-2006).*

For farm 1 the risks of overflows are concentrated between January and August (Fig. 30), a period characterised by larger rainfalls in area 4. Farms 2 and 5 are not concerned by overflow risks because storage capacities are sufficient. N gaseous emissions of farm 1 are represented in Fig. 31; their day-to-day variations combine climate and management effects. Barn N emissions are accentuated by higher temperatures in summer and total N emissions are characterised by peaks corresponding to fertiliser spreading actions.

V.2.3 Learning from testing "hypothetical" options

Changes in management and structural characteristics of the actual farm can be simulated to appraise their consequences on the sustainability of the production system. Three uses of GAMEDE to explore hypothetic management options are presented in this section, from the more "indoor and laboratory approach" to the more "field-based approach": i) use the sensitivity analysis to identify and classify options, ii) simulate options based on expertise of extension agents on actual farms, iii) interactively simulate options directly proposed by the farmers.

V.2.3.1 A sensitivity analysis to identify and classify improvement levers

The farm 2 example is chosen here. The 16 parameters that most influence sustainability indicators are still organised into three types: management, structure, and herd parameters. These are listed in appendix J and are here arranged according to decreasing importance of their effects on the considered sustainability indicator.

- The *N surplus* is mainly sensitive to the milk protein content, the quantity of concentrate feeds distributed to cows, the surface of grassland plots, the adjustment coefficient on quantity of concentrates distributed depending on lactating stage of the cow, and the calving interval. The same parameters were found for the N efficiency except for the area of grasslands, which does not significantly affect this second environmental indicator.

- The *milk productivity* is, as expected, mainly sensitive to herd parameters: namely the genetic potential milk production of herd cows, the milk protein content, the part of milk not sold due to sanitary problems, and the calving interval. The management parameter "quantity of concentrates distributed per cow" also significantly influences the average milk productivity of cows.

- For farm 2, the *forage crop productivity* is mainly sensitive to management parameters: the harvest interval, the quantity of mineral fertiliser spread after each harvest, the interval between cows' changing of pasture (rotation), and a herd parameter, i.e. the calving interval. At first sight it could be surprising that this latter herd parameter influences the forage crop productivity but in reality the calving interval affects crop fertilising via the herd N excretions.

- The *total work time* is sensitive to the herd parameters that also affect milk productivity (listed just below). The milking operation contributes significantly (for about 45%) to the total work time of farm 2 and its duration is determined by milk production.

Even if the rank of the most influential parameters sometimes differs from one farm to another, these parameters were the same for the five other farms. They can be considered as *control levers on the farm sustainability*. In practice, these levers are critical points at which the farmer's decisions are determining and extension agents have to work with farmers.

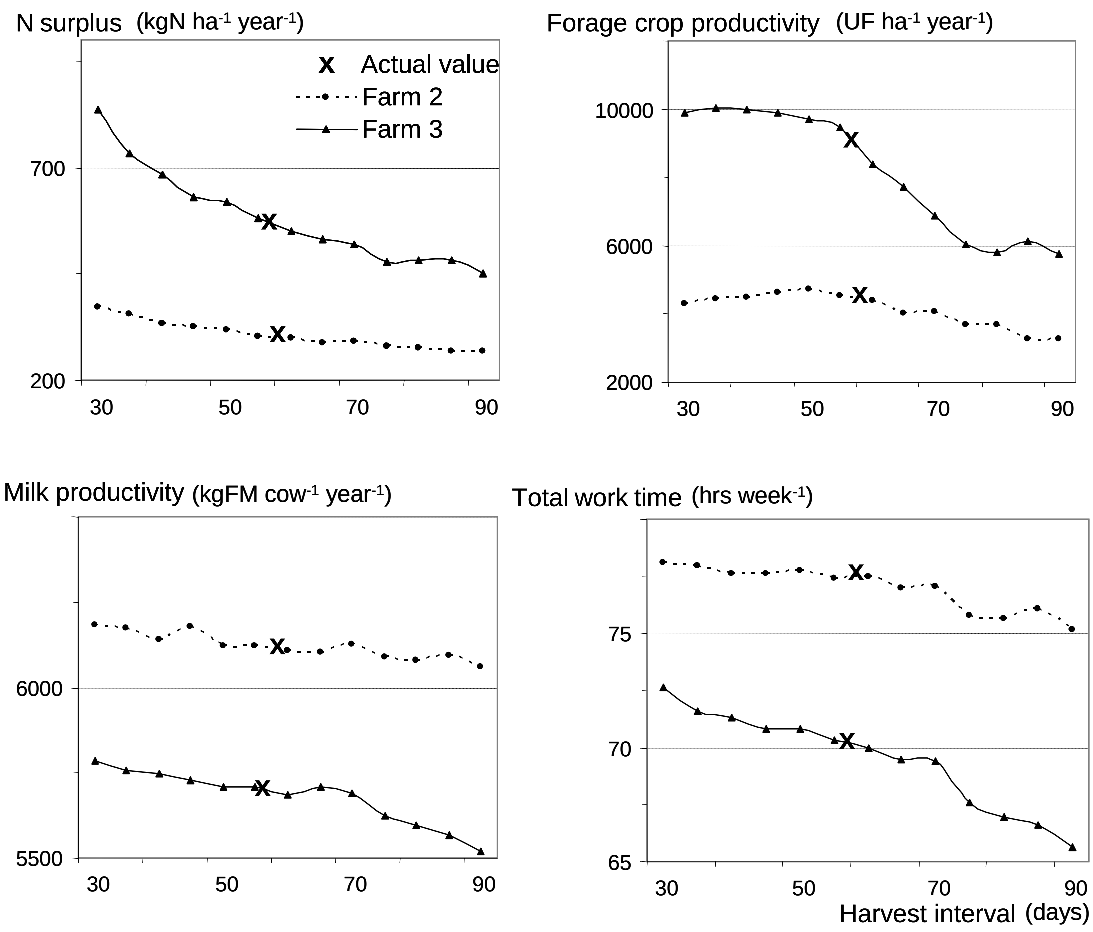

Figure 32. *Sensitivity of four sustainable indicators to the forage harvest interval (farms 2 and 3).*

Some parameters like the calving interval, the quantity of concentrate daily distributed per cow, and the harvest interval influence the six sustainability indicators. In Fig. 32 the sensitivity of four of the six sustainable indicators is related to the harvest interval of two farms, while other farm characteristics such as the quantities of fertilisers spread per cutting stay unchanged. With reference to farm 3, the sustainability of farm 2 is less sensitive to this management parameter because a part of the utilised agricultural area (**UAA**) of farm 2 is grazed whereas the total UAA of farm 3 is ensiled (Tab. 9). Whatever the farm (2 or 3), the common rule is that the earlier the cutting, the greater the N surplus, the milk productivity, and the total work time. This positive relation is also true in the case of the forage crop productivity above a harvest interval limit of 55 days for farm 2 and 45 days for farm 3. The sensitivity of the forage crop productivity to the harvest interval is non-linear. This results from the combination of numerous interacting processes: the earlier the farmers cut, the more frequently they fertilise (increased growth speed) and the greater the feed value of the grass, but if farmers cut too early the grass has not reached its maximum development stage so the biomass production is affected.

Three lessons can be retained from this sensitivity analysis:

- The sustainability indicators' responses to input variations are often non-linear due to the complexity of the production system, which includes multiple interactions between both decisional and biophysical processes;

- Some management variables significantly influence the sustainability of the farm, which implies that farmers can, in theory, improve the sustainability of the farm by changing some decision rules.

- By changing management options, although the farmers gain on one side of sustainability they often lose on another. For example, reduction of the harvest interval improves technical performances of the farm but also increases the environmental risk and the workload of the farm. Discussions with extension agents and farmers could help elucidate these three sustainability aspects.

V.2.3.2 Simulating prospective options based on expertise of extension agents

We consider here the case of farm 3, which has room for progress concerning N efficiency and milk productivity. Discussions with extension agents have underlined technical options that may improve the farm sustainability. The options were simulated with GAMEDE and results are presented in Tab. 13. In this section, these options are discussed from the easier to the more difficult to adopt from the farmer's viewpoint.

Tableau 13. *Effects of diverse hypothetical scenarios on the sustainability of farm 3*

Scenario		Environmental results			Technical results			Social results	
N°	characteristics	N efficiency	N surplus	N overflows from the slurry pit	Milk productivity	Forage crop productivity	Silage productivity	Total work time	Part of repetitive work
		(dmnl)	(kgN ha^{-1} year^{-1})	(kgN year^{-1})	(10^3 kgFM cow^{-1}year^{-1})	(10^3 UF ha^{-1} year^{-1})	(Round bales ha^{-1} year^{-1})	(hrs weak^{-1})	(dmnl)
3.0	"Actual" scenario : the reference values	0.18	547	748	5.8	10.2	69	73	0.91
3.1	Reducing the harvest interval by 10%	-4	6	-15	0	0	-1	0	0
3.2	Increasing the quantity of concentrate distributed per cow and per day by 19.5%	-6	12	8	4	0	0	4	0
3.3	Increasing the quantity of mineral fertiliser spread per ha and per harvest by 26%	-10	13	-1	-1	9	11	1	-1
3.4	Slurry pit roofing	0	0	-74	0	4	4	0	0
3.5	Slurry pit roofing + Spreading slurry on all the farm plots	0	0	-100	0	5	6	1	0
3.6	Composting all the produced solid manure	-12	3	0	0	0	0	1	0
3.7	= Scenario 3.5 + 3.6 + Reducing the quantity of mineral fertiliser spread per ha and per harvest by 16.7%	0	4	-100	4	0	0	4	0

These values are calculated with GAMEDE and are means for the 2004-2006 period. Except for the first line (scenario 3.0), which is in absolute value, all values are percentages of variation of farm results with reference to values of scenario 3.0.

Modification of tactical decision rules

In La Réunion, a frequent piece of advice from extension agents is "the earlier you cut, the better the silage and the greater the milk production of your cows". So we tested scenario 3.1, which consists in reducing by 10 % the harvest interval, without changing the quantity of mineral fertiliser spread per harvest. The result was not up to the technical message; the resulting progress on milk productivity was limited (< + 1%) in comparison with the negative effect on N efficiency (- 4%). This observation is true for the six farms and more marked for the farms that use large amounts of concentrates. The concentrate "dilutes" the forage quality effect on milk production.

A question frequently expressed by extension agents was: "N can enter at two levels: the animal level (import of concentrate feeds) and the plant level (import of mineral fertiliser). Which one leads to a more efficient use of N?" So we simulated two scenarios testing an increase of 1000 kgN (about + 10%) in farm imports per year under the two forms: the feed form (scenario 3.2) and the fertiliser form (scenario 3.3). With reference to trophic ecology (Summerhayes and Elton, 1923), in a food chain biomass, the nutrient and energy efficiencies of each trophic level decrease from the base to the top of the chain. In a dairy farm, "grass → cows" is a portion of the chain where humans are the top consumers. The results given by GAMEDE agreed with this trophic law: the shorter the chain, the more efficient the N use. From an environmental viewpoint, farmers would be well advised to use concentrates instead of mineral fertilisers.

Modification of the farm structure

Farm 3 is in the rainiest part of La Réunion (area 3). According to advisers, roofing of the slurry pit is an interesting option to limit overflow risk (scenario 3.4). Farmer 3 uses slurry to fertilise only the two neighbouring plots of the slurry pit to reduce work time. An additional scenario "roofing of the slurry pit and spreading slurry on all the plots of the farm" (scenario 3.5) shows that the farmer can nullify the N overflow and improve by 6% the silage productivity of the farm (more N spread to grasslands) by working 1 hour more per week without affecting environmental indicators.

Modification of the farmer strategy

In La Réunion, an idealistic prospective scenario (scenario 3.6) proposed by extension agents is on-farm manure composting to sell the production to market gardeners. Today farmer 3 manages to export almost all the solid manure he produces. The compost is easier to export from the farm due to better local market opportunities in comparison with raw solid manure. Under a "total export of compost" hypothesis, the simulations revealed a 12% reduction of the N efficiency. If we look at N flow profiles: in the "actual" scenario (scenario 3.0), of the 11 tons of N imported each year, about 2 are exported, 2 are emitted in gaseous form, and 7 remain at the farm scale (in the 16.5 ha of grasslands); in scenario 3.6 the quantities of N imported and N stocked are the same, but less N is exported (1.7 tons N year^{-1}) and more N is emitted (2.3 tons N year^{-1}). N gaseous emissions are not considered in the standard calculation of "apparent" N efficiency, which explains its decrease in scenario 3.6. This scenario underlines some limits of the composting process: it increases the workload and the quantities of N emitted that are no longer available for crop fertilising while La Réunion imports 6 10^3 tons N year^{-1} of mineral N (Guerrin and Paillat, 2003) to fertilise sugar cane, vegetable, and forage crops.

Advice to farmer 3

Based on the six scenarios, the advice could be "more concentrate given to producing cows, slurry pit roofing with a better recycling of on-farm-produced slurry used to fertilise grasslands" (scenario 3.5 + scenario 3.6). This better recycling of organic fertiliser offers the opportunity to replace a certain amount of mineral N by organic N with the objective to maintain the current silage productivity of the farm. GAMEDE proposes to reduce the quantity of mineral fertiliser spread per hectare and per cut by 16.7 %. This last scenario (scenario 3.7 = scenario 3.5 + scenario 3.6 + "-16.7% lowering of mineral fertiliser spread") is a good compromise between a milk productivity increase (+ 4%) and a constant N efficiency. Discussions with farmer 3 about scenario 3.7 revealed a strong limitation concerning the work capacity of the farm. Consequently the workload surplus (+ 3.5 hrs week^{-1}) generated by this new strategy could limit its adoption.

V.2.3.3 Interactive simulations with the farmer

Information about technical options circulates between extension agents and farmers, and between farmers themselves. The farmers thus already know about options that could be applied to their farms. GAMEDE can be used to improve farmers' knowledge of the consequences of these hypothetical options on their farm functioning.

During an individual meeting aimed at evaluating the realism of the simulations proposed by the model from the farmer's viewpoint (simulation of the actual scenario), farmer 2 asked if we could simulate the building of 50 cow cubicles for lactating cows. An improvised "kitchen table simulation" compared actual management practices (scenario 2.0) to the hypothetical management options proposed by the farmer (scenarios 2.1 and 2.2 in Fig. 33). We used graphic representations given by GAMEDE to follow with the farmer the biomass cycle in the farm: dejecta production in barns → organic fertiliser available in the slurry pit → grassland fertilising → forage production → silage stocked.

The farmer started by "If I build cubicles, my cows will stay in the barn all day and I will convert cows' pastures into silage grasslands". The direct consequence simulated by the model (scenario 2.1) was more production of dejecta in the barn and then more slurry available in the slurry pit (Fig. 33). The resulting slurry was more concentrated (N content increased by + 40%). The farmer said "If I have more slurry I will use all the slurry to fertilise my grasslands". The resulting production of forage was significantly increased (Fig. 33). The farmer's reaction was "What could I do with all this silage?" and we started to consider reducing use of mineral fertiliser without going below the initial level of forage production. The calculation proposed to stop use of mineral fertiliser (scenario 2.2) because the new N supply by slurry was sufficient to produce enough silage. The farmer had already imagined the consequences of such innovations and he was not surprised by GAMEDE's graphic representations. The simulations were more formal confirmation and quantification of these consequences (e.g. amount of mineral fertiliser savings).

The sustainability of the final hypothetical scenario 2.2 was evaluated with GAMEDE at the year level. The N efficiency was improved (+ 25%) without affecting milk and forage crop productivity of the farm. The farmer's reaction facing the N efficiency indicator was "N is nowadays expensive; the more my N use is efficient, the more money I earn". He saw this indicator more as a technico-economic indicator than as an environmental one. The work time surplus generated by the new strategy (+ 9.5 hrs week^{-1}) was carefully considered by the farmer and a discussion with his wife and his son started directly to evaluate if the family was ready to work more on the farm.

Six months after this first interactive simulation farmer 2 built the cubicles, converted the cows' pastures into silage grasslands, and started to reduce mineral fertiliser use progressively. Furthermore, farmer 2 wants today to change the heifers' effluent handling system to produce slurry and to reorganise the farm buildings to allow a still more efficient collection and recycling of organic fertilisers to forage crops. This experience shows that interactive simulations with a farm model can help farmers clearly improve their farming systems.

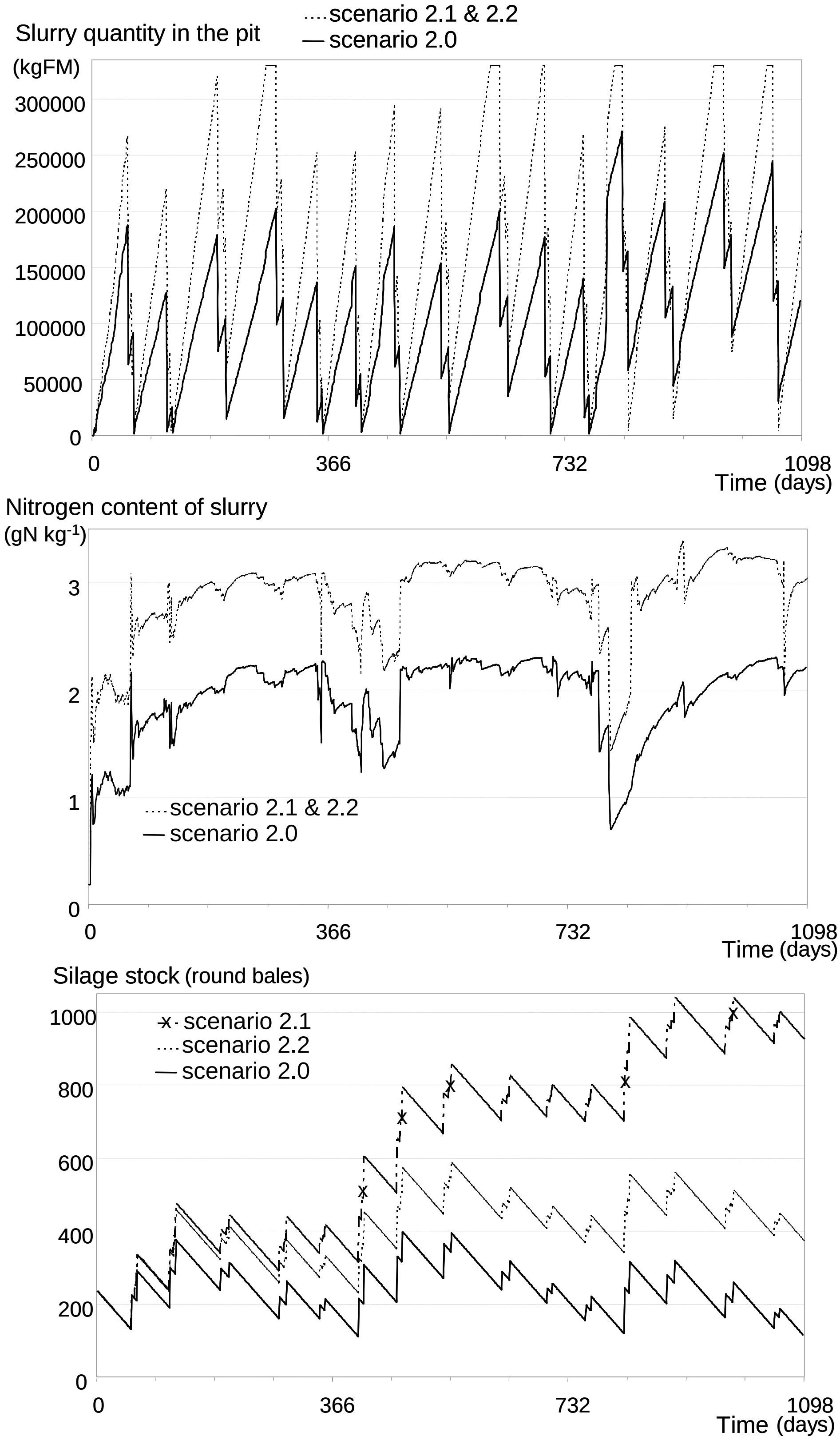

Figure 33. *Effect of three management strategies on dynamics of slurry stock, N content of slurry, and silage stock of farm 2 (data simulated, 2004-2006).*

V.3 Discussion: towards a decision support tool for farmers

Since its beginning in 2004, the modelling project aimed at improving the sustainability of La Réunion dairy farms. This operational and long-term objective strongly influenced the methodology of the project and the nature of the model and opens numerous perspectives to make GAMEDE a decision support tool.

V.3.1 GAMEDE validation by its use

As described in the companion article, GAMEDE has been classically validated by comparing simulated and observed data. It appeared necessary to complete this quantitative validation with subjective and qualitative validations about *consistency* and *realism* of the representations proposed by the model. In an implementation purpose, these latter aspects of validation are important. The more the model is *real* and *credible* for potential users, the more they are likely to learn from simulations.

Models have to be validated according to their objectives (Rykiel, 1996). If the modelling objective is to build a tool that has to support decisions of stakeholders, a new type of validation method should be considered: “validation by use of the model”. Besides the *consistency* and the *realism* of simulations, both necessary to support decisions, other aspects of simulations should be taken into account. The *interest* of actors and the *confidence* they place in the model to make decisions are also fundamental aspects.

GAMEDE has been designed to support dairy farmers’ decisions regarding many management options available to today’s farmers. The first set of interactive simulations organised with the six farmers revealed the capacity of the model to simulate a majority of the hypothetical scenarios imagined by farmers (Tab. 14) and the farmers were particularly interested in annual assessments and dynamical representations comparing different options.

Tableau 14. *Ability of GAMEDE to simulate the hypothetical scenarios proposed by farmers during the first set of interactive simulations*

Farmer n°	Scenarios proposed by the farmer	Model ability to simulate the scenario		
		Yes	Yes but with light modification of the model	No
1	*Ad libitum* distribution of concentrate feeds	x		
	Animal bedding with green wastes of city gardens and Composting of the resulting solid manure		x	
2	Building of cubicles for cows	x		
	Conversion of cow pastures in silage grasslands	x		
3	Concentrates distribution with a mechanical tube feeder		x	
	Poultry droppings import to fertilise grasslands	x		
4	Build of cubicles for cows	x		
5	Adding 3 ha of pastures	x		
6	Adding 20 suckling cows to the actual herd			x

The six farmers' general reaction to simulations was that GAMEDE is a particularly relevant tool to support young farmers in installation phases. From their viewpoint, in a farmer's knowledge building life, it is the period when most questions arise, and GAMEDE responds to a large part of these technical questions. One of the six farmers said "If GAMEDE had existed 15 years ago I would have avoided many mistakes". Further GAMEDE uses with young and experimented farmers not involved in the modelling process appears necessary to confirm that the model is able to respond to the technical questions of La Réunion farmers in general.

V.3.2 Comparison with other experiences of DSS implementation

Whole farm simulation models such as GAMEDE that represent crop-livestock farming systems are scarce. To our knowledge, none of the published models integrate such complexity and no article was found that relates experiences of use to support decisions with such a complex computer system. To situate our work, we were obliged to enlarge the scope of DSS susceptible to support farm management. The published implementation approaches are classified in two groups: top-down approaches and bottom-up approaches.

V.3.2.1 Prescriptive Top-Down approaches

Farm-gate approaches

According to Hanegraaf and den Boer (2003) a nutrients farm-gate budget is the most integrative measure of environmental pressure, and it seems the most suitable as environmental performance indicator (Oenema *et al*., 2003). The farm-gate budgets are often used to identify farming systems (e.g. dairy *vs* pig farming? Simon *et al*., 2000) or strategic choices in a given system (e.g. maize *vs* grass, grazing *vs* cutting?, Goodlass *et al*., 2003) that are environmentally friendlier. Aimed at supporting farmer's decisions, the first limit of the budget approach is that the farm is considered as a "black box" *vs* the "open box" in GAMEDE case. According to calculations from GAMEDE, if only a farm-gate perspective were used, we estimate that more than half of the N flows on a dairy farm would not have been accounted for. The second limit is that since farm-gate approaches are mostly not computerised DSS, they are thus not adapted to exploring non existing cases virtually. Such data are difficult to generate from farm experiments but are required to support farmers' decisions. To bypass this limit, some simulation models were developed (Buysse *et al*., 2005; Modin-Edman *et al*., 2007) but options compared are limited to strategic choices (e.g. conventional *vs* organic farming?). As shown above (§ V.2.3), GAMEDE allows one to compare influences of the actual practices of a given farm with optional "theoretical" solutions, including strategic, tactical, and operational choices, on farm-gate environmental indicators. The third limit of farm-gate approaches is that farms' sustainability is viewed only through its environmental side. GAMEDE's approach shows the interest of considering the farm's sustainability along its three pillars to define alternative strategies adapted to farmers' objectives.

Because of these three limits, farm-gate approaches are less adapted to support farmers' decisions but are used rather to combat nutrient "leaks" from agriculture to the environment (Öborn *et al.*, 2003) and to define *policy recommendations* (e.g. the European Nitrates Directive) from map statistics for estimating the risk factors for water pollution and from general tendencies about environmental risk linked with production system choices or strategic choices in a given production system (Oenema *et al.*, 2003; Schröder *et al.*, 2003; Mulier *et al.*, 2003; Aarts *et al.*, 2003). According to Öborn *et al.*, (2003), "farm-gate balances need to be completed by a better understanding of the process regulating nutrient dynamics…" This knowledge could be provided by models such as GAMEDE that represent all the farm flows.

Optimisation farm models

Most farm models have been designed by economists. A recent review of bio-economic farm models (**BEFM**) focused on mechanistic models (Janssen and Van Ittersum, 2007). Mechanistic BEFM generally use mathematical programming or optimization models, which are often based on linear programming (**LP**). LP represents the farm as a linear combination of activities. These activities contribute to the realisation of defined goals or objectives in modelling terms (Ten Berge *et al.*, 2000). Constraints to the activities are defined that represent the minimum or maximum amount of a certain input or resource that can be used. This system of activities and constraints is then optimised for some objective function, reflecting a user-specified goal, for example the profit.

In the 42 models in the review of Janssen and Van Ittersum (2007), 67% modelled farmer "decision making" using a simple measure of profit maximization (including, for some, some risk factor) where the farmer is assumed to be a rational profit-maximiser (Falconer and Hodge, 2000). In reality decisions of farmers are motivated by multiple, often conflicting, objectives, among which profit maximisation is only one (McCown, 2001; Wallace and Moss, 2002). Personal, family, and farm business objectives and attitudes are not independent and need to be considered jointly, and farmers' behaviour reflects a combination of personality factors as well as lifestyle and economic objectives (McCown, 2001; Wallace and Moss, 2002; Vayssières, 2004). To solve this lack of realism, multi criteria decision making (**MCDM**) methods have been developed that take more than one objective into account (Rehman and Romero, 1993).

Despite these MCDM methods, mechanistic BEFM are often used in a *normative approach*, for example Berentsen (2003) and Pacini (2003). Normative mechanistic approaches are used in explorations of the long term effects of policy assessment (Berentsen and Giesen, 1994; Ramsden *et al.*, 1999) and sometimes with the will to assist farmers' strategic decision making (Beukes *et al.*, 2002; Benoit and Veysset, 2003; Crosson *et al.*, 2006), but effective use of BEFM outputs by farmers is rare.

A shortcoming identified by McCown (2001) in the use of mechanistic BEFM in advising farmers is that a gap exists between the normative, economically and technologically efficient advice given to farmers and the situation on the farm. To bridge this gap McCown (2001) proposes participatory approaches based on dialogue between farmers and researchers instead of classical indoor design approaches. An example is as in Schilizzi and Boulier (1997) and as experimented in the GAMEDE project.

V.3.2.2 Bottom-up approaches

Mainly partial simulation models of the farming system

As stated before, simulation models representing the dairy farm as a whole are scarce. The majority represent grazing systems: WFM in New Zealand (Wastney *et al*., 2002) and SEPATOU in France (Cros *et al*., 2001). Some models are limited in terms of management option testing, such as the Swedish FARMFLOW model (Modin-Edman *et al*., 2007). The IFSM developed in the USA, (Rotz and Coiner, 2006) allows testing numerous management options and is the model most closely related to GAMEDE. But in all cases the farmer actions are not explicitly represented and models were designed to be used mainly by scientists and/or with extension services.

GAMEDE enables one to simulate the diversity of management situations of biomass flows in dairy farms in La Réunion. This model integrates within a coherent dynamical simulation framework the explicit representation of the farmer's practices (decisions and actions) and of biophysical processes, in relation with the main aspects of the physical and socio-economic environment of the farm. This joint representation of both practices and biomass flows at the whole-farm scale differentiates our modelling approach from most simulation DSS in agriculture designed to support farm management. Indeed, these do not consider the farm as a whole and generally ignore the farmer's activities (Garcia *et al*., 2005b).

This is the case for the partial biophysical models we have integrated in GAMEDE such as INRation (INRA, 2003), CNCPS (Fox *et al*., 2004), and GRAZEIN (Delagarde *et al*., 2004). It is also the case for cropping system models such as APSIM (McCown *et al*., 1996). All these simulation models summarize the farmer's practices as static input parameters or data tables. Hence, when used in isolation, these models cannot account for the dynamic interaction between the farmer's actions and these processes.

GAMEDE also differentiates from pure conceptual representations, such as the descriptive framework of work organisation in livestock farms proposed by Madelrieux *et al*. (2006). In contrast with the above cited biophysical models, by focusing only on the work organisation of the farm at a high level of abstraction, this model gets rid of the interdependency between the farmer's actions and the biophysical processes, each of these being both the cause and the consequence of the other.

It is thus impossible with these partial models to assess the impact of a local modification at the scale of the whole, or the converse. Getting back to the distinction made by Thornton and Herrero (2001), at best they allow one to advise "feasible" strategies instead of "practically attainable" strategies and action plans. As demonstrated in the "atypical" FARMSCAPE project (Carberry *et al.*, 2002) simulation models, and even partial models, can be used to accompany a decisional process of farmers but cannot be surrogates of the decision-maker. The FARMSCAPE approach to decision support is a way of using a simulator of cropping systems (APSIM) to support discussions with farmers in order to aid their planning and learning. Similarities exist between the FARMSCAPE and the GAMEDE experiences. In both cases models were i) first seen as discussion support tools to improve farmers' learning and to companion their decisions and ii) used to explore whether farmers and their advisers could gain answers from simulations.

Multi-agent systems in agriculture

With reference to the above "classical" agricultural DSS designed to assist farm management, multi-agent systems (**MAS**) generally go further in participation. Actors are often involved from the beginning of the model design. This early participation is fully justified by the strong attention attached to the representation of the social processes. In comparison with GAMEDE, the biophysical processes of MAS are generally modelled in less detail. GAMEDE was designed with strong farmer participation (§ V.1.4). The most significant influences of farmers on GAMEDE focused on the social components of the model: the decisional system (Vayssières *et al*, 2007a).

MAS and GAMEDE are both simulation models that aim at representing interactions between the natural system (i.e. the biophysical system in GAMEDE) and the social system (i.e. the decisional system in GAMEDE). But the basic difference between GAMEDE and MAS is that, instead of reproducing the reasoning of a single intelligent agent as in GAMEDE, MAS reproduce the knowledge and reasoning of several heterogeneous agents that need to coordinate to jointly solve planning problems. This explains why MAS i) are essentially used in agriculture to represent and solve conflicts around use of a common resources like water (Lansing and Kremer, 1994) or agricultural land (Balmann, 1997) and ii) are generally not used to represent a farm governed by a single decision maker (see the review of Bousquet and Le Page, 2004). MAS and GAMEDE can be used to define problems to be solved with the actors and to construct solutions, via role-playing games in the MAS case (Barreteau *et al.*, 2001). Companion modelling experiences (Atona *et al.*, 2005) in renewable resource management and visual interactive simulations (Chau, 1993) in industry have inspired the methodology of the GAMEDE project. As argued by Hurrion (1980) the participation of end-users should start in the early stages of model design to increase model credibility and acceptance. End-users' involvement during model design is an integral part of problem-solving (Bell *et al.*, 1990). The most efficient approach to DSS design and development is considered to be visual interactive simulations (including both design and implementation phases), which basically involve frequent communication and many short feedback loops between the system builder and the end-user during the whole model building process (Huff, 1985).

V.3.3 Reasons for such success?

In 2004 we started with the question of whether the model would answer farmers' questions. The answer is positive for all the farmers involved in GAMEDE design. McCown (2002a) claimed that delivery of benefits to farmers via DSS is in a state of crisis. As also noted by Carberry *et al*. (2002) about their FARMSCAPE project, we have strong evidence, concerning our own efforts here, relating to farmers' declared and demonstrated interest in accessing the GAMEDE simulator. Initial scepticism to models was progressively replaced by a strong interest in simulations because they realised that the model can answer their questions. What might account for this difference in results? Four reasons can be proposed:

- Firstly, the *nature of the model*: GAMEDE is a complete, versatile simulator. When managed by a skilled intermediary (the builder) it enables simulations specific to farmer's individual questions. The farmer can test the results against the farm functioning/results. Moreover, GAMEDE can be used to explore a broad range of issues raised by the farmers themselves. That the *whole farm* is represented is also clearly a crucial element of the success of this modelling experience because, in practice, farmers have to manage the system as a whole. These characteristics contrast with most DSS designed to deal with a narrowly specified issue of the farm management. Farmers' understanding and acceptance of the model and its outputs were particularly facilitated by GAMEDE's integration of local daily weather (e.g. effects of cyclones) and explicit representation of farmer technical actions. The dynamical and transparent representations proposed by the model permit the simulation to be related to one's own past experience of seasons.

- Secondly, the *methodology of model design*: The participation of farmers has been a key ingredient in model design, including its evaluation. Balci and Nance (1985) claimed that effective communication between the model builder and the model user is the most important factor for establishing the credibility of a simulation model. The reflexive study by an external observer seeking to identify farmers' influence on the model qualified the *immersions* as a turning point in the project (Vayssières *et al*., 2007a). The model designer immerged in farms and living farmers' life was *unconsciously impregnated by farmers' questions*. Frequent visits and meetings involving observations and effective communication between the farmers and the researcher during the model design phase provided a situation of *mutual understanding*. Because questions were formulated throughout the modelling experience, the model was effectively shaped to answer farmers' questions. The early scepticism of farmers was due to a lack of understanding on how a model could answer their questions, because a model was seen as an imported prescription, as were other innovations in the dairy sector of La Réunion. Because farmers participated in model design with lot of transparency, they knew the content of the model and considered themselves as full contributors to the model.

Acceptance of representations proposed by the model is then higher. But the downside of this high level of participation is the high cost in researcher time, attention, and energy.

- Thirdly, the *support approach*: As argued by numerous authors (McCown, 2002a; Carberry *et al*., 2002) substituting a prescriptive approach by a participatory approach to manager learning and action (in-office optimisation *vs* on-farm interactive simulation) makes the simulations more beneficial/constructive: a spiral learning progression, rather than a circular return to the previous knowledge state (Carberry *et al*., 2002). Three of the six farmers involved in GAMEDE design (2004-2007) had already contributed to a previous project (2000-2003) concerning an economic optimisation farm model called AMSTEL (Louhichi, 2004). In the previous modelling experience the three farmers were mobilised only in the initial survey and the final model test phases. The optimum solution found by the model was presented to each farmer as the form "you should do this". Farmers considered these external solutions trivial or inapplicable. The same farmers are today enthusiastic and interested in technical options raised during interactive simulations with GAMEDE because they explored their farming system in a manner akin to learning from on-farm experiments.

The optimisation AMSTEL model was considered less attractive by farmers but was largely used by the milk industry to negotiate subsidies from Europe. This experience in La Réunion goes in the direction of McCown's beliefs: different modelling approaches exist to respond to different questions in agriculture, and simulation models are more relevant when used as discussion support tools to support farmers' decisions.

- Fourthly, (underlined by the farmers) the *context*: the prices of inputs have significantly increased during the past few years and the European subsidies attached to milk production are questioned in ultra-peripheral areas like La Réunion island. Moreover the society is modernising quickly and fewer young people are ready to work 366 days per year. This economic and social crisis affecting the dairy sector in La Réunion (as in other developed countries) is leading farmers to contemplate a change in practices and thus to be more curious about model design and implementation. From FARMSCAPE experience, authors also reported "…farmers who were content with their current circumstance and management practices were less likely to enthusiastically seek simulations beyond the initial interactions."

V.3.4 Model use perspectives

V.3.4.1 A DSS tool used by farmers

The fact that the model answers farmers' questions motivates us to continue in the direction of producing a DSS for farmers as planned in the initial project. We are today studying the case of a decision support mode in which the simulator is in the hands of an expert intermediary as an alternative to easy-to-use software in the hands of farmer. This is the most encountered mode of operational research as underlined by McCown (2002b). The use of GAMEDE directly by farmers could be our long-term goal; this took 10 years for the FARMSCAPE experience. To achieve this, transferring the capability for monitoring and simulation to the extension agents seems to be the best way to extend the implementation domain of the model. Use of the *Internet* in the interface with the user is the option retained by some projects like PCYield in the USA (Welch *et al*., 2002). This could be an additional option concomitant with use by the extension staff.

First, some technical aspects have to be sorted out to allow GAMEDE utilisation by people not used to computers. Little (1970) proposed developing an interface specially designed for farmers. The GAMEDE interface has to be conceptualised with farmers to facilitate input parameterisation. GAMEDE is a complex model: in its present version about 125 parameters have to be informed to simulate a farm. These inputs have to be structured in an input interface. Although Vensim® offers visual facilities and enables the model user to create multiple highly visual graphic displays with colour keys and cursor movement (a functionality called SyntheSym), a simplified output interface has to be designed, targeting the expectations/needs of farmers. In the present version of GAMEDE, the risk is to "overwhelm" users with complexity and information given by the model. A selection has to be made to present only the appropriate/relevant information for farmers. The six farmers have also asked to complete the outputs of GAMEDE with economic indicators. Preliminary discussions have shown that classical economic indicators (e.g. the gross margin) do not have the same significance for farmers as for researchers. The model design is thus not finished and farmers' participation is still going on.

V.3.4.2 Other potential uses of GAMEDE

Unexpected ways of use were discovered during the participative modelling experience. These functions are differentiated into operational and research functions.

An operational tool

Some of the hypothetical options proposed by the six farmers are technical innovations: composting and *ad libitum* distribution of concentrates (Tab. 14). GAMEDE thus can be considered as an *innovation adoption support tool*. This aspect could motivate extension agents to use GAMEDE in expanding the implementation domain of GAMEDE before use of the model by farmers.

We are convinced that GAMEDE can also be used as a *teaching tool* as for other farm models like IFSM (Rotz and Coiner, 2006). As argued in the companion paper, such complex simulators offer a synthesis of much knowledge about the production system. The idea would be to train future farmers or future extension agents about the realities of the dairy farmer trade.

A research tool

Because the model simulates the management actions on a daily basis according to the action plan and the decision rules of the farmer it offers the opportunity *to explore decision profiles* of farmers. In the companion paper we argue that a key way to improve the realism of simulations is to implement a more complete decisional system based on the conceptual structure for action modelling (the SAM, Vayssières *et al.*, 2007b), including more adjustment decision rules. When this is achieved it will be possible to compare the reasoning of several farmers (i.e. intelligent agents) and their influence on the functioning of the production system. For example the proportion of actions defined by the action plan (*vs* adjusted from adjustment decision rules) will be quantifiable and will allow differentiating between "planning farmers" (a majority of planned actions) and "instinctive farmers" (a majority of adjusted actions).

Moreover such computer models will surely renovate methods of inquiry into farmers' practices and strategies, classically based on questionnaires. GAMEDE can be seen as a discussion support tool to better describe and understand with the farmers the logic of their strategies. For example, visual representations were proved relevant support for discussions to explain inter-year variations of practices.

Conclusion

This article shows that GAMEDE is a versatile simulator of dairy farming systems under diverse climatic and forage cropping conditions. The model simulates responses according to weather and various diverse management practices in farm functioning and sustainability and in the biomass and N flows. In the case of La Réunion, GAMEDE simulations of the six farms show that total biomass flows (2.0 - 15.2 10^3 kgFM day^{-1}) and internal N flows (55 - 64% of the total N flows) are substantial in all the studied systems. For further studies on crop-livestock farming systems, this result points out the interest in using such models that include biomass and the nutrient cycling within the farm. Actionable N flows (74 - 91% of the total N flows) are also particularly substantial, underscoring human control of farm nutrient flows.

An important finding from the GAMEDE simulations is that, just by changing management practices, a large margin of progress exists concerning environmental results of La Réunion farms, yet no miraculous option was found that could ameliorate together the three pillars of farm sustainability. Simulations revealed that partial or total replacement of imported mineral fertiliser by on-farm-produced organic fertilisers is a great opportunity to improve the N efficiency of dairy farms of La Réunion. Limits to its adoption are the work time surpluses generated.

Moreover options for improvement on one farm are not always relevant for other farms. We thus argue for a "case by case" use of such a model to look for friendlier practices from an environmental, technical, or social viewpoint, depending on the priorities between the three aspects expressed by the farmer during the diagnosis at the whole-farm scale with the model and with advisers. Thus the model has not been used for forecasting but rather for supporting discussions with farmers. This experience of interactive simulations with stakeholders was the occasion to identify four types of model applications:

- Benchmarking: where the sustainability of a past and "actual" strategy is applied on a farm characterised by its structure in a given climatic context. Hypothetical simulations are compared to benchmark simulations to assist in explaining sustainability changes and elaboration.

- Strategy exploration: where management options are explored at a strategic level; options may include innovative management techniques (e.g. composting) and are often accompanied by farm structural changes (also strategic decisions).

- Tactical planning: where management options are explored at a tactical level; options tested include changes in dates of practical seasons or rhythms of technical operations (e.g. harvest interval according to the season).

- Operational choices: where management options are explored at an operational level; options concern realisation and adjustment decision rules of the farmer (e.g. adjustment on quantity of concentrate feeds distributed per cow according to its lactating stage).

Another important methodological finding from the GAMEDE experience is that farmers' participation during the model design was a facilitating pre-requisite to fruitful exchanges during interactive simulations. The enthusiasm of farmers and extension agents about outputs generated by GAMEDE and about this experience of farm model co-designing encourages us to continue in the direction of producing a decision support tool to be used by farmers to improve their farm sustainability.

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Conclusions intermédiaires et transition

Ce chapitre décrit une gamme d'expériences informatiques, réalisées avec GAMEDE, dont les conclusions ont été positives pour l'aide à la compréhension des interactions entre l'éleveur et sa ferme d'élevage. Ce modèle s'est révélé être un excellent support de dialogue auprès d'éleveurs dans une perspective d'aide à la décision et d'amélioration de la durabilité des élevages laitiers réunionnais.

Un certain nombre d'éléments explicatifs du succès des simulations interactives avec les éleveurs réunionnais sont proposées en référence aux différents types de DSS rencontrés dans la littérature : des approches de types « farm-gate balance » aux systèmes multi-agents, en passant par les modèles bio-économiques d'optimisation.

La discussion générale de cette thèse, dans le chapitre suivant, se recentre plus particulièrement sur les modèles de simulation de l'EBL pour souligner les originalités du modèle GAMEDE et de sa méthode de construction : depuis sa conception jusqu'à son évaluation et son utilisation. La généricité de notre modèle et de notre approche est aussi questionnée.

Chapitre VI. DISCUSSION GENERALE

VI.1 Un modèle original

Concernant la modélisation des systèmes de production comportant un atelier d'élevage de bovins, il existe deux grands types de modèle global d'exploitation : i) des modèles d'optimisation (**BEFM** : Bio-Economic Farm Models) répondant à des questions du type « How to ? » et plus rares, ii) des modèles de simulation (**SFM** : Simulation Farm Models) répondant à des questions du type « What If ? ».

Les modèles d'optimisation sont souvent basés sur des techniques de programmation linéaire et avant tout utilisés pour répondre à des questions économiques. Des aspects environnementaux ont par la suite été introduits (Berentsen et Giesen, 1995). En programmation linéaire la dynamique des processus biophysiques présents au sein de l'exploitation ne peut pas être représentée avec suffisamment de finesse pour permettre une évaluation précise de leurs interactions et de leurs effets sur les performances du système de production (Rotz *et al*. 2005).

Alors qu'il existe certainement plusieurs centaines de modèles partiels de simulation représentant des processus biophysiques particuliers de l'exploitation bovine laitière (cf. § V.3.2.2), les modèles de simulation qui représentent la ferme dans sa globalité se limitent à une dizaine de simulateurs dans le monde actuel. La grande majorité d'entre eux ont été construits en pays industrialisés et sous climats tempérés : aux USA (Rotz et Coiner, 2006), en Australie (Johnson *et al.*, 2002), en Nouvelle-Zélande (Wastney *et al.*, 2002) et dans divers Pays Européens (Cros *et al.*, 2001 ; Modin-Edman *et al.*, 2007 ; Chardon *et al.*, 2007 ; Duretz, 2007). Le projet néerlandais en cours AfricaNUANCES fait exception, il prévoit la construction d'un SFM en Afrique centrale et Afrique de l'Est (Tittonell, 2005). GAMEDE a été construit en contexte intermédiaire : en pays industrialisé et sous climats tempéré et tropical.

Un certain nombre de SFM de la littérature, choisis afin de couvrir la diversité, sont ici comparés. Certains modèles finalisés n'ont pas été repris car redondants c'est le cas de DAIRYMOD développé en Australie (Johnson *et al.*, 2002). D'autres modèles n'ont pas encore été publiés et/ou sont en cours de construction c'est le cas de MELODIE (Chardon *et al.*, 2007) et de FARMSIM-Java (Duretz, 2007).

Le Tab. 15 met en évidence de façon synthétique les différentes aptitudes des modèles de la littérature. Tout comme GAMEDE, la plupart de ces modèles sont dynamiques, ils fonctionnent à un pas de temps quotidien et sont sensibles aux conditions pédo-climatiques et à certaines options techniques choisies selon leur pertinence dans leur contexte de modélisation. Certains sont centrés sur le pâturage (c'est le cas du WFM et de SEPATOU), d'autres intègrent d'autres techniques de récolte de fourrages telle que l'ensilage et y associent la conduite de cultures non fourragères commercialisées (IFSM).

Tableau 15. *Aptitudes des principaux modèles de simulation (SFM) publiés représentant l'EBL dans sa globalité*

Nom du modèle		FARMFLOW	WFM	SEPATOU	IFSM	GAMEDE
Référence		Modin-Edman *et al.*, 2007	Wastney *et al.*, 2002	Cros *et al.*, 2001	Rotz et Coiner, 2006	Vayssières *et al.*, in review
Le SFM fonctionne-t-il à un pas de temps quotidien ?		N	O	O	+/-	O
Son domaine d'application couvre-t-il à la fois des zones tempérées et tropicales ?		N	N	N	N	O
Le SFM permet-t-il de simuler l'enchaînement de plusieurs campagnes de production ?		O	N	N	N	O
L'ensemble du troupeau (animaux de renouvellement inclus) est-t-il considéré ?		O	N	N	O	O
Le modèle permet-t-il de représenter des SP variés d'un point de vue des processus biophysiques et des techniques représentés ?		N	N	N	O	O
Les pratiques sont-elles représentées avec réalisme ?		N	N	O	+/-	O
L'ensemble des flux de l'exploitation est-t-il représenté ?		O	N	N	N	O
Le SFM offre-t-il une évaluation de la durabilité d'un point de vue	Technique ?	N	O	O	O	O
	Economique ?	N	N	N	O	N
	Environnemental ?	O	N	N	O	O
	Social ?	N	N	N	N	O

O : oui, N : non

Dans la famille restreinte des modèles de simulation représentant l'exploitation laitière dans sa globalité, GAMEDE se distingue par : la variété des systèmes laitiers qu'il représente d'un point de vue biophysique et des options techniques qu'il simule, la modélisation explicite des pratiques décisionnelles et des actions de conduite des éleveurs, et le fait qu'il évalue les systèmes de production selon les trois aspects de la durabilité.

- GAMEDE représente dans leur globalité des systèmes de production laitiers particulièrement variés via *un unique modèle informatique*. D'un point de vue biophysique les SFM qui simulent avec détail aussi bien la repousse et le conditionnement de fourrages, les productions de bovins (démographie incluse) et l'évolution des effluents d'élevage sont particulièrement peu nombreux. Les modèles IFSM et GAMEDE répondent à cette caractéristique et sont, de ce point de vue, deux modèles similaires.

- Une telle finesse biophysique permet à ces deux modèles de simuler une *grande variété de façon de conduire un EBL* que ce soit en termes de fertilisation et de récolte des surfaces fourragères, d'alimentation du troupeau ou de gestion des effluents d'élevage. Concernant GAMEDE, si l'on prend l'exemple du système de récolte des fourrages, trois techniques sont considérées (le pâturage, l'ensilage et la fauche en vert) et leur combinaison au sein d'une exploitation peut être simulée, alors que la plupart des autres SFM sont centrés sur une seule technique d'exploitation : le pâturage par exemple (c'est le cas du WFM et de SEPATOU). Le modèle FARMFLOW reste encore plus limité en terme de simulation de scénarios puisque la plupart des flux et résultats techniques sont des entrées du modèle.

- Le fait que les *pratiques décisionnelles* de l'éleveur soient *explicitement représentées* pour l'ensemble des opérations de conduite de l'exploitation constitue la principale originalité de GAMEDE. SEPATOU comprend lui aussi un système décisionnel (**DS**) et un système biophysique (**BS**) bien distincts et en interaction. Le système de règles de décision de GAMEDE basé sur un plan d'action et des règles de réalisation et d'ajustement est similaire à celui de SEPATOU. Cependant dans le cas de SEPATOU il est uniquement appliqué à la conduite du pâturage alors que dans GAMEDE des pratiques de conduite *réalistes* (i.e. *décidées au jour le jour selon l'état du système de production et de son environnement*) sont simulées pour l'ensemble des 19 opérations techniques à l'origine de flux de biomasse. Par exemple, dans GAMEDE la ration alimentaire est définie selon l'état quotidien des stocks de fourrages conservés et sur pied, à l'inverse des autres SFM où les rations alimentaires sont soit prédéfinies soit calculées uniquement selon la couverture des besoins en référence à un potentiel de production.

- Parallèlement à ce gain de réalisme, *simuler les actions de conduite à partir de règles de décision* et non pas à partir d'une grille prédéfinie de pratiques de conduite (comme c'est le cas de la majorité des SFM, mis à part SEPATOU) garantit dans GAMEDE la cohérence entre les différentes pratiques simulées et permet d'aller plus loin dans la compréhension du système de production, des interactions entre décisions et processus biophysiques et des conséquences de décisions sur la durabilité des systèmes de production (**SP**). En effet dans GAMEDE les scénarios prospectifs ne se limitent pas à des changements stratégiques (e.g. passage d'un système fumier à un système tout lisier), ils concernent aussi des choix tactiques (e.g. pré-définition du stade de récolte des fourrages pour les différentes saisons pratiques) et des choix opérationnels (e.g. ajustement de la quantité de concentré distribuée par VL selon son stade de lactation).

- GAMEDE est aujourd'hui le seul modèle à simuler l'*influence de choix techniques sur l'ensemble des flux* de biomasse et d'azote (flux internes inclus) à l'échelle globale de l'exploitation. Certes le modèle FARMFLOW représente l'ensemble des flux de P, toutefois ces flux sont donnés à un pas de temps annuel et sont des données d'entrée du modèle ce qui limite fortement la gamme des simulations. Dans FARMFLOW seul l'influence du dimensionnement du troupeau est simulée sous hypothèse de linéarité. Or cette hypothèse a été infirmée par notre étude (cf. § V.2.3.1) en relation avec la complexité des interactions intervenant au sein du SP.

- Enfin alors que la majorité des SFM sont destinés à évaluer des systèmes de production uniquement sur un aspect technique (WFM et SEPATOU) ou environnemental (FARMFLOW), GAMEDE offre une évaluation couvrant les trois aspects de la durabilité : des aspects techniques, environnementaux et sociaux.

C'est bien la combinaison de ces traits majeurs qui font l'originalité de GAMEDE et qui permettent à ce modèle de répondre à ses objectifs à savoir :

« la représentation de l'influence des pratiques de conduite sur les flux d'azote et sur la durabilité des EBL en vue d'une compréhension des interactions éleveur/ processus biophysiques et d'aide à la décision stratégique, tactique et opérationnelle des éleveurs ».

VI.2 Innovation méthodologique

L'approche de modélisation a largement été décrite dans les chapitres II et IV. Elle a permis de souligner quatre grands traits de ce travail de modélisation : sa transdisciplinarité, la forte participation des acteurs de la filière laitière, l'intégration de travaux et de modèles partiels préexistants dans le domaine biophysique, une évaluation du modèle qui a croisé de nombreux regards sur les représentations apportées.

Transdisciplinarité

La transdisciplinarité est souvent annoncée comme un objectif à atteindre dans les appels à projets de recherche mais elle est en pratique rarement mise en œuvre du fait des difficultés de compréhension entre chercheurs de disciplines différentes. Ce type de travail de modélisation visant la synthèse de nombreuses connaissances à propos d'un agro-écosystème particulièrement complexe, l'EBL, montre tout l'intérêt de ce type de collaboration en terme de *renouvellement des méthodes* et de *compréhension du système étudié*. L'EBL est un système conduit par un individu où interviennent à la fois des processus biophysiques animaux et végétaux en lien avec le sol et le climat. Les caractéristiques de l'objet d'étude ont justifié la mobilisation de chercheurs rattachés à quatre disciplines de sciences sociales et cinq disciplines biophysiques. L'apport des différentes disciplines s'est ressenti aussi bien sur la nature du modèle : intégration effective d'un DS et d'un BS, que sur les méthodes de construction de ces différents systèmes. Concernant cet aspect méthodologique on notera par exemple que des méthodes d'ethnologie telles que l'immersion ont été mobilisées pour étudier des pratiques techniques et qu'inversement des comportements humains à l'origine d'actions on été traduits en langage mathématique. Par ailleurs, nous restons aujourd'hui convaincus que le DD est un concept fédérateur et favorable à cette transdisciplinarité. Si l'on prend l'exemple des indicateurs que l'évaluation de la durabilité demande, leur définition suppose la collaboration de différentes disciplines : des chercheurs de sciences sociales en ce qui concerne les indicateurs sociaux et économiques, et des chercheurs des sciences biophysiques en ce qui concerne les indicateurs techniques et environnementaux.

Participation des acteurs agricoles

Ce projet n'a pas uniquement demandé la participation de chercheurs de disciplines différentes, il a aussi mobilisé l'ensemble des acteurs de la filière laitière réunionnaise. Un certain nombre de techniciens dans différents domaines (e.g. nutrition animale, conduite du pâturage) ont par exemple apporté leur expertise pour le choix des fermes types, pour le zonage agro-écologique et pour la validation des modèles partiels et enfin du modèle global. Les acteurs qui ont été les plus impliqués dans ce projet de modélisation restent les six éleveurs du groupe de travail qui ont participé de manière continue depuis la conception jusqu'à l'évaluation de GAMEDE. Il existe des expériences de co-construction de modèles informatiques, en particulier du côté des Systèmes Multi Agents (MAS), où le degré de participation des acteurs et leur influence sur le modèle final ont été plus significatifs. Cependant les MAS portent surtout attention aux mécanismes sociaux. Le projet GAMEDE constitue une expérience originale où des agriculteurs ont été fortement impliqués dans la construction d'un modèle dont le BS est particulièrement complexe et modélisé avec finesse.

Dans le cadre du projet GAMEDE, les conséquences d'un tel niveau de participation sont nombreuses. Elles ont été mesurées à propos de la nature du modèle (e.g. prise en compte des ajustements dans l'action) et de la méthode de modélisation (Vayssières *et al*., 2007a). La participation des éleveurs a permis entre autres, d'avoir accès à des données fiables et potentiellement conflictuelles sur des fermes réelles alors que la quantification des flux se fait classiquement en domaines expérimentaux. Toutes les retombées d'une telle participation n'ont pas pu être évaluées, certaines restent à explorer : en particulier les mécanismes d'*apprentissages réciproques* générés à la fois chez les éleveurs et le chercheur. Ces apprentissages en cours de construction du modèle peuvent certainement expliquer pourquoi certains éleveurs ont orienté, au cours de la période couverte par cette thèse, leurs pratiques vers un meilleur recyclage de l'azote et un plus grand respect de l'environnement. Le pendant d'un tel niveau de participation reste le fort investissement humain et le temps de travail qu'il suppose. C'est d'ailleurs probablement pour cela que la recherche participative reste relativement peu pratiquée alors qu'elle est pourtant fréquemment revendiquée.

Intégration de résultats et de modèles biophysiques préexistants

Dans un souci d'efficacité et de valorisation de résultats de recherche préexistants le projet GAMEDE est caractérisé par l'intégration de travaux divers dans le domaine biophysique aussi bien concernant des expérimentations menées à La Réunion que des modèles disponibles dans la littérature.

L'agriculture est particulièrement étudiée par le CIRAD à La Réunion. Le fait que ce territoire insulaire soit clairement délimité en fait un contexte d'étude privilégié. Depuis une vingtaine d'années de nombreuses études souvent indépendantes ont été conduites aussi bien concernant l'élevage de bovins, la conduite de prairies et de la canne à sucre, la gestion des matières organiques. Il nous semble profitable que l'essentiel de ces résultats de recherche fondamentale ou appliquée puissent être réutilisés dans de nouveaux projets de recherche. L'expérience GAMEDE pourrait être, de par son envergure systémique, typiquement un projet de recherche offrant une nouvelle *unité et cohérence* à ces différentes actions de recherches passées ou actuelles.

D'autre part, concernant le BS de GAMEDE, il existe dans la littérature un grand nombre de modèles partiels traitant de façon précise des processus biophysiques majeurs rencontrés en EBL. En modélisation, de notre point de vue, l'enjeu majeur aujourd'hui n'est pas tant de produire de nouveaux modèles partiels que d'évaluer leur validité dans des contextes différents de celui de leur conception et de les réunir dans des projets de modélisation plus larges tels que le cadre de cette thèse.

Evaluer le modèle selon de multiples regards

Toujours dans le cadre d'une approche systémique et transdisciplinaire l'évaluation du modèle GAMEDE a croisé de nombreux regards : une vérification de la *justesse* des simulations par une confrontation du simulé à l'observé (méthode plutôt issue des sciences biophysiques) et une vérification subjective du *réalisme* des simulations selon l'expertise de chercheurs et de nombreux acteurs de la filière laitière choisis selon leur domaine d'expertise (méthode plutôt issue des sciences sociales).

Comme décrit dans les chapitres II et V : une troisième méthode dite de « validation par l'usage » peut être envisagée, dans laquelle les critères d'évaluation sont choisis en accord avec les objectifs opérationnels de modélisation :

- validation par la *pertinence* et la *crédibilité* des réponses apportées aux décideurs dans le cas d'une utilisation en tant qu'outil d'aide à la décision,

- validation par l'*importance des échanges et des réflexions* générés chez les acteurs dans le cas d'une utilisation en tant que modèle d'accompagnement,

- validation par le *progrès* généré dans le cadre d'une utilisation comme outil de développement, de formation et/ou de diffusion d'innovations.

De manière générale, nous considérons l'*utilisation du modèle* comme une *étape à part entière de sa construction*.

VI.3 Limites et généricité du modèle GAMEDE

Limites de GAMEDE

Un certain nombre de limites du modèle GAMEDE sont ici présentées. Elles concernent le DS, le BS et l'évaluation de la durabilité.

D'un point de vue décisionnel les pratiques de conduite peuvent être simulées avec encore plus de réalisme comme démontré dans le chapitre IV. L'implémentation de la totalité des règles d'action (prévues par la SAM) pour l'ensemble des 19 opérations techniques à l'origine des flux de biomasse pourrait être assez facilement réalisée afin de permettre plus d'ajustements dans l'action.

L'ensemble des règles d'ajustement à ajouter est déjà disponible. Il se posera alors la question de l'opérationnalité d'un modèle atteignant un tel niveau de raffinement.

D'un point de vue biophysique, le lessivage et la fixation symbiotique d'azote au niveau des surfaces fourragères ne sont pas modélisés. Concernant le lessivage, les modèles de la littérature calculent la quantité d'azote lessivée selon une fonction du drainage. L'eau drainée est déjà calculée par le sous-module sol de la version actuelle de GAMEDE. Concernant la fixation symbiotique, il existe des facteurs de fixation (tout comme les facteurs d'émissions du § III.3.6) qui sont fonction de la proportion de légumineuses dans le couvert végétal de la surface fourragère. Un travail complémentaire permettrait d'affiner le modèle sur ces points particuliers. La validation n'en restera pas moins difficile tant les données sont rares en ce qui concerne des contextes tels que La Réunion.

L'évaluation de la durabilité des SP est incomplète. A la demande des acteurs de la filière un module d'évaluation économique (déjà défini d'un point de vue conceptuel ; Slegten, 2007) va prochainement être incorporé à GAMEDE. De même un module de consommation d'énergies non renouvelables et d'émissions de gaz à effet de serre, inspiré des approches du type analyses de cycles de vie, a été défini conceptuellement (Vigne, 2007). Il reste à l'implémenter pour compléter l'évaluation environnementale. En ce qui concerne les indicateurs sociaux ils se limitent au point de vue de l'éleveur (ses temps de travail), d'autres indicateurs tels que la participation de l'EBL à la création d'emplois et au maintien d'une population rurale à une échelle régionale pourraient être envisagés.

L'évaluation de la durabilité des systèmes de production s'arrête aux frontières de la ferme. Ce qui limite l'appréhension des complémentarités entre les différents systèmes de production au sein du territoire. Par exemple concernant le bilan de l'azote, une exploitation d'élevage peut être excédentaire alors que des exploitations voisines cannières ou maraîchères peuvent s'avérer déficitaires. La construction d'un MAS à l'échelle des différentes zones d'élevage serait une démarche tout à fait complémentaire.

Enfin l'évaluation de la durabilité proposée par GAMEDE se limite à une représentation du système dans son contexte actuel. Un système de production peut être évalué comme durable dans le contexte actuel et peut ne plus l'être dans un autre contexte (e.g. modification du climat). En effet, GAMEDE n'a pas été conçu pour simuler le développement d'une exploitation: la structure de l'exploitation et la stratégie de l'éleveur restent inchangées au cours de la simulation. Le DS simule la mise en œuvre de la stratégie, il ne simule pas la réactualisation de cette stratégie face à un contexte économique, climatique ou/et sociétal changeant. Par conséquent l'évaluation de la durabilité du système de production se limite au moyen terme, elle ne renseigne pas sur la flexibilité et la capacité adaptative des systèmes de production.

Généricité du modèle ?

Les approches détaillées de type ethnographiques permettent d'aller loin dans la compréhension des organisations. Cependant leur limite est que par définition elles sont fortement liées à leur contexte d'étude ce qui rend difficile l'extraction de règles génériques. Concernant le projet GAMEDE basé sur une étude fine de six exploitations et un contact privilégié avec leurs gestionnaires, il est légitime de s'interroger sur la généricité des résultats obtenus dans ce travail de modélisation. Le risque est d'avoir produit un modèle « sur mesure » pour les six éleveurs du groupe de travail.

La phase d'échantillonnage de ces six EBL a joué un rôle essentiel. Comme expliqué en chapitre IV cet échantillon a veillé à couvrir les différentes zones pédo-climatiques de l'île et a croisé deux typologies : une typologie technico-économique (Alary *et al.*, 2002) et une typologie de combinaison de pratiques (Vayssières *et al.*, 2006) qui ont toutes deux concerné 27% des EBL réunionnais. Du point de vue du profil décisionnel des éleveurs la représentativité de l'échantillon des six EBL a aussi été évaluée par des éleveurs et des techniciens de la filière. La qualité de cet échantillon nous laisse augurer que GAMEDE est capable de représenter la grande majorité des systèmes de production laitiers existants à La Réunion et de simuler les changements techniques envisagés par la majorité des éleveurs réunionnais.

Le fait que GAMEDE représente des systèmes laitiers très différents localisés dans des contextes climatiques très contrastés nous laisse à penser que le domaine d'application de GAMEDE dépasse celui de La Réunion. Cependant une des limites à la généricité de GAMEDE est qu'il représente uniquement des EBL spécialisés dont les surfaces sont exclusivement destinées à des cultures semi-pérennes. La question de l'assolement ne s'est donc pas présentée dans le cas de GAMEDE contrairement au projet MELODIE (Chardon *et al.*, 2007) qui vise la modélisation de systèmes polyculture-élevage dans le grand Ouest français. Dans ce dernier projet la question de l'assolement est résolue par le module d'optimisation TOURNESOL (Garcia *et al.*, 2005a). Si l'on souhaite tester GAMEDE dans d'autres contextes, l'existence de cultures différentes (e.g. maïs, blé en contexte tempéré ou riz, manioc en contexte tropical) suppose l'ajout de nouveaux sous-modules biophysiques et de nouvelles opérations techniques (e.g. préparation du sol, désherbage). Mises à part ces questions d'assolement et d'ajout de nouvelles cultures/opérations techniques, nous sommes convaincus que la structure générale de GAMEDE est générique ; à savoir :

- l'intégration d'un DS et d'un BS (Martin-Clouaire and Rellier, 2000) déjà expérimentée dans d'autres modèles d'exploitation (Cros *et al.*, 2001),
- la simulation de l'action comme concept charnière entre ce DS et ce BS,

- la SAM organisant et articulant des règles de décisions opérationnelles pour donner une place importante aux ajustements dans l'action et pour représenter des pratiques de conduite réalistes,
- et la représentation du fonctionnement de l'exploitation par des flux de biomasse permettant ensuite de représenter les flux de nombreux « éléments à risque » (N, P, C) et le calcul de nombreux indicateurs potentiels tels que les temps de travaux, les flux monétaires et la consommation d'énergies non renouvelables.

De notre point de vue, ces quatre éléments seraient les points fixes du modèle GAMEDE si ce dernier devait être appliqué à d'autres contextes tels que les pays en développement sous climat tropical et les pays industrialisés sous climat tempéré. Toutefois cette généricité reste à démontrer.

Au-delà des systèmes bovins laitiers, GAMEDE fournit le cadre dans lequel les différentes composantes du fonctionnement d'une ferme d'élevage comportant des cultures peuvent être intégrés de façon cohérente au sein du modèle et vis-à-vis de la nature du système représenté. Ce cadre devrait être transposable à des systèmes d'élevage autres que bovin laitier étant donné que ce dernier est le plus complexe. Ce cadre proposé par GAMEDE reste souple et offre la possibilité d'incorporer de nouveaux composants, de développer de nouvelles sorties et de raffiner le modèle aussi bien d'un point de vue biophysique que décisionnel.

CONCLUSION GENERALE

La thèse qui est ici présentée comprend la conception, le développement, l'évaluation, l'amélioration et l'utilisation de GAMEDE, un modèle représentant le fonctionnement et les flux d'azote à l'échelle globale de l'exploitation bovine laitière.

En EBL à La Réunion, 83% des flux d'azote sont actionnables, i.e. résultent d'actions de conduite et donc de décisions de l'éleveur. Ainsi, nous avons intégré au modèle les « pratiques décisionnelles des éleveurs », i.e. nous avons modélisé les actions de conduite avec réalisme en tenant compte des aléas climatiques et des concurrences autour de l'utilisation des ressources de l'exploitation.

Pour aboutir à cette représentation le modèle GAMEDE comprend un système décisionnel (**DS**) original qui a été construit pour simuler la réalisation quotidienne de l'ensemble des 19 opérations de conduite qui génèrent des flux d'azote dans l'exploitation. Ce DS contrôle et interagit avec un système biophysique (**BS**) complexe représentant à un pas de temps quotidien les phénomènes biophysiques majeurs intervenant dans les exploitations d'élevage. Ce sont la repousse des graminées fourragères, leur conditionnement après récolte, la démographie et les différentes productions du troupeau, le pâturage et l'évolution des engrais de fermes, émissions d'azote sous forme gazeuse incluses. La finesse du DS et la complexité du BS sont étroitement liées.

A ce modèle d'exploitation original correspond une approche de modélisation innovante basée sur la complémentarité des disciplines, une forte participation d'éleveurs, une importante valorisation des travaux existants dans le domaine biophysique et le croisement de nombreux regards pour l'évaluation du modèle. Les approches classiques concernant l'azote sont basées sur des « farm-gate nutrient balances ». Elles conduisent généralement à la production de normes connues pour être mal vécues par la majorité des agriculteurs. A l'inverse, ce projet de modélisation à montré que la co-construction et l'utilisation d'un modèle de simulation tel que GAMEDE à des fins de représentation et de dialogue permet i) de faire le lien explicite entre les choix de l'éleveur et la durabilité de son exploitation, ii) d'identifier des systèmes de production offrant un compromis entre intensification et respect de l'environnement, et iii) de conduire des éleveurs à repenser leur système de production et ainsi définir eux-mêmes des alternatives techniques favorables à la durabilité de leur élevage.

L'intégration des pratiques décisionnelles et la participation d'éleveurs vont de pair ; en effet, la modélisation de la décision a été rendue possible par la participation des éleveurs et réciproquement, simuler avec réalisme des actions de conduite des éleveurs accroît leur intérêt pour le modèle et donc leur motivation à participer.

Ainsi, compte tenu de l'objectif finalisé de produire un outil d'aide à la décision d'éleveurs et d'améliorer la durabilité des élevages, cette thèse démontre qu'**il est pertinent de modéliser les pratiques décisionnelles d'éleveurs et de faire participer des éleveurs au processus de modélisation lorsque l'on veut formaliser les interactions entre :**

- **l'éleveur** (les décisions et les pratiques de l'individu),
- **et son outil de production** (le fonctionnement et les performances du système de production dans sa globalité).

De plus, nos résultats confortent l'hypothèse que le changement volontaire et raisonné des pratiques des éleveurs appuyé par les sorties d'un tel modèle peut constituer une alternative aux normes environnementales efficace pour l'amélioration de la durabilité des systèmes de production. Ces résultats sont aussi particulièrement intéressants pour les pays n'ayant pas les moyens de mettre en œuvre une politique agricole nationale aussi drastique que la politique européenne.

Nous considérons que la structure globale du modèle, centrée sur l'action et les flux de biomasse, et la démarche générale de modélisation sont génériques et tout à fait transposables à d'autres contextes, que ce soit celui de pays industrialisés sous climats tempérés ou de pays en développement sous climats tropicaux.

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LISTE DES ANNEXES

Annexe A. List of acronyms

Acronym	Signification
ADEME	Agence de l'Environnement et de la Maîtrise de l'Energie
Al	Animal
ANR	Agence Nationale de Recherche
AP	Action Plan
ARIBEV	Association. Réunionnaise Interprofessionnelle du BEtail, de la Viande et du lait
AWU	Agricultural Workforce Unit
BEFM	Bio-Economic Farm Model
BS	Biophysical System
CIRAD	Centre de coopération Internationale en Recherche Agronomique pour le Développement
CSIRO	Australia's Commonwealth Scientific and Industrial Research Organisation
DD	Développement Durable
DISCOTECH	DISpositifs innovants pour la COnception et l'évaluation de systèmes TECHniques
DM	Dry Matter
dmnl	dimensionless
DS	Decisional System
DSS	Decision Support System
EBL	Elevage Bovin Laitier
EF	Emission Factor
EHS	Effluent Handling System
EO	External Observer
F	Farmer
FAO	Food and Agriculture Organisation: l'organisation des Nations Unies pour l'alimentation et l'agriculture
FM	Fresh Matter
FRCA	Fédération Réunionnaise des Coopératives Agricoles
GAMEDE	Global Activity Model for Evaluating the Sustainability of Dairy Enterprises
I	Immersion
IMP	Individual Milk Production
INRA	Institut National de la Recherche Agronomique
LP	Linear Programming
LU	Livestock Unit
MAS	Multi-Agent System
MCDM	Multi Criteria Decision Making
MCF	Module de Conditionnement des Fourrages
MD	Module de Démographie du troupeau
MEA	Module d'Emissions Azotées
MP	Module de Pâturage
MPA	Module de Productions Animales
MPF	Module de Production de Fourrages verts
N	Nitrogen
R	Researcher
RMSE	Root Mean-Squared Error
SAM	Structure for Action Modelling
SFM	Simulation Farm Model
SP	Système de Production
SPADD	Systèmes de Production Animale et Développement Durable
UAA	Utilised Agricultural Area
UGB	Unité Gros Bovin

Variables abbreviations are not considered; for these see Appendix B

Annexe B. List of the 90 main variables of GAMEDE

Abbreviation	Signification	Unit
AB	Available uncut forage biomass of a plot	kgDM ha^{-1}
AD	Action duration	hrs day^{-1}
AF	Flow the action generates	kgFM day^{-1}
AOG	Abundance indicator of offered grass on a pasture	kgDM LU^{-1}
AN	Annual N amount spread to a considered plot	kgN ha^{-1} $year^{-1}$
AR	Binary variable accounting for action realisation	dmnl
C	Concentrate feed subscript	-
CCR	Cow culling rate	dmnl
CorTg	Correction factor of potential defoliation	dmnl
CorUF	Correction of energy supply taking account concentrate-forage interactions in the rumen	UF Al^{-1} Day^{-1}
D	Water drainage	mm day^{-1}
dB	Daily growth rate of a plot	kgDM day^{-1}
DI	Drying intensity during silage	kgDM $kgFM^{-1}$ hr^{-1}
DMC	Dry mater content	kgDM $kgFM^{-1}$
DT	Drying time	hrs
dW	Rate of change in soil water content	mm day^{-1}
E	Nitrogen gaseous emission	kgN day^{-1}
ED	Effective defoliation during grazing	kgDM day^{-1}
EF	Nitrogen gaseous emission factor	dmnl
EMP	Effective milk production	kgFM Al^{-1} day^{-1}
ETP	Potential Evapotranspiration	mm day^{-1}
ETR	Actual Evapotranspiration	mm day^{-1}
F	Forage subscript	-
FC	Field capacity	mm m^{-1}
Fe	Fertiliser subscript	-
FP	Quantity of faeces produced	kgFM Al^{-1} day^{-1}
FT	Photosynthesis efficiency factor	dmnl
FUV	Fill value of a feed	FU $kgDM^{-1}$
FY	Forage yield	kgDM ha^{-1}
GDMC	Gain of dry mater content during silage	kgDM $kgFM^{-1}$
h	Depth	mm day^{-1}
HF	Handling biomass flow	kgFM day^{-1}
IC	Ingestion capacity of an animal cohort	FU Al^{-1}
ICC	Calving interval	day
IEA	Time interval between event prior to action and action	day
In	Nitrogen stress index	dmnl
Ir	Forage yield index	dmnl
Irf	Rainfall correction index of ammonia volatilisation	dmnl
IT	Temperature stress index	dmnl
Ith	Thermal correction index of ammonia volatilisation	dmnl
Iw	Water stress index	dmnl
Kc	Cultural coefficient	dmnl
Keag	Eagleman coefficient	dmnl
Kn	Nitrogen efficiency coefficient	dmnl
LAI	Leaf area Index	m^2 of limb m^{-2} of soil
LW	Average liveweight of an animal of the considered cohort	kgFM Al^{-1}
LWG	Daily liveweight gain	kgFM Al^{-1} day^{-1}
MADV	Feed value: digestible crude proteins	MAD $kgDM^{-1}$
MATV	Feed value: total proteins	MAT $kgDM^{-1}$
MConv	Maximum conversion rate of the crop	kgDM MJ^{-1}
MOP	Management option corresponding to a practical season	-
MPAB	Milk production allowed by loss of body reserves	kgFM Al^{-1} Day^{-1}
MPAE	Milk production allowed by diet energy	kgFM Al^{-1} Day^{-1}
MPAR	Milk production allowed by the ration	kgFM Al^{-1} Day^{-1}
NbLU	Number of livestock units of a cohort	LU
NC	Nitrogen content of biomasses (e.g. fertilisers)	kgN $kgFM^{-1}$
P	Water percolation	mm day^{-1}
PARc	Corrected photosynthetically active radiation	MJ ha day^{-1}
PD	Potential defoliation	kgDM day^{-1}
PDc	Corrected potential defoliation	kgDM day^{-1}

PDIAV	Feed value: digestible proteins in the small intestine from diet	PDIA $kgDM^{-1}$
PDIEV	Feed value: digestible proteins in the small intestine from microbes (energy limited)	PDIE $kgDM^{-1}$
PDINV	Feed value: digestible proteins in the small intestine from microbes (proteins limited)	PDIN $kgDM^{-1}$
pl	Plot subscript	-
PMP	Potential milk production	kgFM Al^{-1} day^{-1}
Q	Quantity of fertiliser to be spread according to the management option	kgFM ha^{-1} day^{-1}
QCons	Quantity of conservator spread per round bale	kgFM Round $Bale^{-1}$
QI	Quantity of feed ingested	kgDM Al^{-1} Day^{-1}
Qpe	Quantity of primary effluent produced	kgFM day^{-1}
QSc	Corrected quantity of straw spread for bedding	kgFM LU^{-1} day^{-1}
QSP	Quantity of fertiliser spread	kgFM day^{-1}
RB	Residual biomass	kgDM ha^{-1}
RCE	Radiation conversion efficiency	dmnl
Rf	Rainfall	mm day^{-1}
RG	Global solar radiation	MJ ha day^{-1}
RIC	Remaining intake capacity available for grazing	FU Al^{-1} Day^{-1}
S	Area of a plot	ha
Sh	Hydric satisfaction coefficient	dmnl
SPE	Speed of action realisation according to the action modality	kgFM hrs^{-1}
Tbase	Temperature below which the plant growth is stopped	°C
TEA	Time interval elapsed since the event prior to action	
Tg	Grazing time	hr day^{-1}
Th	Actual soil moisture	dmnl
Topt	Temperature above which the radiation conversion efficiency is optimum	°C
TT	Transit time of animal cohorts	day
U	Water Upward fluxes	mm day^{-1}
UAA	Utilised Agricultural Area	ha
UFV	Energy value of a feed	UF $kgDM^{-1}$
UP	Quantity of urine produced	kgFM Al^{-1} day^{-1}
W	Soil water content capacity	mm
Wcap	Soil water content capacity	mm

Annexe C. Thermal parameters of the forage crops considered in GAMEDE

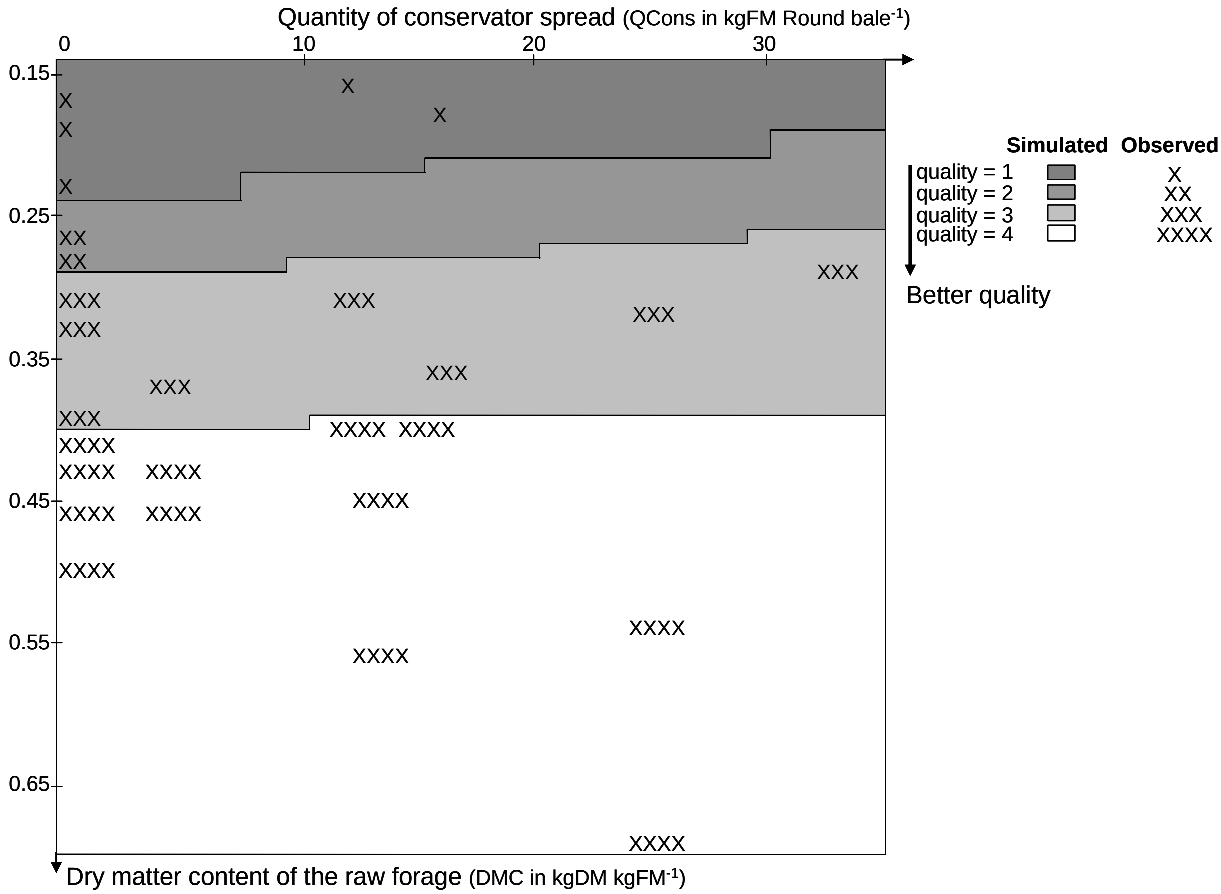
Forage crop		Tbase (°C)	Topt (°C)
Sugar cane		12	30
Grasses	Chloris (*Chloris gayana*)	8	20
	Kikuyu (*Pennisetum clandestinum*)	5	18
	Mixed population with temperate species dominating (*Dactylic glomerata*, *Lolium sp.*, *Bromus catharticus and Pennisetum clandestinum*)	3	8

Annexe D. Main characteristics of the 11 fertilisers considered in GAMEDE

Fertiliser		Nitrogen content (*) (NC in gN $kgFM^{-1}$) (Chabalier *et al*., 2006)	Nitrogen efficiency coefficient (Kn, dmnl) (Leteinturier *et al*., 2004)
Organic fertilisers	Cattle urine	Var. (11)	1
	Cattle faeces	Var. (3.3)	0.83
	Cattle slurry	Var. (2.85)	0.83
	Pig slurry	3.5	0.7
	Cattle solid manure	Var. (6.2)	0.83
	Compost of cattle solid manure	Var. (8)	0.8
	Poultry droppings	12.4	1
Mineral fertilisers (N – P – K)	15-12-24	150	1
	30-10-10	300	1
	33-11-06	330	1
	26-00-00	260	1

* For on-farm produced fertilisers the N content is variable "Var." and dynamically calculated according to farmer's practices. A default value is given between brackets.

Annexe E. The abacus used in GAMEDE to define the quality of silage produced (four classes) depending on the dry matter content of the raw silage and the quantity of conservator spread



Annexe F. The 21 animal cohorts of GAMEDE

Physiological stage		**Age** (month)	**Transit time** (TT in days)
Calves		1-3	90
Heifers		4-6	
		7-9	
		10-12	
		13-15	
		16-18	
		19-21	
		22-24	
		25-27	
		28-30	
		31-33	
		34-36	
Primiparus producing cows	Beginning lactation		60
	Middle lactation		120
	End lactation		Var. (150)
Primiparus dry cows	Dring off		60
Multiparus producing cows	Beginning lactation		60
	Middle lactation		120
	End lactation		Var. (150)
Multiparus dry cows	Dring off		60
Dry cows	Fattening		Var. (1)

Dynamically calculated variables are indicated by “Var.” A default value is given in brackets.

Annexe G. Feeding values of the 21 forages considered in GAMEDE

Forage name	**DMC** (kgDM $kgFM^{-1}$)	**UFV** (UF $kgDM^{-1}$)	**PDIAV** (PDIA $kgDM^{-1}$)	**PDINV** (PDIN $kgDM^{-1}$)	**PDIEV** (PDIE $kgDM^{-1}$)	**MATV** (gMAT $kgDM^{-1}$)	**MADV** (gMAD $kgDM^{-1}$)	**FUV** (FU $kgDM^{-1}$)
Green Forage								
Oat	0.18	0.83	43	119	87	174	138	1.02
Bromus	0.18	0.78	34	96	83	164	129	1.07
Sugar cane	0.24	0.70	13	36	67	61	30	1.21
On farm produced cane	Var.	Var.	Var.	Var.	Var.	Var.	Var.	Var.
Napier grass	0.20	0.64	34	60	76	51	20	1.21
Chloris	0.24	0.61	44	76	87	73	41	1.25
Mixed C3 – C4 (Ryegras, Kikuyu)	0.20	0.73	46	94	96	172	136	1.08
Kikuyu	0.24	0.73	55	97	105	126	92	1.13
On farm produced grass	Var.	Var.	Var.	Var.	Var.	Var.	Var.	Var.
Ryegras	0.22	0.92	42	118	96	188	152	0.99
Silage								
Bromus	0.27	0.75	22	79	63	148	113	1.27
Chloris	0.28	0.6	17	58	50	122	88	1.5
Mixed C3-C4.	0.26	0.72	23	74	61	97	64	1.39
Cocksfoot	0.25	0.71	27	92	67	148	113	1.23
On farm produced	Var.	Var.	Var.	Var.	Var.	Var.	Var.	Var.
Ryegras	0.30	0.79	17	64	60	138	104	1.16
Hay								
Chloris	0.85	0.61	44	76	87	121	87	1.25
Cocksfoot	0.85	0.60	25	58	69	93	60	1.15
Sugar Cane by products								
Tops	0.30	0.63	22	38	63	59	28	1.24
Straw	0.80	0.52	6	14	50	40	9	1.32
Bagasse	0.44	0.31	7	12	34	17	0	1.65

For on-farm produced forages the feed values are variable “Var.” and dynamically calculated according to farmer’s practices and weather conditions. Default values are feeding values of the corresponding forage in INRA feed tables.

Annexe H. Feeding values of the 19 concentrate feeds considered in GAMEDE

Concentrate name	DMC (kgDM $kgFM^{-1}$)	UFV (UF $kgDM^{-1}$)	PDIAV (PDIA $kgDM^{-1}$)	PDINV (PDIN $kgDM^{-1}$)	PDIEV (PDIE $kgDM^{-1}$)	MATV (gMAT $kgDM^{-1}$)	MADV (gMAD $kgDM^{-1}$)	FUV (FU $kgDM^{-1}$)
B45	0.90	0.95	63	125	115	180	144	1
B48	0.90	1	62	112	110	174	138	1
B75	0.90	1.05	79	120	126	176	140	1
B80	0.90	1.05	55	85	100	137	103	1
Rice ground	0.90	1.07	26	60	74	112	79	1
M48	0.90	0.95	0	110	103	160	125	1
M49	0.90	0.92	59	115	108	165	130	1
Corn ground	0.90	1.09	50	67	101	96	63	1
Molasse	0.74	0.67	0	24	50	41	10	1
Pulco	0.90	0.88	43	77	97	120	86	1
Pulco special cotton	0.90	0.92	0	93	90	146	111	1
Beet pulp	0.90	0.9	36	56	94	91	59	1
SandiEnergie	0.90	1.01	44	114	90	130	96	1
SandiLait	0.90	0.92	52	120	118	175	139	1
Wheat bran	0.90	0.9	41	96	114	173	137	1
Soja cake	0.90	0.99	166	312	215	416	371	1
Urea	0.98	0	0	1610	0	2875	0	1
Whole milk powder	0.96	1.71	0	140	58	275	215	1
Fresh milk	0.12	1.71	0	140	58	275	215	1

Annexe I. Emission factors (EF, dmnl) for the fertilisers considered in GAMEDE and distinguishing the different handling steps

Fertiliser		In barns NH_3	In barns N_2O	In barns N_2	During storage NH_3	During storage N_2O	During storage N_2	During conditioning NH_3	During conditioning N_2O	During conditioning N_2	On field NH_3	On field N_2O	On field N_2
Bovine urine		-			-			-			Grazing: 0.15[17]	0.02[8]	0.06[+]
Bovine faeces											Grazing: 0.03[17]		
Bovine slurry		0.306[*, 3]	0.002[12]	0.006[+]	0.031[3]	0.0025[4]	0.0075[+]	Mixing : 0.018[11]	0.0015	0.0045[+]	Spreading on grasslands: 0.14[7] Spreading on sugar cane: 0.247[7]	0.009[6]	0.027[+]
Bovine solid manure	soft	0.294[*, 3]	0.005[4]	0.015[+]	0.032[3]	0.02[8]	0.06[+]	-			Spreading: 0.14[9]		
	strawy	0.407[*, 3]	0.02[8]	0.06[+]	0.092[3]			Swathing: 0.1[14, 15] 1st turning: 0.06[14, 15] 2nd turning: 0.01[14, 15]	0.02[16] 0.01[16] 0.01[16]	0.09[16] 0.05[16] 0.1[16]	Spreading: 0.1[10]		
	very strawy	0.328[*, 3]						Swathing: 0.11[14, 15] 1st turning: 0.04[14, 15] 2nd turning: 0.01[14, 15]	0.01[16] 0.003[16] 0.003[16]	0[16] 0.05[16] 0.08[16]	Spreading: 0.06[10]		
Compost of bovine solid manure		-			0[2]			-			Spreading: 0[1]		
Pig slurry					-						Spreading: 0.12[13]	0.009[6]	0.027[+]
Poultry droppings											Spreading: 0.315[5]		
Mineral fertilisers											Spreading: 0.02[5]	0.0125[8]	0.0375[+]

Reference conditions: temperature = 10°C and rainfall = 0 mm.
[*] EF relative to ammoniac N (others are relative to total N)
[+] EF estimated from the Webb (2001) equation: $EF_{N2} = 3 * EF_{N2O}$
[1] Amon *et al*., 1998; [2] Chadwick *et al*., 2002; [3] Dollé *et al*., 2000; [4] Dollé and Robin, 2006; [5] EMEP-CORINAIR., 2001; [6] Gac *et al*., 2006; [7] Génermont *et al*., 2003; [8] IPCC, 1997; [9] Karisson and Salomon, 2002; [10] Le Gall and Cabaret, 1998; [11] Levasseur *et al*., 1999; [12] Marquis, 2002; [13] Morvan and Leterme, 2001; [14] Paillat *et al*., 2005; [15] Parkinson *et al*., 2004; [16] Robin *et al*., 2001; [17] Whitehead, 1995.

Annexe J. Sensitivity analysis of four sustainability indicators to the most influential input parameters of GAMEDE (farm 2)

Parameter type	Parameter	Unit	Actual value	N surplus		Milk productivity		Forage crop productivity		Total work time	
				-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%
Management parameters	Harvest interval	day	60	**1.9**	0.3	0.2	0.1	**2.2**	**-2.6**	-0.1	-0.3
	Quantity of mineral fertiliser spread after each harvest	KgFM ha^{-1} $harvest^{-1}$	152.5	-0.8	0.8	0.0	0.0	**-0.6**	**0.6**	-0.1	0.1
	Quantity of slurry spread after each harvest	KgFM ha^{-1} $harvest^{-1}$	16500	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0
	Grazing time	Hrs day^{-1}	15.75	0.0	0.0	0.0	0.0	**0.5**	**-0.6**	0.9	-0.9
	Forage ration composition	KgFM Al^{-1} day^{-1}	1.3	0.1	-0.1	0.0	0.0	0.0	0.0	-0.4	0.3
	Quantity of concentrate feeds distributed	KgFM Al^{-1} day^{-1}	5.2	**-2.2**	**1.5**	**-2.7**	**2.7**	-0.1	0.1	-0.5	0.5
	Adjustment coefficient on quantity of concentrates distributed depending on the lactating stage of the cow	dmnl	1	**-4.5**	-0.4	-0.9	0.9	0.0	0.0	-0.2	0.2
	Herd growing rate	dmnl	0.05	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Cow culling rate	dmnl	0.1	-0.4	0.1	0.0	0.0	0.0	0.0	0.2	-0.2
Herd parameters	Calving interval	day	400	-4.5	-0.3	**5.2**	**1.7**	**0.9**	**-0.7**	**3.7**	**6.7**
	Genetic potential milk production	KgFM cow^{-1} $year^{-1}$	9000	0.4	-0.4	**1.2**	**5.2**	0.0	0.0	**5.6**	**5.4**
	Milk protein content	kgN $kgFM^{-1}$	30.8	**2.5**	**-2.5**	**3.4**	**3.4**	0.0	0.0	**5.5**	**5.5**
	Part of milk not sold due to sanitary problems	dmnl	0.96	-0.3	0.3	**4.5**	**2.3**	0.0	0.0	**5.5**	**5.5**
Farm structure parameters	Surface of grassland plots	ha	4.5	**1.1**	**-1.1**	0.0	0.0	-0.2	0.2	-0.1	0.1
	Initial size of the herd	Al	6	0.3	-0.6	0.0	0.0	-0.1	0.1	-0.5	0.5
	Water collection surfaces	m^2	137	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

These values are calculated with GAMEDE and are means for the 2004-2006 period. Except for the first column (the actual value), which is in absolute value, all values are percentages of variation of farm results as the consequence of +/- 10% variation of the input parameter around the actual value.

Annexe K. Diversity of agro-eclological areas where dairy farming is encountered in La Réunion[8]

Troupeau de vaches laitières au pâturage dans les Hauts de l'Ouest (zone 1)

Elevage bovin allaitant à la Plaine des Cafres (zone 2)

Plaine des Palmistes (zone 3)

Pression de l'urbanisation dans les Hauts de St Joseph (zone 4)

[8] Les photographies présentées dans cette thèse ont été prises par l'auteur.