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Mathieu Vigne. Flux d'énergie dans des systèmes d'élevage laitier contrastés : élaboration d'indicateurs et analyse de la diversité inter et intra-territoire. Sciences du Vivant [q-bio]. AGRO-CAMPUS OUEST; Université de Bretagne Occidentale, 2012. Français. NNT: . tel-02806942

**HAL Id: tel-02806942**

**<https://hal.inrae.fr/tel-02806942v1>**

Submitted on 6 Jun 2020

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N° ordre :  
N° Série :

## **THESE / AGROCAMPUS OUEST**

Sous le label de l'Université Européenne de Bretagne

pour obtenir le diplôme de :

**DOCTEUR DE L'INSTITUT SUPERIEUR DES SCIENCES AGRONOMIQUES,  
AGRO-ALIMENTAIRES, HORTICOLES ET DU PAYSAGE**

Spécialité : Biologie et Agronomie

**Ecole Doctorale : Vie – Agro – Santé**

présentée par :

**Mathieu VIGNE**

**FLUX D'ENERGIE DANS DES SYSTEMES D'ELEVAGE LAITIER CONTRASTES**  
-  
**ELABORATION D'INDICATEURS ET ANALYSE DE LA DIVERSITE INTER ET  
INTRA-TERRITOIRE**

soutenue le 19/12/2012 devant la commission d'Examen

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# Résumé

## **Flux d'énergie dans des systèmes d'élevage laitiers contrastés: Elaboration d'indicateurs et analyse de la diversité inter et intra-territoire**

Le doublement futur de la demande mondiale en produits laitiers nécessite de concevoir des systèmes plus productifs mais également écologiquement plus durables. Les objectifs de la thèse étaient i) d'évaluer l'intérêt de la prise en compte de l'ensemble des énergies mobilisées dans un système d'élevage (énergie fossile, énergie calorifique contenue dans les produits, énergie liée au travail humain et animal et énergie solaire) à travers des méthodes existantes ou originales pour développer des indicateurs robustes, ii) d'analyser finement le fonctionnement énergétique de systèmes laitiers contrastés situés dans différents territoires et iii) de déterminer à travers la diversité d'efficacité des exploitations sur ces indicateurs des sources de progrès réalistes dans les divers territoires.

Deux méthodes se sont révélées pertinentes: l'Analyse pluri-énergétique et l'Emergy. Leur application sur des systèmes laitiers issus de quatre territoires contrastés (Mali Sud, SM, la Réunion, RI, le Poitou-Charentes, PC, et la Bretagne, BR) a démontré leur intérêt pour mettre en lumière des modes de gestion plus ou moins efficaces des ressources. Les systèmes familiaux du SM sont apparus les plus efficaces du fait de l'utilisation de ressources naturelles issues des parcours et de la force de traction animale et humaine. Parmi les systèmes intensifs étudiés, les systèmes de BR sont apparus comme les plus efficaces du fait d'une mobilisation de ressources plus directe via le pâturage. L'efficacité s'est avérée plus faible en PC du fait d'une utilisation moins directe des ressources à travers l'ensilage de maïs et dans les systèmes RI qui sont fortement pénalisés par l'utilisation très importante de concentrés importés.

L'analyse pluri-énergétique s'est également montrée utile pour mettre en lumière des voies d'intensification écologique en SM. Le recours à la traction animale par exemple améliore la productivité des surfaces et leur efficacité énergétique fossile. Elle diminue également le coût en énergie fossile des résidus de culture, base de l'alimentation du troupeau. L'analyse des performances des systèmes par la méthode Data Envelopment Analysis a permis de mettre en lumière des objectifs optimaux de consommation d'énergie fossile propre à chaque type de système sur chacun des territoires permettant de diminuer le coût environnemental de la production de lait.

**Mots-clés :** système laitier, énergie, emergy, intensification écologique



# Abstract

## **Energy flow in contrasted dairy farming systems: Development of indicators and analysis of inter- and intra-territory diversity**

The future doubling in world demand for dairy products requires the design of more productive and sustainable systems. The broadly acknowledged impact of the use of different energy sources on the environment render the need for a better understanding of energy flows and indicators essential to identify realistic lines of progress according to system diversity, to territories and to their respective assets and constraints. The aims of the thesis were i) to assess the benefits of considering all energies involved in a livestock farming system (fossil energy, gross energy contained in products, energy from human and animal labour and solar energy), using existing or original methods for developing robust indicators, ii) to conduct a fine energy efficiency analysis of contrasting dairy systems in different territories and iii) to determine realistic lines of progress in these territories, based on the diversity of farm efficiency according to these indicators.

Two methods were found to be relevant: Pluri-energy analysis and Emergy. Their application to the dairy systems of four contrasted territories (South Mali, SM, Reunion Island, RI, Poitou-Charentes, PC and Bretagne, BR) demonstrated that they could be advantageously used to highlight on more or less efficient resource management methods. The smallholder systems in SM appeared most efficient due to the use of natural resources obtained from animal and human workforce. Among the intensive systems studied, those in BR appeared most efficient due to the more direct mobilisation of resources through grazing. Efficiency was lower in PC due to less direct resource use through maize silage, and in RI systems that are significantly penalized by the large use of imported feed concentrates.

Pluri-energy analysis also proved useful in highlighting routes of ecological intensification in SM. For example, the use of animal draught power improves the productivity and fossil energy efficiency of crops. It consequently reduces the fossil energy cost of crop residues, used as a staple of the herd's diet. System performance analysis using the Data Envelopment Analysis method shed light on the optimum fossil energy consumption targets of each system type in each territory for reducing the environmental cost of milk production.

**Keywords:** *dairy system, energy, emergy, ecological intensification*



## Avant-propos

Ce travail de thèse a été réalisé au sein de l'Unité Mixte de Recherches INRA - Agrocampus Ouest Physiologie, Environnement et Génétique pour l'Animal et les Systèmes d'Élevage de St Gilles. Etant sous co-financement INRA - CIRAD, il a également profité de la participation de l'Unité Mixte de Recherche CIRAD - INRA Systèmes d'Élevage Méditerranéen et Tropicaux notamment dans le cadre du projet ANR «Efficience Environnementale et productions animales pour le développement durable» (Décision n° ANR-09-STRA-01-01).

Cette thèse a donné lieu à l'écriture de sept articles scientifiques et de quatre communications courtes sous forme de poster.

### *Articles scientifiques :*

- Vigne, M.,** Ba, A., Coulibaly, D., Dembélé B., 2011. Efficience énergétique des systèmes mixtes agriculture-élevage en zone périurbaine de Sikasso, Mali Sud. *Les Cahiers de l'Economie Rurale* 14 (*sous presse*)
- Vigne, M.,** Vayssières, J., Lecomte, P., Peyraud, J.L., 2012. Evaluating the ability of current energy use assessment methods to study contrasting livestock production systems. *Journal of Environmental Management* 112, 199-212.
- Vigne, M.,** Martin, O., Faverdin, P., Peyraud, J.L., 2012. Comparative uncertainty analysis of energy coefficients in energy analysis of dairy farms from two French territories. *Journal of Cleaner Production* 37, 185-191.
- Vigne, M.,** Vayssières, J., Lecomte, P., Peyraud, J.L., 2012. Pluri-energy analysis of livestock systems - a comparison of dairy systems in different territories. *Journal of Environmental Management* (*soumis*)
- Vigne, M.,** Peyraud, J.L., Corson, M., Wilfart, A., 2012. Emergy evaluation at different levels of contrasting dairy systems from low-input smallholder systems to high-input intensive systems. *Journal of Environmental Management* (*soumis*)
- Vigne, M.,** Ba, A., Coulibaly, D., Dembélé, B., Corniaux, C., Lecomte, P., 2012. Variability of energy efficiency in dairy systems from periurban area of Sikasso (Mali). *Animal* (*soumis*)



**Vigne, M.**, J.L. Peyraud, Faverdin, P., 2012. Improving fossil energy efficiency of dairy systems from West of France – An application of data envelopment analysis. (*en préparation*)

***Communications courtes :***





**Vigne, M.**, Peyraud, J-L., Lecomte, P., 2011. Impact du choix des coefficients énergétiques sur les résultats de l'analyse énergétique : Exemple de la consommation énergétique des élevages bovins laitiers réunionnais. *XVIIIème Rencontres Recherches Ruminants*, 7-8 décembre 2011, Paris, France. (Poster) (Annexe I)

**Vigne, M.**, Faverdin, P., Peyraud, J.L., 2012. Energy analysis of agricultural systems Uncertainty associated to energy coefficients non-adapted to local conditions. *8<sup>th</sup> International conference on Life Cycle Assessment in the Agri-Food sector*, 1-4 october 2012, St Malo, France. (Poster) (Annexe II)

**Vigne, M.**, Ba, A., Dembele, B., Coulibaly, D., 2012. Efficience énergétique des systèmes mixtes agriculture-élevage en zone périurbaine de Sikasso, Mali Sud. *XIXème Rencontres Recherches Ruminants*, 5-6 décembre 2012, Paris, France. (Poster) (Annexe III)

**Vigne, M.**, LeLan, B., Rubin, B., Faverdin, P., Peyraud, J.L., 2012. Analyse de la variabilité de l'efficience énergétique fossile dans les systèmes laitiers de l'Ouest de la France. *XIXème Rencontres Recherches Ruminants*, 5-6 décembre 2012, Paris, France. (Poster) (Annexe IV)

# Liste des abréviations

| Abréviation   |   | Signification   |  |
|---|---|---|--|
|  |  |  |  |
| %R  | %R  | Renouvelabilité   | Renewability   |
| BR  | -   | Bretagne  | Bretagne   |
| -   | DEA   |   | Data Envelopment Analysis  |
| E   | -   | Energie totale produite   | -  |
| -   | EA  | Analyse énergétique   | Energy Analysis  |
| -   | EF  | Empreinte écologique  | Ecological Footprint   |
| -   | EIR   | -   | Energy Investment Ratio  |
| -   | ELR   | -   | Energy Loading Ratio   |
| -   | Em  | Méthode Emergy  | Emergy synthesis   |
| -   | ESI   | -   | Emergy Sustainability Index  |
| -   | EYR   | -   | Emergy Yield Ratio   |
| -   | FE  | Energie fossile   | Fossil energy  |
| -   | FEE   | Efficience énergétique fossile  | Fossil energy efficiency   |
| -   | FEU   | Consommation d'énergie fossile  | Fossil energy use  |
| -   | GE  | Energie brute   | Gross energy   |
| -   | GEE   | Efficience énergétique brute  | Gross energy efficiency  |
| -   | GEP   | Production d'énergie brute  | Gross energy production  |
| -   | GEU   | Consommation d'énergie brute  | Gross energy use   |
| -   | LE  | Energie liée au travail   | Labour energy  |
| -   | LEE   | Efficience énergétique du travail   | Labour energy efficiency   |
| -   | LEU   | Consommation d'énergie liée au travail  | Labour energy use  |
| -   | M   | Emergy issue des matériaux achetés  | Emergy from purchased materials  |
| MJ  | MJ  | megajoule   | megajoule  |
| -   | M <sub>N</sub>  | Emergy non-renouvelable issue des matériaux achetés                               | Non-renewable emergy from purchased materials                                      |
| -   | M <sub>R</sub>  | Emergy renouvelable issue des matériaux achetés                                   | Renewable emergy from purchased materials  |
| -   | N   | Emergy non-renouvelable   | Non-renewable emergy   |
| OTEX  | -   | Orientation technique et économique des exploitation                              | -  |
| PC  | -   | Poitou-Charentes  | Poitou-Charentes   |
| -   | PTE   | Efficience technique pure   | Pure Technical Efficiency  |
| -   | R   | Emergy renouvelable   | Renewable emergy   |
| -   | RI  | Ile de la Réunion   | Reunion Island   |
| -   | S   | Emergy issue des services   | Emergy from services   |
| -   | SE  | Energie solaire (Analyse pluri-énergétique)                                       | Solar energy (Pluri-emergy analysis)   |
| -   |   | Efficience d'échelle (DEA)  | Scale efficiency (DEA)   |
| -   | SEE   | Efficience d'utilisation de l'énergie solaire                                     | Solar energy efficiency  |
| -   | sej   | emjoule solaire   | solar emjoule  |
| -   | SEU   | Consommation d'énergie solaire  | Solar energy use   |

## *Liste des abréviations*

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|     |                |  |                                    |
|-----|----------------|--|------------------------------------|
| -   | SM             | Mali Sud                                   | South Mali                         |
| -   | S <sub>N</sub> | Emergy non-renouvelable issue des services | Non-renewable emergy from services |
| SPL | DPS            | Stratégie de production laitière           | Dairy Production Strategy          |
| -   | S <sub>R</sub> | Emergy renouvelable issue des services     | Renewable emergy from services     |
| -   | TE             | Efficiency technique                       | Technical Efficiency               |
| Tr  | Tr             | Transformité                               | Transformity                       |
| -   | UEV            | -  | Unit Emergy Values                 |
| UMO | AWU            | Unité Main-d'Oeuvre                        | Agricultural Workforce Unit        |
| VL  | -              | Vaches laitières                           | -                                  |
| -   | Y              | Emergy totale                              | Total emergy                       |

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**Chapitre I**

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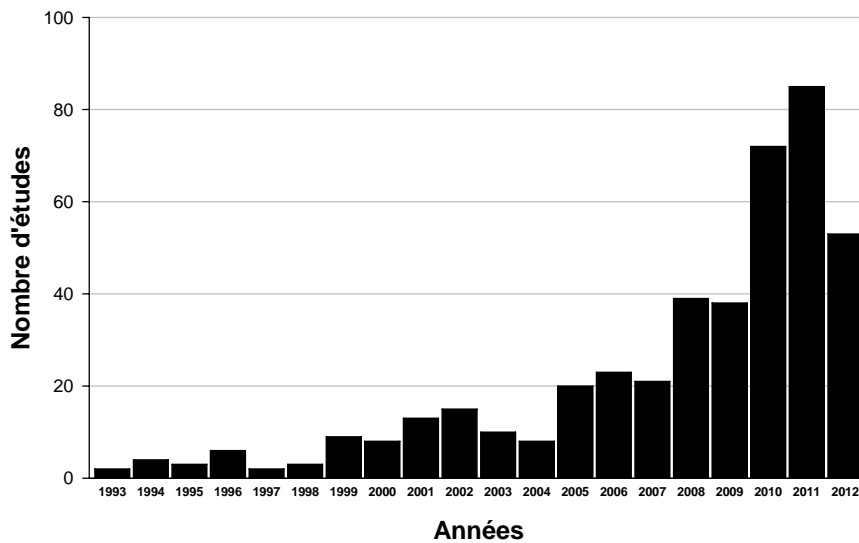
# **INTRODUCTION GENERALE**





Les observations sur le changement climatique de ces 50 dernières années lié aux émissions de gaz à effet de serre (GES) ont fait du réchauffement climatique l'un des débats sociétaux majeurs. La responsabilité des activités humaines et de leur développement est aujourd'hui admise par une très large partie de la communauté scientifique (IPCC, 2007) même si certains réfutent encore l'origine anthropique d'une telle augmentation de la température, argumentant sur un effet naturel d'alternance entre périodes froides et chaudes à l'échelle de l'histoire de la Terre (Rittaud, 2010). Quelle qu'en soit l'origine, il y a lieu de ralentir le processus.

Parmi les activités humaines couramment mises en cause, l'agriculture et plus particulièrement l'élevage tient une part de responsabilité importante dans ces dynamiques notamment depuis la parution d'un rapport en 2006 produit par l'organisation mondiale pour l'alimentation et l'agriculture (FAO, 2006a). Parmi les nombreuses dégradations envers l'environnement, ce rapport accuse notamment le secteur d'élevage dans sa globalité, c'est-à-dire de la production d'aliment nécessaire aux troupeaux à la vente du produit final, d'être responsable de 18% des émissions de GES d'origine anthropique. Le secteur laitier n'échappe pas à cette analyse (FAO, 2010). Il apparaît comme un contributeur important aux émissions de GES d'origine anthropogénique (4%) notamment du fait de l'émission de méthane (CH<sub>4</sub>) provenant des fermentations ruminales. Loin d'être une fatalité, l'atténuation de ces émissions est devenu un objectif majeur du secteur agricole et de la recherche. Les études référencées depuis 1993 dans la base Web of Knowledge (Thomson Reuters, 2012) et traitant des émissions de gaz à effet de serre dans le secteur de l'élevage témoignent de l'intérêt grandissant de la communauté scientifique pour ce sujet.



**Figure 1** Répartition annuelle des 434 études référencées dans la base de données Web of Knowledge comportant les mots « greenhouse gas » et « livestock » comme mots-clés

L'élevage laitier représente une activité majeure de l'économie agricole mondiale. En 2010, la quantité de lait produit dans le monde s'est élevée à environ 723 millions de tonnes dont près de la moitié est issue des pays en développement (FAOSTAT, 2012). Dans ces zones, il assure même un revenu substantiel pour bon nombre d'éleveurs parmi lesquels certains sont issus de populations défavorisées (FAO, 2006b).

L'importance des systèmes laitiers à travers le monde en fait donc un sujet d'étude majeur quant à la réduction des émissions de GES des systèmes d'élevage. La perspective de l'augmentation conjointe de la population mondiale, qui devrait atteindre 9.2 milliards d'êtres humains d'ici 2050 (UN, 2007), et du niveau de vie moyen dans les pays en développement auront pour conséquence un doublement de la demande mondiale en produits laitiers (FAO, 2009a). L'augmentation potentielle des émissions actuelles qu'entraînerait une croissance de l'élevage laitier sans changement dans les modes de production interpelle les sociétés. Au delà des questions de croissance de la production, il devient ainsi nécessaire de concevoir des systèmes laitiers plus durables et qui correspondent au concept d'intensification écologique (Cassman, 1999 ; FAO, 2009b ; Griffon, 2009, Doré et al., 2011, Dugué et al., 2012).

Les systèmes de production laitiers varient considérablement d'une zone géographique à une autre mais parfois même au sein d'une même zone en fonction de facteurs aussi divers que les conditions climatiques, l'accès à des surfaces arables ou encore aux intrants commerciaux. Il existe ainsi un gradient de systèmes allant de petits exploitants associant cultures de subsistance et élevage où les rendements dépassent rarement 100 kg de lait par vache par lactation (Coulibaly et al., 2007) à des systèmes hautement productifs de plusieurs milliers d'animaux (Al-Otaibi and Robinson, 2002). Cette grande diversité nécessite sans doute des voies d'intensification écologique variées. Ainsi, pendant que les petits producteurs laitiers des zones en développement augmenteront leur production tout en limitant la hausse des impacts environnementaux, les systèmes hautement productifs devront maintenir leur niveau de production déjà très élevé tout en diminuant leurs impacts sur l'environnement.

L'énergie fossile tient un rôle particulier dans ces considérations. Par le passé, l'accroissement de la demande alimentaire mondiale a été couvert en grande partie par l'augmentation de la productivité des systèmes agricoles rendue possible par un recours illimité à l'énergie fossile bon marché (Pimentel et al., 1973; Leach, 1976; Fluck and Baird, 1980). Mais l'application d'un tel modèle est aujourd'hui questionnée. D'abord parce que ces consommations ont lieu à toutes les étapes de la chaîne de production (en amont de l'exploitation pour la fabrication et la production des intrants, sur l'exploitation pour faire fonctionner les tracteurs et les machines et en aval pour transformer et transporter les

produits) aboutissant à une forte dépendance du secteur aux ressources énergétiques fossiles. Ceci n'est pas sans conséquence économique, l'accroissement tendanciel et la variabilité du prix du pétrole brut participant à l'envolée des prix des intrants et par conséquent celui des denrées alimentaires (Heinberg and Bomford, 2009). De plus, au-delà de la déplétion des ressources naturelles, l'impact environnemental de la consommation d'énergie fossile est relié à l'émission de dioxyde de carbone (CO<sub>2</sub>) durant sa combustion.

À l'échelle globale du secteur alimentaire, la FAO a estimé que les émissions de CO<sub>2</sub> représentaient plus de 30% des émissions globales (FAO, 2011). Dans les systèmes de production laitiers, la part du CO<sub>2</sub> lié à la combustion d'énergie fossile en amont de l'exploitation pour produire les intrants et sur l'exploitation est variable. Elle peut représenter moins de 10% dans des systèmes très herbagers (Haas et al., 2001 ; Basset-Mens et al., 2005) ou plus de 30% dans des systèmes hors-sol (O'Brien et al., 2012), ce chiffre dépassant même les 50% dans des systèmes insulaires fortement dépendants d'intrants importés (Vigne et al., 2009). La recherche d'une efficacité<sup>1</sup> d'utilisation maximale de la ressource fossile est donc l'un des enjeux majeurs de l'intensification écologique des systèmes laitiers à travers le monde.

Cependant, la mobilisation de l'énergie fossile dans les systèmes agricoles est fortement liée aux autres types d'énergie consommée ce qui fait de l'évaluation de l'efficacité énergétique un sujet complexe. Ses apports ont pour but principal d'améliorer la capacité unique des systèmes végétaux à transformer via la photosynthèse l'énergie solaire en énergie métabolisable pour l'homme et les animaux (Ferrière et al., 1997). Elle permet également de remplacer l'énergie physique dépensée lors des travaux agricoles par les hommes et les animaux qui constituent encore la majeure source d'énergie mécanique dans les systèmes manuels des pays en développement et d'améliorer *in fine* la productivité du travail.

Nous faisons ici l'hypothèse que la prise en compte de l'ensemble des consommations et productions énergétiques au sein d'un système laitier à travers un mode de représentation générique doit :

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<sup>1</sup> L'efficacité est une notion souvent reprise dans ce manuscrit. L'efficacité et l'efficacités sont des notions assez proches dans le langage français, l'un des termes étant souvent utilisé en lieu et place de l'autre. À l'inverse, ces deux notions sont assez bien différenciées dans le langage anglophone. L'efficacité (efficacy) se définit comme le ratio entre l'objectif fixé et les résultats obtenus sans prise en compte des moyens mis en œuvre pour atteindre ces résultats. Elle tend donc à maximiser un seul objectif de performance productive. L'efficacité (efficiency) en appelle quant à elle à la notion d'optimisation de différentes ressources (naturelles, humaines, matérielles, financières, ...) mises en œuvre pour parvenir à la réalisation de biens et services.

- permettre de mieux comprendre les modes de gestion de l'énergie, notamment de l'énergie fossile,
- d'analyser finement le fonctionnement des systèmes laitiers dans leur grande diversité au niveau mondial,
- de repérer les postes les moins efficaces,
- et finalement d'en comprendre les déterminants de l'efficacité globale d'utilisation de l'énergie.

**L'objectif de ce travail de thèse est donc d'analyser l'intérêt d'une approche pluri-énergétique à travers des méthodes existantes ou originales afin d'analyser le fonctionnement de systèmes laitiers contrastés et de fournir des voies d'amélioration de l'efficacité d'utilisation des ressources.**

Cet objectif général a été divisé en cinq questions scientifiques :

- 1/ Les méthodes d'évaluation environnementales existantes dans la littérature permettent-elles d'analyser les différents flux d'énergie dans des systèmes d'élevage laitiers aussi contrastés que ceux présents à travers le monde ?
- 2/ Dans le cas contraire, quelles améliorations sont à apporter pour accroître leur capacité à fournir des analyses énergétiques pertinentes et précises de la diversité de ces systèmes d'élevage ?
- 3/ Quelle est la sensibilité des résultats des méthodes d'évaluation à l'incertitude sur les facteurs de conversion dans le cadre d'une analyse de la diversité de ces systèmes d'élevage ?
- 4/ Quelles sont les performances énergétiques de ces systèmes d'élevage ?
- 5/ L'analyse de la variabilité des performances obtenue à partir des méthodes mises en place au sein des systèmes issues d'un même territoire permet-elle de fournir des voies d'amélioration de leur efficacité notamment dans un objectif d'intensification écologique ?

La constitution du présent manuscrit en 8 chapitres résulte principalement de la démarche scientifique mise en place pour répondre à ces questions. A la suite de cette introduction générale (**Chapitre 1**), une synthèse bibliographique (**Chapitre 2**) a été réalisée afin de cerner les différentes méthodes environnementales prenant ou pouvant prendre en compte les différents flux d'énergie. Le **Chapitre 3** présente les différentes méthodes retenues ainsi que les différents territoires et systèmes laitiers étudiés. Le **Chapitre 4** est une analyse

préliminaire à l'application des méthodes retenues. L'impact de l'incertitude des facteurs de conversion dans la pertinence des résultats obtenus, notamment dans le cadre d'analyses sur différents territoires, est évalué à travers les coefficients énergétiques de l'analyse énergétique fossile. Les deux chapitres suivants constituent la partie Résultats du manuscrit. La première partie (**Chapitre 5**) traite de la comparaison des résultats moyens obtenus sur chacun des 4 territoires d'étude à partir des deux méthodes d'évaluation. La seconde partie (**Chapitre 6**) traite de l'analyse de la variabilité obtenue dans les territoires. Cette variabilité est analysée selon deux approches : une analyse des indicateurs obtenus de l'analyse pluri-énergétique au Mali Sud menée sous le prisme des différents types de systèmes existants et une analyse des consommations d'énergie fossile sur les territoires du Poitou-Charentes et de la Bretagne menée grâce à la méthode Data Envelopment Analysis. Le **Chapitre 7** constitue la discussion générale de la thèse et aborde la méthodologie et les forces et faiblesses des deux méthodes utilisées avec une attention spéciale pour l'analyse pluri-énergétique du fait de son originalité scientifique. Une seconde partie de la discussion traite plus spécifiquement de la gestion des différentes ressources énergétiques selon les types de système étudiés. Enfin, le **Chapitre 8** présente les conclusions du travail et les perspectives qui peuvent en être tirées.

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**Chapitre II**

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**SYNTHESE BIBLIOGRAPHIQUE**

**Ce chapitre consiste à faire le point sur les trois méthodes d'évaluation environnementale actuellement disponibles dans la littérature pour décrire de façon partielle ou complète les flux d'énergie au sein des systèmes laitiers: l'Analyse énergétique fossile, l'Empreinte Ecologique et la méthode Emergy.**

**Il démontre que l'Empreinte Ecologique ne semble pas réellement adaptée pour analyser les différents flux d'énergie dans des systèmes laitiers présents à travers le monde. La méthode Emergy semble plus convenir dans son état actuel. L'Analyse énergétique fossile pourraient adaptée mais nécessite quelques adaptations dont (i) la prise en compte de l'ensemble des autres flux énergétiques à travers la comptabilisation des travaux humains et animaux, de la radiation solaire reçue sur les surfaces et de l'énergie calorifique contenue dans la biomasse et ii) la mesure de l'ensemble de ces flux en entrée du système, à l'intérieur du système et en sortie du système.**

**Evaluating the ability of current energy use assessment methods to study contrasting livestock production systems<sup>2</sup>**

**Capacité des méthodes d'évaluation environnementales actuelles à prendre en compte les consommations d'énergie dans des systèmes d'élevages contrastés**

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Review - *Journal of Environmental Management* 112 (2012) 199-212

**Résumé**

L'impact environnemental de l'agriculture est devenue un sujet d'attention particulière depuis des dizaines d'années ayant pour résultat le développement de nombreuses méthodes. Parmi celles-ci, trois traitent spécifiquement ou en partie de l'énergie : l'Analyse énergétique (EA), l'Empreinte Ecologique (EF) et la méthode Emergy (Em). Basé sur une revue de 197 références traitant de l'application des ces trois méthodes sur différents systèmes agricoles, cet article discute leur capacité à évaluer les consommations d'énergie. Si l'EF évalue les consommations d'énergie fossile à travers une approche global de la mesure de l'utilisation de surfaces, l'EA et l'Em se concentrent sur l'énergie et apparaissent plus appropriée pour mettre en lumière les voies d'amélioration de l'efficacité énergétique. Cependant, si l'EA présente une méthodologie claire de mesure des consommations d'énergie fossile et des impacts associés, elle ne considère pas toutes les sources d'énergie. Avec la prise en compte des ressources renouvelables et naturelles, l'Em prend en compte les autres sources d'énergie telles que le rayonnement solaire ou l'énergie du travail. Cependant, les indicateurs proposés ne représentent pas clairement le lien entre activités agricoles et impact environnemental.

Des améliorations des méthodes EA et Em pourraient toutefois augmenter leur capacité à fournir des analyses énergétiques pertinentes et précises de la diversité des systèmes d'élevage rencontrés dans le monde. Cela consisterait pour l'EA à la prise en compte de toutes les sources d'énergie, comme le fait l'Em, via le rayonnement solaire reçue par les surfaces et l'énergie dépensée par les humains et les animaux pour réaliser les travaux. De plus, une redéfinition des limites du système étudié dans l'EA et l'Em devrait inclure les animaux de labour, les humains et les parcours naturels pâturés. Enfin une attention particulière devrait être portée sur le calcul de facteurs de conversion (coefficients énergétiques et Unit Emergy Values) réactualisés et adaptés aux conditions locales.

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<sup>2</sup> Cette partie est présentée sous forme d'un article scientifique accepté dans *Journal of Environmental Management* auquel a été ajouté un résumé en français



## Review

## Evaluating the ability of current energy use assessment methods to study contrasting livestock production systems

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## ARTICLE INFO

## Article history:

Received 10 April 2012

Received in revised form

13 July 2012

Accepted 21 July 2012

Available online

## Keywords:

Energy analysis

Energy synthesis

Ecological footprint

Environmental assessment

Livestock systems

## ABSTRACT

Environmental impact assessment of agriculture has received increased attention over recent decades, leading to development of numerous methods. Among them, three deal with energy use: Energy Analysis (EA), Ecological Footprint (EF) and Emergy synthesis (Em). Based on a review of 197 references applying them to a variety of agricultural systems, this paper evaluates their ability to assess energy use. While EF assesses energy use as land use via a global accounting approach in which energy is only one component of the assessment, EA and Em are energy-focused and appear more appropriate to highlight ways to increase energy-use efficiency. EA presents a clear methodology via fossil energy use and its associated impacts but does not consider all energy sources. With inclusion of natural and renewable resources, Em focuses on other energy resources, such as solar radiation and energy from labour, but does not present impact indicators nor establish a clear link between activities and their environmental impacts. Improvements of the EA and Em methods could increase their ability to perform realistic and unbiased energy analysis or the diversity of livestock systems encountered in the world. First, to consider all energy sources, as Em does, EA could include solar radiation received by farm surfaces and energy expenditure by humans and animals to accomplish farm operations. Second, boundaries of the studied system in EA and Em must include draft animals, humans and communal grazing lands. Third, special attention should be given to update and locally adapt energy coefficients and transformities.

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## 1. Introduction

Climate change and pollution have led to global concern about environmental impacts of human activities. Agriculture, particularly livestock farming, is primary among these societal challenges. Since human population will potentially increase to 9.2 billion by 2050 (United Nations, 2007), global demand for animal products will increase over the next few decades (FAO, 2009). Demand for meat and milk is expected to double between 2000 and 2050 (Steinfeld et al., 2006). Livestock production should be increased while substantially decreasing its environmental impacts. Whereas in OECD and North American countries agricultural yields are already high, and land available for agriculture is limited (Paillard et al., 2010), future challenges particularly concern developing countries, where emergence of middle classes will accentuate the demand for livestock products.

The link between environment and energy is often represented by fossil energy use, which contributes to natural-resource depletion and carbon dioxide emissions (a greenhouse gas (GHG)). However, fossil energy is only a portion of energy resources in agricultural systems. Large subsidies of fossil energy have been introduced into agricultural systems through intensification in developed countries to substitute energy from human and animal labour (Fluck and Baird, 1980; Leach, 1976; Pimentel et al., 1973). In this case, intensive agriculture aims to maximise the unique ability of agriculture to feed people and domestic animals from solar energy via photosynthesis (Ferrière et al., 1997). Although similar dynamics are observed in developing countries (Alam et al., 2005; Ozkan et al., 2004; Tabar et al., 2010), most smallholder agricultural systems are still based on energy from human and animal labour, the main mechanical energy sources.

Three methods of environmental assessment in the literature focus partly or exclusively on energy use in agricultural systems. Energy analysis (EA), one of the earliest methods (Pimentel et al., 1973), estimates the direct and indirect fossil energy used to produce a specific good or service (IFIAS, 1974). EA has been applied mainly in single criterion assessment or in multicriteria

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assessment, such life cycle analysis, to offer a simple inventory of energy use for a specific agricultural system or product (Franzluebbers and Francis, 1995), to study impacts of management changes on energy use (Cleveland, 1995) or to compare production systems such as organic vs. conventional (Grönroos et al., 2006) or manual vs. mechanised (Gajaseeni, 1995). Ecological footprint (EF) estimates land requirements in terms of the area necessary to sustain a specific national, regional or urban population (Wackernagel and Rees, 1996). The number of studies concerning industrial sectors or production processes that include agriculture has increased. EF is currently used to estimate the area necessary to produce goods and services, to assess the environmental efficiency of agricultural systems at the farm scale (Liu et al., 2008) or agricultural sector at a regional scale (Kissinger and Rees, 2009) and to compare different production approaches, such as conventional and organic systems (Niccolucci et al., 2008). Measuring only fossil energy use has been criticised (Nilsson, 1997), which led to the concept of Emergy synthesis (Em) (Odum, 1984). Em is defined as a measure of the available energy used and degraded in a process and during previous transformations to generate resources, services and products. For convenience and to follow thermodynamic laws, available energies are expressed in units of solar energy, considered as the initial energy needed for global operation of the geobiosphere. Em has received recent interest for evaluating agricultural systems and has been used to evaluate the emergy balance of a specific agricultural system (Bastianoni et al., 2001) or a country's agricultural sector (Chen et al., 2006) and to compare contrasting agricultural systems (Lefroy and Rydberg, 2003).

In focussing only on depletion of abiotic resources and a part of global warming (EA), land use (EF) or depletion of full biotic and abiotic resources (Em), the three methods are far from complete environmental assessments (Brentrup et al., 2004). However, the wide diversity of energy sources and their environmental effects that they assess are interesting and raise the question of which methods to use to assess livestock production systems. Small-holder farming systems in developing countries and intensive systems in OECD countries could be perceived as too different to be compared. Therefore, comparing agricultural systems with generic and well-adapted methods that focus on energy resources

use would, among other factors, represent a real advance. The objectives of this paper are to provide an overview of these three methods (EA, EF, Em) used to estimate the energy use of agricultural systems from a global assessment perspective and to discuss their ability to encompass the diversity of livestock production systems encountered in the world. Based on the strengths and weakness of the methods, an agenda research is proposed in order to develop and implement an energy-based method to assess the environmental impacts of livestock production systems around the world.

## 2. Overview of the methods

### 2.1. Use of energy analysis in agricultural systems

Interest in energy use in agricultural systems began just after the first oil crisis in the 1970s. An extensive review of the literature identified 197 references dealing with energy use in one or several types of agricultural systems from an environmental perspective, beginning with Pimentel et al. (1973) and increasing in number over time (Fig. 1).

In these 197 references, 304 assessments of energy use in field- or farm-scale case studies were published. Approximately 42% of the case studies concerned European systems, of which 92% were based on EA (Fig. 2).

There were significantly fewer case studies in North and South America, perhaps because decreasing fossil energy use was not considered a priority until recently. In other regions of the world, studies were most often performed in particular countries. For example, Turkey represented 26 out of 36 studies from the Middle East, India represented 26 out of 35 studies from South Asia and North Asia was represented only by China. As in Europe and the Americas, most studies in other regions were based on EA, with the noticeable exception of China and Brazil, where Em was the main method used. With only 9 studies, Africa has been relatively forsaken, especially as two studies among the nine were performed on Reunion Island, which has intensive production similar to that in Europe (Vayssières et al., 2011; Vigne et al., 2009). Of European case studies, 78 considered crop production and 50 considered livestock

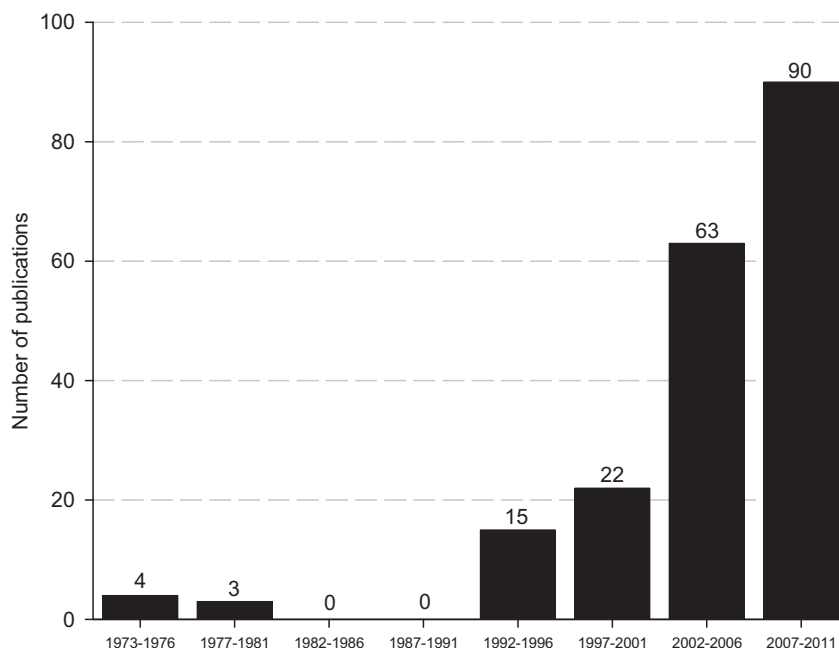


Fig. 1. Number of publications in the international literature dealing with energy use assessment in agricultural systems since 1973.

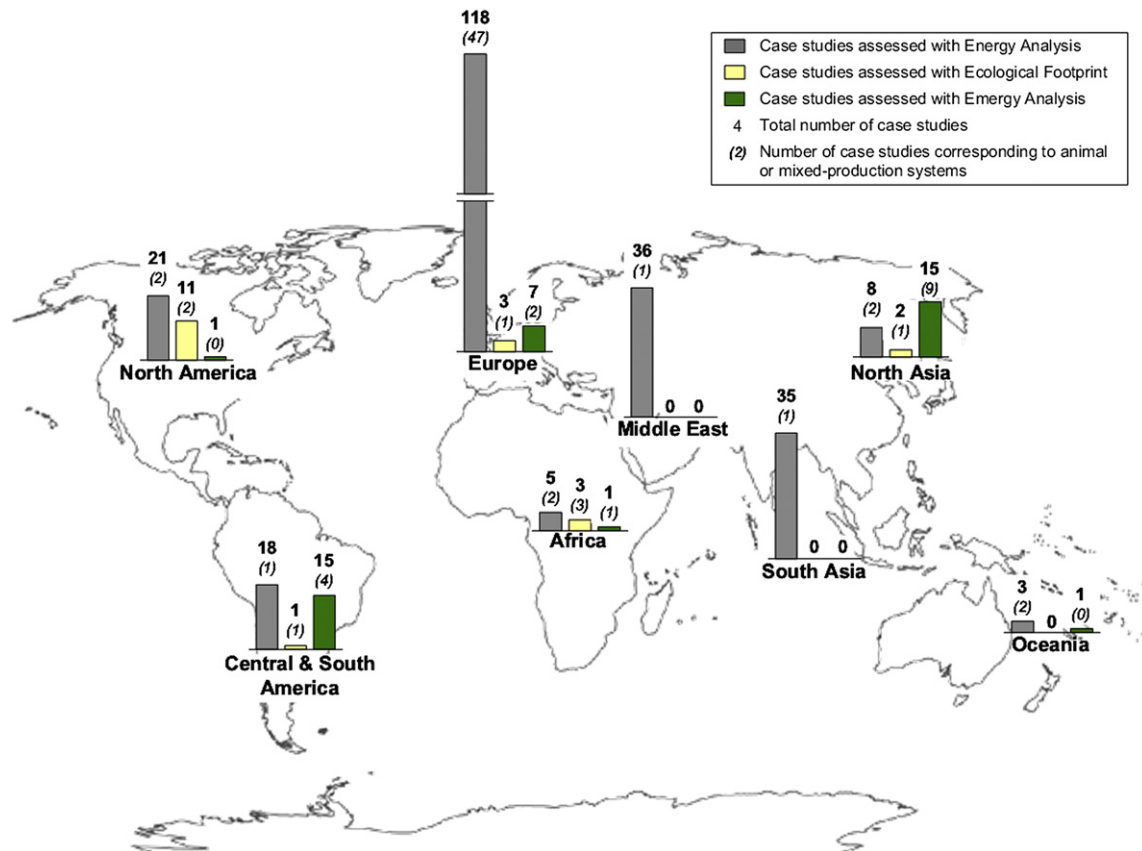


Fig. 2. Geographical distribution for the 304 case studies application of Energy Analysis (EA), Ecological Footprint (EF) and Energy Analysis (Em).

and/or mixed farming systems. From developing countries, only 26 out of 131 case studies dealt with livestock and/or mixed crop-livestock systems, thus revealing a relative lack of research of these systems.

Before focussing on environmental impacts, research on livestock or mixed systems in developing countries was mainly focused on increasing herd or farm productivity (Sumberg, 2002). Moreover, many of these systems were aquacultural (Berg et al., 1996; Li et al., 2011; Mungkung et al., 2006) or almost intensive (Agostinho et al., 2008; Koknaroglu, 2010), in which system boundaries were always well-defined and corresponded to common OECD farming systems. But with extensive livestock systems, especially ruminant systems based on off-farm resources (e.g., external pasture area or crop residuals from other farms), definition of system boundaries becomes more difficult. Finally, in contrast to intensive systems where feeds are well-identified, use of uncommon feeds and forages by extensive systems needs additional investigation.

## 2.2. Categories of energy considered and their role in the methods

The three methods differ in their conception, the sources of energy included and thus in their ability to represent energy consumption and associated environmental impacts for livestock production systems. EA is focused on fossil energy use and generally considers both direct and indirect consumption of energy. Direct consumption includes the use of non-renewable resources (e.g., oil, natural gas) and electricity. Indirect consumption considers the energy required to produce mineral fertilisers and purchased feeds. Other sources of indirect consumption are not usually considered. These include plastics (Veysset et al., 2010), pesticides (Hanegraaf et al., 1998), veterinary services (Rabier et al.,

2010) and buildings or machinery (Schils et al., 2007). EA studies regularly show that livestock systems barely reach 1 MJ (megajoule) of food energy produced per MJ of non-renewable energy consumed (Benoit and Laignel, 2010; Veysset et al., 2010). Plant production is usually estimated to be more efficient: fruits and vegetables commonly range from 1 (Kizilaslan, 2009) to 5 MJ·MJ<sup>-1</sup> (Ozkan et al., 2007), and cropping systems can reach 15 MJ·MJ<sup>-1</sup> (Deike et al., 2008; Nguyen and Haynes, 1995). By focussing on fossil energy use, EA enables a link between energy consumption and associated environmental impacts mainly through natural-resource depletion and partly through GHG emissions, the CO<sub>2</sub> resulting from extraction and consumption of fossil energy, representing fewer GHG emissions from livestock systems than N<sub>2</sub>O and CH<sub>4</sub> (Bos et al., 2007; Veysset et al., 2010). It is an effective method for detecting large energy fluxes and for proposing actions to decrease them; however, it only calculates fossil energy flux and thus precludes the calculation of a global environmental impact.

In contrast to EA, energy consumption in EF is only part of the assessment. The main indicator is the biologically productive area resulting from the sum of four components (Wackernagel and Rees, 1996): (i) direct surface area, corresponding to buildings, crops, pasture, and managed forest directly involved in the production process; (ii) non-used surface area, corresponding to unmanaged forests and non-productive areas; (iii) indirect surface area, corresponding to the area required to produce all purchased inputs; and (iv) surface area corresponding to fossil energy use. EF is an efficient method for providing a clear, comprehensive and pedagogic message (Moffatt, 2000) because it visualises, in terms of land area, the global resources required to sustain human activity, highlighting unsustainable behaviour. Using this method, the World Wildlife Fund (2010) estimated that humans currently use the

equivalent of 1.5 Earths to support their activities, thus compromising humanity's future well-being. Applying EF to agricultural systems, van der Werf et al. (2007) demonstrated that a conventional French pig farm can indirectly use 4.6 times its own surface area. However, unlike EA, EF does not clearly highlight ways to increase energy efficiency, and its representation of energy use as land use has been discussed (McDonald and Patterson, 2004).

The Em method focuses on total energy use, estimating ecosystem contributions to a human process such as agricultural production. It calculates energy fluxes into natural resources such as solar, rain or wind energy as the amount of initial solar energy needed to produce these natural resources. Em also considers energy in fossil energy, industrial inputs and services. This enables comparison of a system's dependency on economic vs. natural resources. In addition, the renewable-energy portion of each input is defined to assess the proportion of renewable inputs in the total energy flux of the system. Applications on agricultural systems have globally shown a large dependence on non-renewable and purchased (economic) inputs in both conventional and organic systems (La Rosa et al., 2008; Castellini et al., 2006; Cavalett et al., 2006; de Barros et al., 2009; Pizzigallo et al., 2008). Because solar energy is considered an unlimited and renewable resource, its use

does not have negative impact on the environment. In this sense, the method is not able to quantify links between renewable energy use and environmental impacts.

2.3. Approaches for calculating energy use

The general architecture for energy accounting does not differ between the three methods, but the calculation procedures show several differences (Fig. 3). Inputs of the system initially quantified in time, physical or monetary units are transformed via conversion factors into total fossil energy use for EA, land use for EF and solar energy use for Em.

EA and Em use a one-step conversion procedure. Equivalence factors in EA are called "energy coefficients", expressing in MJ per unit of input the amount of fossil energy consumed to produce and transport the input. In Em, conversion factors are named "transformities", expressing in solar emjoules (sej) per unit of input the amount of solar energy needed to produce the inputs. Energy flows from natural origins (renewable or not) and the economy are then calculated. This additional step is due to the ability of Em to encompass inputs other than purchased inputs, such as renewable and non-renewable flows from nature and labour and services.

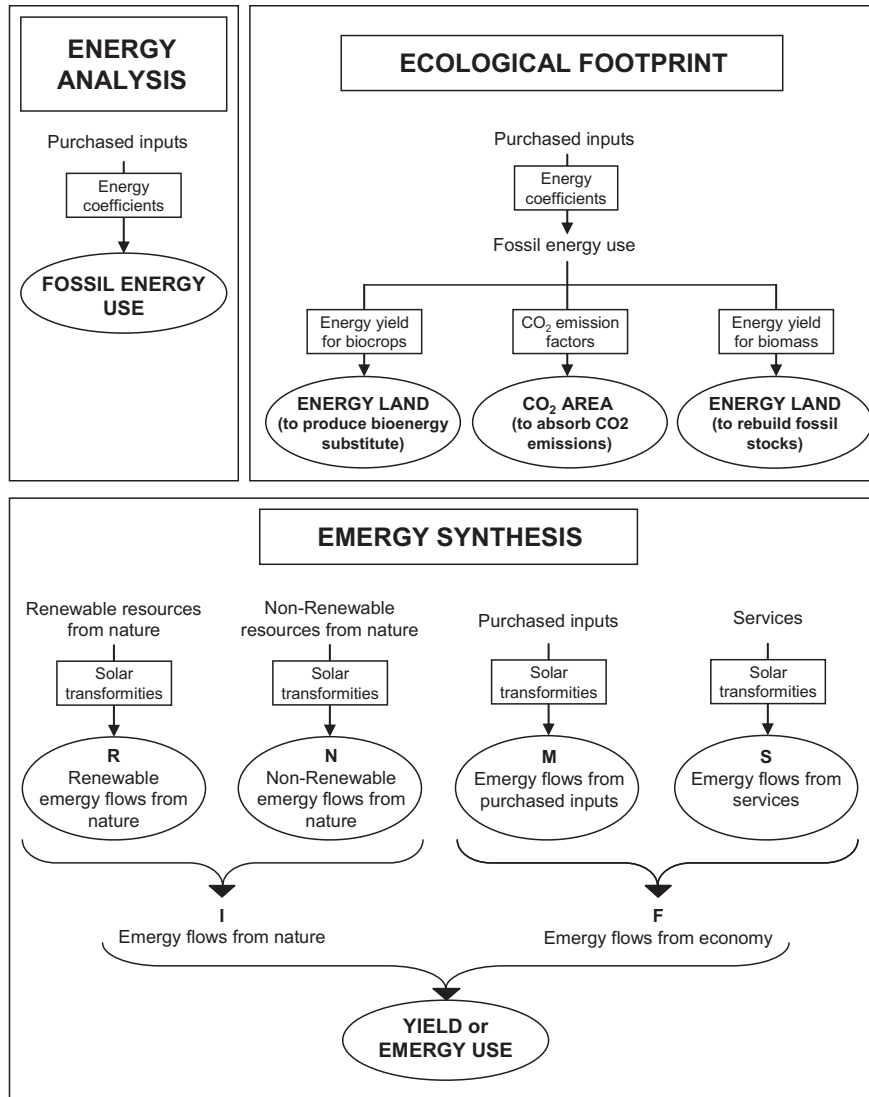


Fig. 3. Comparison of energy use calculation in the three methods.



EF uses a two-step conversion procedure. First, all inputs are converted into fossil energy consumption using coefficients. Second, energy consumption is converted into land use according to one of the three following approaches: (i) the area required to produce an amount of renewable energy equivalent to the amount of non-renewable energy consumed, (ii) the area required to absorb CO<sub>2</sub> emissions resulting from consumption of this non-renewable energy or (iii) the area required to rebuild the quantity of fossil energy consumed (Fig. 3). The calculation of “energy land” by the first approach is based on an estimate of biomass ethanol production of 80 GJ·ha<sup>-1</sup>·yr<sup>-1</sup>. The second approach assumes that CO<sub>2</sub> emissions can be sequestered at a rate of 1.8 t C·ha<sup>-1</sup>·yr<sup>-1</sup>, an average value for temperate, boreal and tropical forests, equivalent to the consumption of 100 GJ of fossil fuel. For the third approach, “energy land” is based on estimates that an average forest can accumulate about 80 GJ·ha<sup>-1</sup>·yr<sup>-1</sup> of recoverable biomass energy per year in standing timber. Thus, each method produces nearly the same result, around 1 ha of ecologically productive land for 80–100 GJ of fossil energy consumed (Wackernagel and Rees, 1996). Factors to use could be subject to debate, which tends to decrease interest in EF. Although the CO<sub>2</sub>-emission factor is based on an average forest sequestration of 1.8 t C·ha<sup>-1</sup>·yr<sup>-1</sup>, the lower and currently accepted sequestration rate of permanent grassland, 0.5 t C·ha<sup>-1</sup>·yr<sup>-1</sup> (Arrouays et al., 2002) could lead to a revision of this factor. Also, land-use equivalence factors based on bioenergy crop yields consider the most optimistic estimate for ethanol production; however, some studies have shown a range from 58.4 GJ·ha<sup>-1</sup> for alfalfa (Gelfand et al., 2010) to 167 GJ·ha<sup>-1</sup> for poplars (Scholz et al., 1998).

#### 2.4. Indicators used to estimate energetic performance of livestock systems

Energy consumption quantified as fossil energy use (EA), energy land (EF) or solar energy (Em) is most often expressed per unit of structural factor or per unit of product, which raises difficulties for data interpretation.

Units of structural factors, such as area or livestock units, are useful for illustrating intensification within a system, but they are questionable when the objective is to compare systems of varying intensification (e.g., indoor industrial monogastric production vs. extensive pastoral ruminant production). Since these factors are not functions of system productivity, and consequently efficiency in energy use, using them to express energy use can lead to opposite results from the same dataset. van der Werf et al. (2007) illustrated this when comparing intensive and organic pig production systems. When expressed per ha of land, intensive farms consumed more energy than organic farms, whereas when expressed per kg of pig produced the reverse was observed.

Calculating energy use only per physical unit of product avoids this difficulty, assuming that the more efficiently a system transforms energy into products, the lower its environmental impacts due to resource use. Undoubtedly, considering only a single product can be useful for evaluating specialised intensive systems, but doing so raises difficulties when the objective is to evaluate non-specialised or mixed farming systems. When doing so, one must allocate energy consumption between different products and associated co-products. Researchers (Høgaas Eide, 2002; Hospido et al., 2003) have proposed a variety of allocation rules, but the results widely vary according to the rules. For example, Cederberg and Stadig (2003) compared four allocation methods between cattle milk and meat: no allocation, economic allocation, biological allocation based on protein and energy production and finally system expansion, which consists of removing a quantity of environmental impacts equal to those generated by an alternative

method of producing a co-product. According to these four allocation rules, the percentage of energy use allocated to milk ranged from 85 to 100%, leading to an energy-use value from 2.55 to 3.00 MJ per kg of ECM milk<sup>-1</sup>. The range was even larger when considering acidification and eutrophication impacts (60–100% to milk).

To calculate energy use per unit while avoiding allocation, two alternative ways have been chosen. First, product outputs can be added according to their gross-energy contents, leading to the ratios “energy efficiency” (EE, Eq. (1)) for EA and “transformity” (T, Eq. (2)) for Em.

$$EE(\text{dimensionless}) = \frac{\text{Gross energy produced (MJ)}}{\text{Fossil energy use (MJ)}} \quad (1)$$

$$T(\text{seJ} \cdot \text{J}^{-1}) = \frac{\text{Total solar energy input (seJ)}}{\text{energy produced (J)}} \quad (2)$$

These energy ratios can combine animal and plant products to allow evaluation of mixed crop-livestock systems (Vayssières et al., 2010), but the choice of energy as the unit of output is debatable. Agricultural products supply not only calories but also proteins, vitamins and minerals.

Another way to avoid allocation is to add product outputs according to their economic values. But the choice of an economic indicator based on products sold depends strongly on economic values of a product, which can vary among territories and even among periods within the same country, for example due to religious celebration (Toure et al., 2005).

More globally, expressing energy use per unit of products reduces agricultural systems to only the amount of food produced. This challenges the ability of the indicators to express the environmental sustainability and multiple objectives of agriculture. For example, they are not well suited for smallholder systems in developing countries, where other agricultural products, such as dung for fertilisation, are crucial for overall sustainability (Giller et al., 2002). This also concerns the social role of livestock systems, for example, the role of livestock systems to maintain cultural landscapes (Quetier et al., 2005), which is not considered.

Em proposes two other indicators which focus only on resource use (Brown and Ulgiati, 1997). Environmental Loading Ratio (ELR) is the total non-renewable and purchased energy used per unit of local renewable energy (Eq. (3)), which estimates how much pressure is placed on the local environment.

$$ELR(\text{dimensionless}) = \frac{\text{non-renewable inputs (seJ)}}{\text{renewable inputs (seJ)}} \quad (3)$$

Brown and Ulgiati (2004) considered that an ELR below 2 indicates low environmental impact. Some mixed systems (Agostinho et al., 2008; Rótolo et al., 2007; Xi and Qin, 2009) even have ELRs below 1, which indicates that they use more renewable resources than non-renewable. A value from 2 to 10 indicates that the system causes moderate impact, whereas a value exceeding 10 indicates high environmental impact. Banana production systems in Guadeloupe, for example, can reach an ELR of approximately 22 (de Barros et al., 2009).

Emergy Yield Ratio (EYR) is the total emergy input divided by the purchased emergy inputs (Eq. (4)), which estimates the dependence on purchased inputs.

$$EYR(\text{dimensionless}) = \frac{\text{total emergy inputs (seJ)}}{\text{purchased inputs (seJ)}} \quad (4)$$

Intensive production systems have an EYR value close to 1 (Castellini et al., 2006; de Barros et al., 2009; Martin et al., 2006),

whereas that of extensive systems can reach 10 (Agostinho et al., 2008; Rótoló et al., 2007).

Systems with a low ELR and/or a high EYR are usually considered environmentally sustainable; however, the ability of these

is to calculate a mechanisation rate (MR, Eq. (6)).

$$\text{MR}(\text{dimensionless}) = \frac{\text{Direct Fossil Energy} + \text{Indirect Fossil Energy for equipment (J)}}{\text{Energy expenditure for labour (J)}} \quad (6)$$

quantitative indicators to express environmental impact is debatable, especially ELR, which does not clearly express the amount of non-renewable resources used. Therefore, even if a system uses a large amount of non-renewable resources, it will remain sustainable if it receives an even larger amount of renewable resources.

### 3. Strengths and limits of the methods for application to livestock production systems

Agricultural systems from developing countries are probably more complex than those in OECD countries due to the larger number of interactions within them, such as animal labour or auto-consumption and the greater importance of physical energy from humans or draft animals. Preliminary overview of the three methods has highlighted different capacities to assess the energy use of contrasting livestock systems and energy efficiency resulting. Because EF assesses energy use as land use with a global accounting approach, Em and EA appear more appropriate. But improvements in Em and EA's methodologies and application could improve their robustness.

#### 3.1. Complementing fossil energy accounting with solar energy and energy from labour

Em encompasses all energy resources, including solar radiation and labour (Bastianoni et al., 2001; Cavalett and Ortega, 2009; Lu et al., 2009). Several studies have included energy from labour when expanding the EA method in developing countries (Gajaseni, 1995; Kaltsas et al., 2007; Mrini et al., 2001). However, when labour is included, it is commonly quantified as the calorific expenditure of humans and animals and is added to direct and indirect fossil energy use. This moves away from the initial aim of EA to quantify non-renewable resource use and convert it into fossil energy (Jones, 1989). In this sense, inclusion of labour in EA should be based on the fossil energy needed to feed and house humans and animals and even to clothe humans. Moreover, labour quantified as calorific expenditure represents no more than 13% of total energy use in smallholder systems (Esengun et al., 2007), which obscures the major role of human (Mobtaker et al., 2010) and animal labour (Williams, 1997) in those systems. Maintaining them independently appears more appropriate, first to calculate standard indicators such as fossil energy use or energy expenditure or to calculate innovative indicators such as Feed Energy Efficiency of Labour (FEEL, Eq. (5)) for energy from labour.

This enables comparison, for both environmental and yield aspects, the total energy from manual labour (both internal and external and human and animal) and direct fossil energy to perform farm operations.

Omitting solar energy in EA corresponds to the global approach of the method because it considers that natural resources are not generated from non-renewable energy. Moreover, when solar energy is based on the solar radiation received by farm surfaces, it could exceed the input of fossil energy by three orders of magnitude (Rathke and Diepenbrock, 2006), thus concealing differences in fossil energy use. Combining solar and fossil energy would enable quantification of the contribution of direct and indirect fossil energy on efficiency of solar capture by crops (Curt et al., 1998) assessed through the Solar Energy Productivity (SEP, Eq. (7)).

$$\text{SEP}(\text{dimensionless}) = \frac{\text{Gross Energy produced (J)}}{\text{Solar Radiation (J)}} \quad (7)$$

However, including renewable resources and labour requires a lot of data. The robustness of such methods when data are lacking must be assessed.

#### 3.2. Redefining the boundaries of studied systems

Definition of system boundaries is a central issue when assessing an agricultural system (Dixon et al., 2001), especially for mixed crop-livestock systems in smallholder farming. Em and EA are based on an input–output accounting approach. The choice of components included or excluded from the system will generate large consequences in terms of energy input accounting. Because the methods were initially developed for intensive farms and focused on productive components, EA and Em consider only crops and productive animals inside mixed crop-livestock systems (Fig. 4a). They thus exclude draft animal and human labour, which are key components of smallholder systems in developing countries, where the family strongly interacts with other system components (Netting, 1993).

Given a lack of mechanisation in developing countries, the family is a major source of labour (sometimes the only source). Animal and crop production first aims to reach food self-sufficiency, which represents the majority of auto-consumption in the system. Although draft animals are an insignificant component of livestock systems in OECD countries, they must be considered an integral part of systems in developing countries. They provide labour and manure and contribute to increased yields and labour productivity (Savado et al., 1998) despite providing no animal products.

$$\text{FEEL}(\text{dimensionless}) = \frac{\text{Gross Energy produced for human feed (J)}}{\text{Energy expenditure for labour (J)}} \quad (5)$$

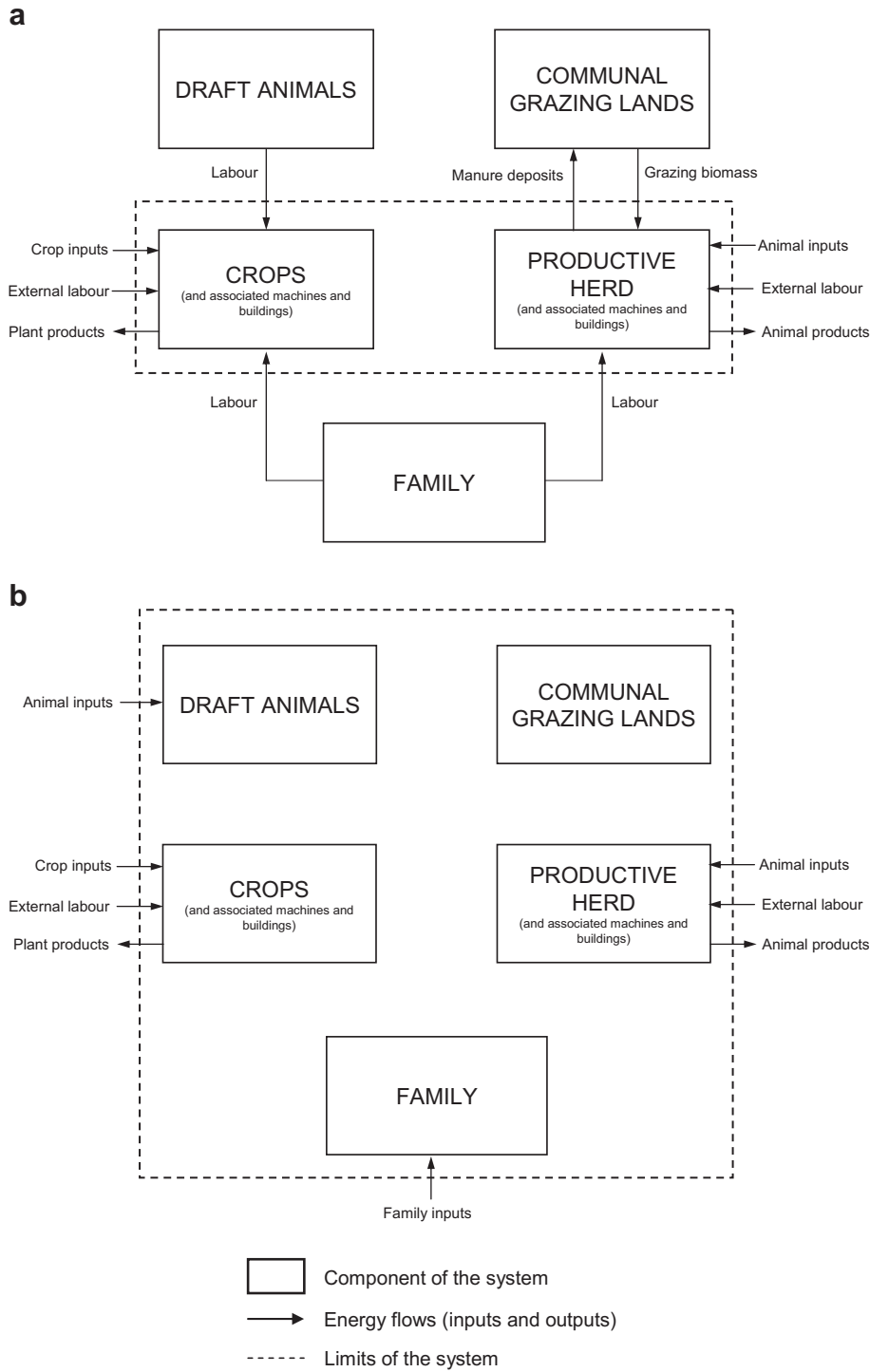


Fig. 4. Boundaries of the studied system including only productive components (a) or including all the components of the agricultural system (b).

Moreover, draft animals have positive environmental impacts, such as increasing soil organic matter and decreasing dependence on external inputs (Schiere et al., 2002).

But when scale of the studied system includes all components of the agricultural system, an input–output accounting approach does not consider energy from on-farm human and animal labour because they are internal flows (Fig. 4b), which questions the interest in including labour. Moreover, farm auto-consumption

(e.g., feeds, food, dung as fertiliser) is excluded, which decreases the perceived energy efficiency of smallholder farming systems.

Two approaches are possible for proposing system boundaries that closely represent agricultural systems and for producing a complete assessment of energy resources used and produced by the systems. First, one could transcend an output–input accounting approach by calculating input of fossil energy and solar energy at the farm scale and labour and products at the scale of productive

components (animals and crops). Alternately, one could focus on productive components and allocate fossil inputs based on their gross energy (Rótolo et al., 2007). However, the allocation problem previously outlined remains, which decreases its interest as an overall assessment of innovative systems.

External pasture area, mainly communal grazing lands, is an important feed resource for livestock in many systems in developing countries (Herrero et al., 2010), and it is reasonable to assume that it should be included as a component of studied systems. Including communal grazing lands will influence energy use estimates in two ways. First, since these lands do not have inputs of fossil energy or labour, energy and energy use indicators will decrease when expressed per hectare. Second, biomass consumption from these lands is associated with manure deposition. Because these deposits will be considered internal flows in these lands, energy efficiency and transformity indicators will tend to increase. For OECD livestock systems, no system based on transhumance has been studied. A calculation based on average biomass intake by animals and average yield of these areas could offer an acceptable estimate of their contribution to a given system.

### 3.3. Developing context-specific conversion factors

Equivalence factors, which allow the conversion of inputs into energy equivalents, are the core of the methods and should be adapted to local conditions to include differences in origins, transport and processing of inputs. Precise and locally adapted values are required for producing unbiased estimates, but until now, coefficients from fewer than 10 references from North American and European contexts were widely used in all contexts (Bhat et al., 1994; Bonny, 1986; Fluck, 1992; Fluck and Baird, 1980; Green, 1987; Kaltschmitt and Reinhardt, 1997; Pimentel, 1980; Pimentel and Pimentel, 1979; Stout, 1979).

Different energy coefficients have been used in the same context. For example, in studies analysing crop production in Ontario, the energy coefficients used for diesel were 37.4 (McLaughlin et al., 2000), 42.0 (Franzluebbers and Francis, 1995) and 45.1 MJ·l<sup>-1</sup> (Clements et al., 1995). From a more detailed study, Zentner et al. (2004) used 44.0 MJ·l<sup>-1</sup> in a Canadian context. The lack of information has also led several authors to apply coefficients determined in OECD countries to systems in developing countries. For example, a fertiliser coefficient adapted for a Canadian context (Bhat et al., 1994) was used in Turkey (Canakci et al., 2005) and Iran (Mohammadi et al., 2008). Pesticide coefficients derived from US conditions (Green, 1987) were indifferently accepted in European (Bennett et al., 2004; Hülsbergen et al., 2001) and Middle-Eastern contexts (Gezer et al., 2003).

This is one of the weakest points for all methods, and coefficient choice can have a significant influence on results. This is illustrated in a case study of 31 dairy farms on Reunion Island. Using a modified PLANETE method (Bochu, 2002) with locally adapted coefficients, energy use averaged 8.0 MJ·l<sup>-1</sup> of milk produced (Vigne et al., 2009). Re-analysis of these farms with 10 different sets of coefficients showed a highly significant effect of the coefficient set on estimated mean energy use (Vigne et al., submitted for publication), which ranged from 4.6 to 7.3 MJ·l<sup>-1</sup> milk.

Large discrepancies have also been observed for transformities in the Em method. Because Odum (1996) suggested 10 methods to calculate solar transformities, others (Brown and Ulgati, 2002) considered that transformities were more a range of values rather than a single value. This has led to great variability in transformity values. For example, diesel transformity in Brazil has ranged from  $1.11 \times 10^5$  (Agostinho et al., 2008) to  $5.5 \times 10^5$  seJ·J<sup>-1</sup> (Cavalett and Ortega, 2009). Similarly, wind transformity has ranged from  $0.47 \times 10^3$  (Lu et al., 2009) to  $2.52 \times 10^3$  seJ·J<sup>-1</sup> (Pizzigallo et al.,

2008), whereas this should be a constant value. Conversely, although the mix of energy sources used to produce 1 J of electricity varies, a single transformity value of  $2 \times 10^5$  seJ·J<sup>-1</sup> has been used in Denmark (Coppola et al., 2009), Italy (Pizzigallo et al., 2008), Scotland (Burgess et al., 2009), the US and Mexico (Martin et al., 2006).

## 4. Research needs

### 4.1. Databases of adapted conversion factors

A clear and comprehensive methodology for calculating conversion factors adapted to highly diverse contexts is needed. This will enable building global databases containing conversion factors for all contexts or at least by country or region. Conforti and Giampietro (1997) attempted to regionalise energy coefficients for pesticides and irrigation with the aim of comparing fossil energy use in agriculture in 75 countries. However, due to lack of data, the scale chosen still appears too large. They thus proposed only two or three coefficients per input category. This is undoubtedly an important step, but it is still under construction. Large databases already exist for energy coefficients, for example ecoinvent (Frischknecht et al., 2004), but they are often expensive, and data from developing countries are lacking (Hertwich, 2005). Similarly, development of the National Environmental Accounting Database (NEAD) (Sweeney et al., 2006) represents an initial step to build a global energy methodology database. It provides energy conversion ratios and transformities, but data for several regions are lacking, and the scale chosen is sometimes too large to provide accurate conversion factors.

Construction of such databases will require recalculation or at least an update of commonly used energy coefficients. Transformities mainly come from recent calculations (Odum, 1996), but energy coefficients were mainly calculated in the 1980s. Thus, their ability to represent current conditions can be challenged. For example, Pervanchon et al. (2002) considered that energy requirements in the fertiliser sector had decreased by 30% since 1983; consequently, they multiplied the energy coefficient for fertiliser of Mudahar and Hignett (1987) by 0.7. Databases will be supplemented with factor conversions from newly studied contexts that have been calculated with previously described methodologies. In this sense, databases will be both freely available to users and updated by them. Construction of such databases will need collaboration among researchers and the industrial sector to update, harmonise and check the data. Indeed, calculation of adapted conversion factors needs to trace the life cycle of every input accurately and know the energy use for each step. But this information is barely available for industrial processes.

### 4.2. Quantification of energy expenditure during animal and human labour

Research is needed on more accurate estimates of energy expenditure during human and animal labour. As previously proposed, an initial EA should be performed by accounting for labour energy through calorie expenditure. Energy expenditure can be assessed either by direct measurement of energy expenditure or indirectly by characterisation of type and duration of activities and transformation into energy expenditure through conversion factors. Direct measurements can be performed in several ways (Acheson et al., 1980), but all require equipment and time. In this sense, indirect methods are probably more suitable. Description of the activities in a work calendar can be obtained from surveys for the studied period. Surveys could consist of regular records (e.g., monthly, for a one-year study) to increase data accuracy. Conway

et al. (2002) observed few differences in energy expenditure over a two-week period between the two methods. However, regular follow-up surveys only studying the current period and do not account for previous years or previous studies in which labour was not included. One promising method is a “work assessment” method developed in France (Dedieu, 1993; Madelrieux and Dedieu, 2008) and applied to systems such as forage systems in dairy farms of Amazonia (Hostiou and Dedieu, 2009) or Vietnam (Hostiou et al., 2010). In any case, accurate records of activities depend greatly on the ability of the subjects to correctly estimate time spent in activities of different intensities. The robustness of such data should be assessed, especially in developing countries, where activities are numerous and diverse.

The conversion factors chosen to convert activities into energy expenditure could be derived from the literature, since several studies have measured energy expenditure for human labour in different systems. Vaz et al. (2005) propose energy costs for a variety of physical activities, including agricultural activities. Energy expenditure for animal labour has been also studied for different species and activities (Brosh et al., 1998; Dijkman and Lawrence, 1997; Lawrence and Stibbards, 1990). Values often differ among studies; for example, manual weeding by humans can vary from 1.98 (Lawrence et al., 1985) to 6.02 kcal·min<sup>-1</sup> (Costa et al., 1989). Since such values probably depend greatly on numerous factors, such as work context and technologies, a global study of different situations is required.

#### 4.3. Application of pluri-energy analysis and emergy to contrasting livestock systems

Simultaneously applying pluri-energy analysis and emergy synthesis to several contrasting livestock systems and territories will (i) confirm the importance of accounting for all energy types when studying systems in developing countries, (ii) identify other limitations not considered in this review, (iii) test hypotheses for defining boundaries of the type of system studied here and (iv) continue to highlight complementarities and differences between the two methods to assess their strengths and limits better. Until now, these methods had been compared only for individual case studies of poultry production (Bastianoni et al., 2010) or pig production (van der Werf et al., 2007). In this sense, the classification of livestock systems into 11 types proposed by Seré and Steinfeld (1996) could represent an interesting approach (Table 1).

**Table 1**  
Classification of livestock systems from Seré and Steinfeld (1996).

| Global type           | Subdivision    | Specific type   |
|-----------------------|----------------|---|
| Solely livestock      | Grassland (LG) | Livestock only systems, highland/temperate (LGT)  |
|                       |                | Livestock only systems, arid-semiarid (LGA)   |
|                       |                | Livestock only systems, humid-subhumid (LGH)  |
|                       | Landless (LL)  | Landless monogastric systems (LLM)<br>Landless ruminant systems (LLR)   |
| Mixed farming systems | Rainfed (MR)   | Mixed rainfed crop/livestock systems, highland/temperate (MRT)  |
|                       |                | Mixed rainfed crop/livestock systems, arid-semiarid (MRA)   |
|                       |                | Mixed rainfed crop/livestock systems, humid-subhumid (MRH)  |
|                       | Irrigated (MI) | Mixed irrigated crop/livestock systems, highland/temperate (MIT)  |
|                       |                | Mixed irrigated crop/livestock systems, arid-semiarid (MIA)<br>Mixed irrigated crop/livestock systems, humid-subhumid (MIH) |

## 5. Conclusion

Three methods dealing partly or exclusively with energy use are currently used to assess environmental impacts of livestock production systems throughout the world: Energy Analysis (EA), the Ecological Footprint (EF) and the Emergy synthesis (Em). The analysis of these methods from 304 case studies of their application at the field or farm scale highlighted several differences among them as well as common and specific limitations, especially for their application to a wide range of livestock production systems from intensive systems in OECD countries to smallholder systems in developing countries which rarely have been studied.

Energy consumption in EF is only part of the assessment and does not clearly identify ways to increase energy efficiency. Em and EA appear the most appropriate methods, but improvements are required to increase their robustness.

First, while EA presents a clear methodology, it remains limited to fossil energy use and its associated environmental impacts. An adaptation of this method could enable consideration of additional energy resources. Inclusion of labour and natural resources seems possible through incorporation of physical and solar energies to evaluate energy fluxes with a more holistic approach. Combining them instead of adding them to produce innovative indicators could improve understanding of the links between farming operations and environmental impacts, such as the effect of fossil energy use on solar-radiation capture by crops or the relative efficiency of direct fossil energy use and that of animal and human labour. Second, boundaries of studied systems should be carefully defined. In this sense, it appears relevant to consider draft animals, communal grazing lands and families when analysing smallholder livestock systems and to analyse energy use more accurately at the scale of productive components through internal flows. Finally, special attention should be given to developing updated and locally adapted energy coefficients and transformities to produce unbiased estimates and accurate comparisons between contrasting livestock systems from different contexts.

Considering these refinements in knowledge of the strengths and weaknesses of the methods, four main research needs are highlighted: (i) construction of databases containing conversion factors adapted to highly diverse livestock systems, (ii) definition of a generic methodology for accurate description of on-farm work activities, (iii) measurement of accurate values for energy expenditure of human and animal labour in diverse contexts and (iv) application of pluri-energy analysis and emergy synthesis to contrasting livestock systems.

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## **Chapitre III**

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# **MATERIEL ET METHODES**

**Le précédent chapitre a permis de faire le point sur les méthodes actuellement disponibles dans la littérature pour décrire les flux d'énergie au sein des systèmes laitiers. Nous avons démontré que les méthodes d'Analyse énergétique fossile et Emergy présentent des potentialités intéressantes sous condition d'un certain nombre d'améliorations méthodologiques principalement pour la méthode d'Analyse énergétique fossile.**

**Ce chapitre présente dans un premier temps les deux méthodes retenues la méthode Emergy et la méthode d'« Analyse pluri-énergétique » correspondant à la méthode améliorée d'Analyse énergétique fossile. De plus, les différents territoires et systèmes de production laitiers choisis pour l'application des deux méthodes ainsi que la méthodologie de récolte des données nécessaires à leur mise en place y sont également explicités.**

## 1. Description des méthodes

### 1.1. Méthode d'analyse pluri-énergétique

#### 1.1.1. Principes de base de la méthode

La méthode d'analyse pluri-énergétique est basée sur trois grands principes.

**Le premier principe** est la comptabilisation de quatre types d'énergie utilisée dans les systèmes agricoles : l'énergie fossile (fossil energy, FE), l'énergie brute (gross energy, GE), l'énergie liée au travail (labor energy, LE) et l'énergie solaire (solar energy, SE). La FE correspond à l'énergie fossile consommée directement sur l'exploitation (carburants, électricité et gaz) ou indirectement pour produire les intrants des cultures (fertilisants, semences, phytosanitaires et eau d'irrigation), les intrant des troupeaux (fourrages, concentrés, soins vétérinaires et animaux de renouvellement) ainsi que les équipements agricoles (matériel et bâtiments). La GE correspond à l'énergie calorifique contenue dans les produits animaux et végétaux ainsi que l'énergie renouvelable produit sur l'exploitation telle que l'électricité photovoltaïque. La LE correspond à l'énergie physique dépensée lors des travaux agricoles réalisés par les animaux ou les humains sur l'exploitation. Enfin la SE correspond au rayonnement photosynthétiquement actif (photosynthetically active radiation, PAR) qui est la part du rayonnement solaire dont les longueurs d'onde s'étendent de 400 à 700 nm.

**Le second principe** de l'analyse pluri-énergétique consiste à diviser le système agricole en composantes. Afin de concevoir un système le plus générique possible, nous avons retenu six composantes : i) les infrastructures qui contiennent le matériel et les bâtiments de l'exploitation, ii) le troupeau qui inclue les animaux en production et les animaux nécessaires à la traction animale, iii) les surfaces directement utilisées par l'exploitation, iv) le stockage des productions végétales, v) le stockage des effluents and iv) la famille. La décomposition du système permet de mener conjointement une analyse globale des systèmes et une analyse plus fine de chaque composante. Cependant, une analyse à l'échelle des composantes nécessite pour chacune d'entre elles une allocation des différentes sources d'énergie entre ses produits afin de quantifier les flux internes. Par exemple, la biomasse produite sur les surfaces de l'exploitation et distribuée au troupeau porte une partie de l'énergie fossile utilisée pour les produire. Afin de produire des bilans pertinents à l'échelle de la composante troupeau, il convient d'estimer cette part.

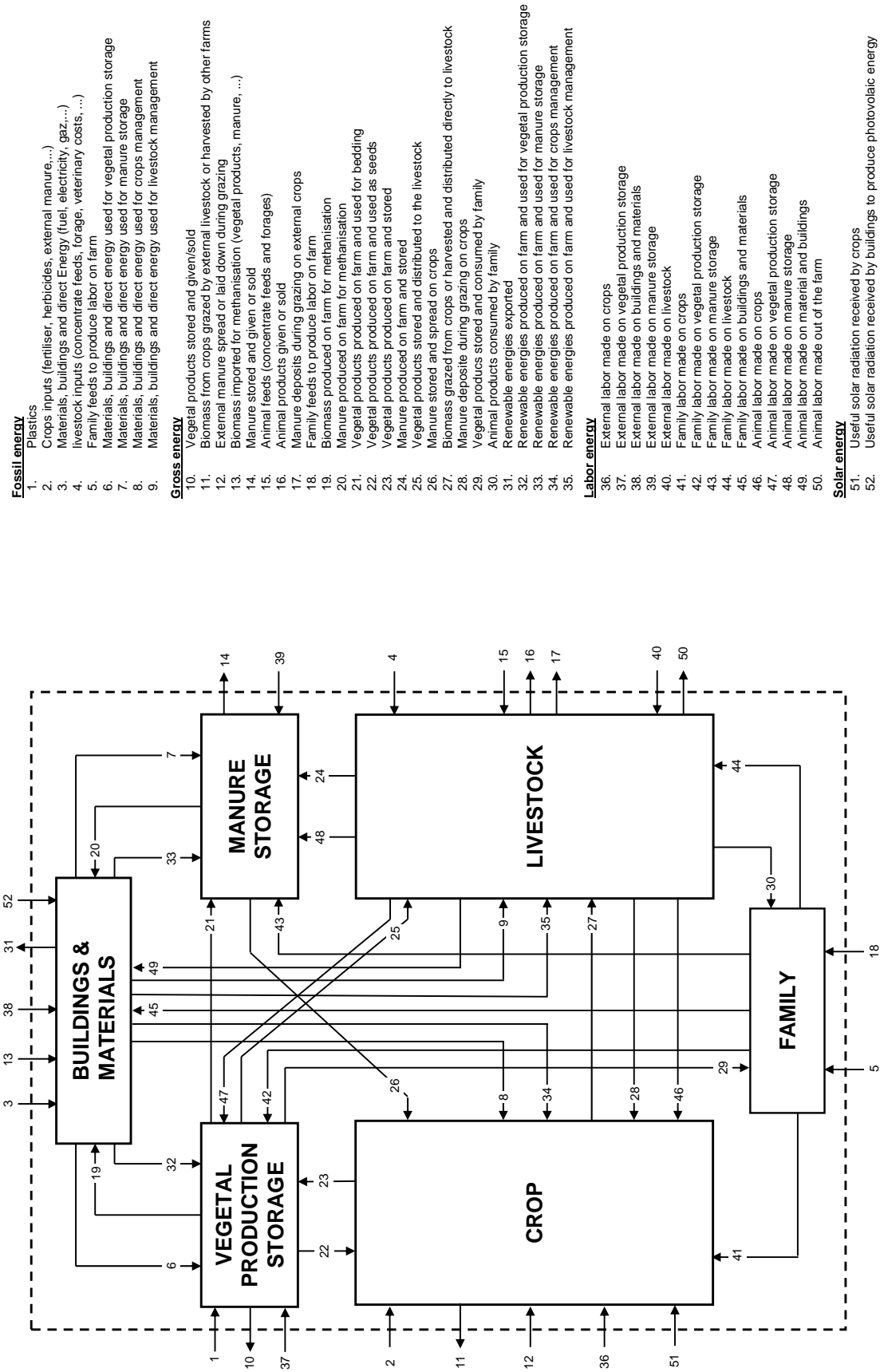


Figure 1 Schéma générique des flux énergétiques entrant, circulant et sortant dans un système d'élevage

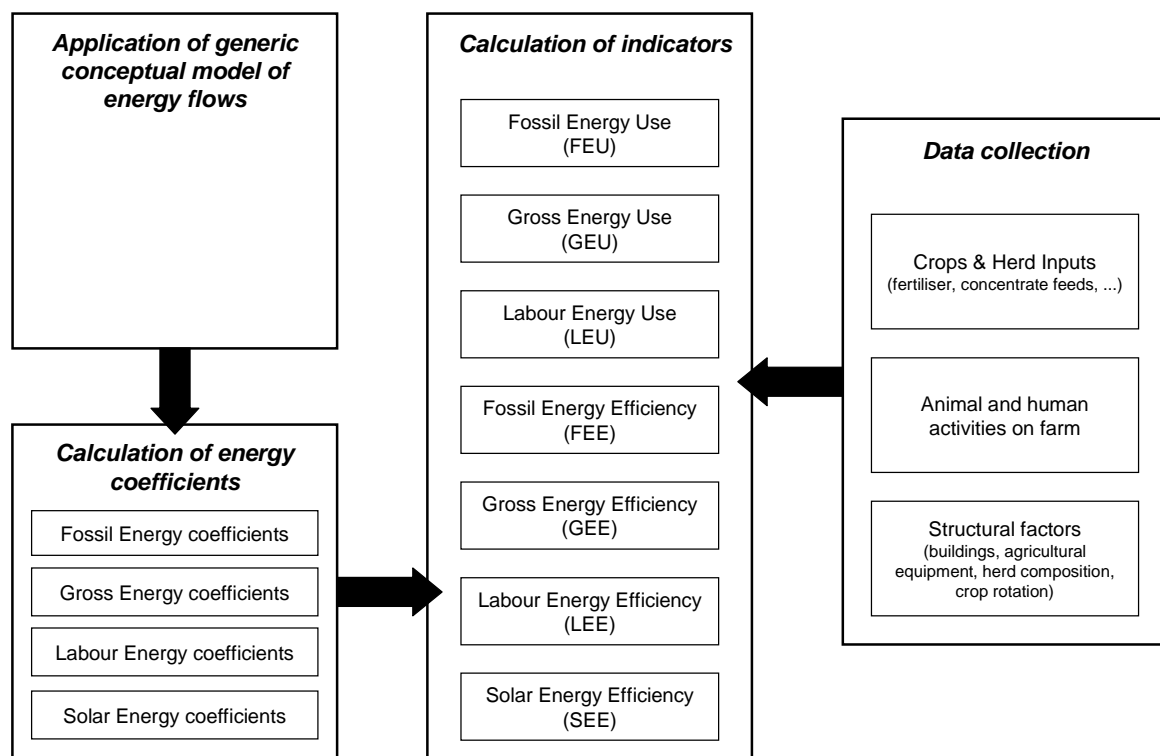
Dans l'analyse pluri-énergétique, cette allocation se fait grâce à une allocation énergétique basée sur le contenu en énergie calorifique des différents produits.

**Le troisième principe** considère la prise en compte de tous les flux d'énergie entrant dans le système, circulant à l'intérieur du système entre les différentes composantes et quittant le système.

Au final, ces principes aboutissent à un schéma générique des flux énergétiques dans un système agricole composé de cinquante-deux flux (Figure 1).

### 1.1.2. Application de la méthode d'analyse pluri-énergétique

L'application de l'analyse pluri-énergétique est organisée en quatre étapes successives (Figure 2).



**Figure 2** Description schématique des différentes étapes de l'application de l'analyse pluri-énergétique

**La première étape** consiste à lister les différents flux énergétiques existants parmi les 52 flux génériques précédemment mis en lumière. Cette étape a pour résultat une première représentation du système de flux énergétique propre au système étudié.

**La seconde étape** consiste à calculer des coefficients énergétiques adaptés au contexte des systèmes étudiés pour les différents types d'énergie et les différents flux précédemment mis



en lumière. Nous faisons en effet ici l'hypothèse que ces coefficients doivent être représentatifs de chaque territoire étudié car ils peuvent varier selon l'origine géographique des intrants ou la technique utilisée pour les produire. Le coût en énergie fossile de l'électricité par exemple peut varier fortement au sein de chaque territoire selon le mix énergétique nécessaire à sa production (énergie nucléaire, charbon, hydraulique, etc...).

**La troisième étape** consiste en la récolte des données d'exploitation et la transformation de ces données brutes en flux énergétiques grâce aux coefficients énergétiques précédemment calculés. L'application de l'analyse pluri-énergétique nécessite des données sur les facteurs structurels (matériel et bâtiments), la gestion des cultures (assolement, fertilisation, production végétale, ...), la gestion du troupeau (composition du troupeau, alimentation, productions, ...) et les différents travaux humains et animaux réalisés sur l'exploitation (type d'activité, durée, ...).

**La dernière étape** correspond au calcul des différents indicateurs énergétiques à l'échelle (i) de l'exploitation, (ii) des surfaces en distinguant les surfaces fourragères et les surfaces dédiées aux cultures alimentaires ou de ventes et (iii) des troupeaux. L'ensemble des indicateurs et des équations utilisées pour leur calcul est indiqué dans le Tableau 1. L'énergie totale consommée pour chaque type d'énergie (FEU, GEU, LEU et SEU) est la somme des différents flux entrants. Seule l'énergie brute est comptabilisée en sortie (GEP). Elle correspond à la somme des flux d'énergie brute produite par le système. L'énergie consommée et produite est exprimée en mégajoule par hectare ( $\text{MJ}\cdot\text{ha}^{-1}$ ) à l'échelle de l'exploitation et des surfaces et en mégajoule par unité animale présente ( $\text{MJ}\cdot\text{UGB}$  ou  $\text{UBT}^{-1}$ ) à l'échelle du troupeau. L'efficacité énergétique pour chaque type de flux à chaque niveau d'échelle (FEE, GEE, LEE et SEE) est le ratio de la GEP sur l'énergie entrante de chaque type. Les indicateurs d'efficacité sont sans dimension.

## 1.2. Méthode Emergy

### 1.2.1. Principes de bases

La méthode Emergy a été développée par Odum depuis plusieurs dizaines d'années (Odum, 1967, 1971, 1996). L'emergy est initialement définie comme l'ensemble de l'énergie disponible qui est utilisée directement ou indirectement pour produire un produit ou un service. Elle permet par conséquent de quantifier l'ensemble des services et des ressources industrielles ou naturelles utilisés par un système.

**Tableau 1** Equations de calcul des différents indicateurs de l'analyse pluri-énergétique à l'échelle de l'exploitation, des surfaces et du troupeau

| Echelle      | Equation   |
|--------------|--|
| Exploitation | $FEU_{Fam} (MJ.ha^{-1}) = FE_{(1)} + FE_{(2)} + FE_{(3)} + FE_{(4)} + FE_{(5)} + FE_{(6)} + FE_{(7)} + FE_{(8)} + FE_{(9)}$ (1)  |
|              | $GEU_{Fam} (MJ.ha^{-1}) = GE_{(12)} + GE_{(13)} + GE_{(15)} + GE_{(18)}$ (2)   |
|              | $LEU_{Fam} (MJ.ha^{-1}) = LE_{(36)} + LE_{(37)} + LE_{(38)} + LE_{(39)} + LE_{(40)}$ (3)   |
|              | $SEU_{Fam} (MJ.ha^{-1}) = SE_{(51)} + SE_{(52)}$ (4)   |
|              | $GEP_{Fam} (MJ.ha^{-1}) = GE_{(10)} + GE_{(11)} + GE_{(14)} + GE_{(16)} + GE_{(17)} + GE_{(31)} + GE_{(50)}$ (5)   |
|              | $FEE_{Fam} (dmnl) = GEP_{Fam} / FEU_{Fam}$ (6)   |
|              | $GEE_{Fam} (dmnl) = GEP_{Fam} / GEU_{Fam}$ (7)   |
|              | $LEE_{Fam} (dmnl) = GEP_{Fam} / LEU_{Fam}$ (8)   |
|              | $SEE_{Fam} (dmnl) = GEP_{Fam} / SEU_{Fam}$ (9)   |
| Cultures     | $FEU_{Crop} (MJ.ha^{-1}) = FE_{(2)} + FE_{(8)} + (FE_{(4)} + FE_{(9)}) \times \frac{GE_{(28)} + LE_{(46)}}{GE_{(16)} + GE_{(17)} + GE_{(24)} + GE_{(28)} + GE_{(30)} + LE_{(46)} + LE_{(47)} + LE_{(48)} + LE_{(49)} + LE_{(50)}} \times$ (10) |
|              | $(1 + \frac{GE_{(26)}}{GE_{(24)}}) + FE_{(7)} \times \frac{GE_{(26)}}{GE_{(14)} + GE_{(20)} + GE_{(26)}}) + FE_{(5)} \times \frac{LE_{(41)}}{LE_{(41)} + LE_{(42)} + LE_{(43)} + LE_{(44)} + LE_{(45)}}$                                       |
|              | $LEU_{Crop} (MJ.ha^{-1}) = LE_{(36)} + LE_{(41)} + LE_{(46)}$ (11)   |
|              | $SEU_{Crop} (MJ.ha^{-1}) = SE_{(51)} + SE_{(52)} \times \frac{GE_{(34)}}{GE_{(31)} + GE_{(32)} + GE_{(33)} + GE_{(34)} + GE_{(35)}}$ (12)  |
|              | $GEP_{Crop} (MJ.ha^{-1}) = GE_{(11)} + GE_{(23)} + GE_{(27)}$ (13)   |
|              | $FEE_{Crop} (dmnl) = GEP_{Cash\&Food} / FEU_{Cash\&Food}$ (14)   |

Les numéros dans chacune des équations correspondent au numéro des flux décrits dans la figure 3.1.

**Tableau 1** (suite)

| Echelle  | Equation  |      |
|----------|---|------|
| Cultures | $LEE_{Crop} (dmnl) = GEP_{Cash\&Food} / LEU_{Cash\&Food}$   | (15) |
|          | $SEE_{Crop} (dmnl) = GEP_{cash\&Food} / SEU_{Cash\&Food}$   | (16) |
| Troupeau | $FEU_{Lvsstk} (MJ.LU^{-1}) = FE_{(4)} + FE_{(9)} + (FE_{(2)} + FE_{(8)}) \times \frac{GE_{(27)}}{GE_{(11)} + GE_{(23)} + GE_{(27)}} \times (1 + \frac{GE_{(25)}}{GE_{(10)} + GE_{(19)} + GE_{(22)} + GE_{(25)}}) + (FE_{(1)} + FE_{(6)})$<br>$\times \frac{GE_{(25)}}{GE_{(10)} + GE_{(19)} + GE_{(22)} + GE_{(25)}} + FE_{(5)} \times \frac{LE_{(44)}}{LE_{(41)} + LE_{(42)} + LE_{(43)} + LE_{(44)} + LE_{(45)}}$ | (17) |
|          | $GEU_{Lvsstk} (MJ.LU^{-1}) = GE_{(15)} + GE_{(25)} + GE_{(27)} + GE_{(29)}$   | (18) |
|          | $LEU_{Lvsstk} (MJ.LU^{-1}) = LE_{(40)} + LE_{(44)} + (LE_{(36)} + LE_{(41)} + LE_{(46)}) \times \frac{GE_{(27)}}{GE_{(11)} + GE_{(23)} + GE_{(27)}} \times (1 + \frac{GE_{(25)}}{GE_{(10)} + GE_{(19)} + GE_{(22)} + GE_{(25)}})$<br>$+ (LE_{(37)} + LE_{(42)} + LE_{(47)}) \times \frac{GE_{(25)}}{GE_{(10)} + GE_{(19)} + GE_{(22)} + GE_{(25)}}$   | (19) |
|          | $SEU_{Lvsstk} (MJ.LU^{-1}) = SE_{(51)} \times \frac{GE_{(27)}}{GE_{(11)} + GE_{(23)} + GE_{(27)}} \times (1 + \frac{GE_{(25)}}{GE_{(10)} + GE_{(19)} + GE_{(22)} + GE_{(25)}}) + SE_{(52)}$<br>$\times \frac{GE_{(35)}}{GE_{(31)} + GE_{(32)} + GE_{(33)} + GE_{(34)} + GE_{(35)}}$   | (20) |
|          | $GEP_{Lvsstk} (MJ.LU^{-1}) = GE_{(11)} + GE_{(23)} + GE_{(27)}$   | (21) |
|          | $FEU_{Lvsstk} (dmnl) = GEP_{Lvsstk} / FEU_{Lvsstk}$   | (22) |
|          | $GEE_{Lvsstk} (dmnl) = GEP_{Lvsstk} / GEU_{Lvsstk}$   | (23) |
|          | $LEE_{Lvsstk} (dmnl) = GEP_{Lvsstk} / LEU_{Lvsstk}$   | (24) |
|          | $SEE_{Lvsstk} (dmnl) = GEP_{Lvsstk} / SEU_{Lvsstk}$   | (25) |

Les numéros dans chacune des équations correspondent au numéro des flux décrits dans la figure 3.1.

Le concept de base de la méthode considère que la Terre est un système ayant comme seuls intrants énergétiques majeurs et constants l'énergie solaire, la chaleur interne de la terre et l'énergie marémotrice. Toutes les autres formes d'énergie existantes sur Terre sont ainsi dérivées de ces trois sources principalement par le biais de transformation énergétique.

L'énergie solaire étant l'intrant énergétique majoritaire sur terre, toutes les autres formes d'énergie peuvent être converties en équivalent solaire afin d'être exprimées dans une unité commune. Ainsi, l'ensemble de l'énergie consommée par un produit ou un service est exprimée en énergie solaire totale utilisée appelée *emergy* solaire et exprimée en joules d'*emergy* solaire (*solar emjoule, sej*). Des facteurs de conversions appelés *Unit Emery Values (UEV)* exprimant cette quantité d'énergie solaire par unité de produit ou de service sont disponibles dans la littérature (Odum et al., 2000 ; Odum, 2000 ; Brown and Bardi, 2002 ; Brandt-Williams, 2002). On trouve plusieurs types d'UEV :

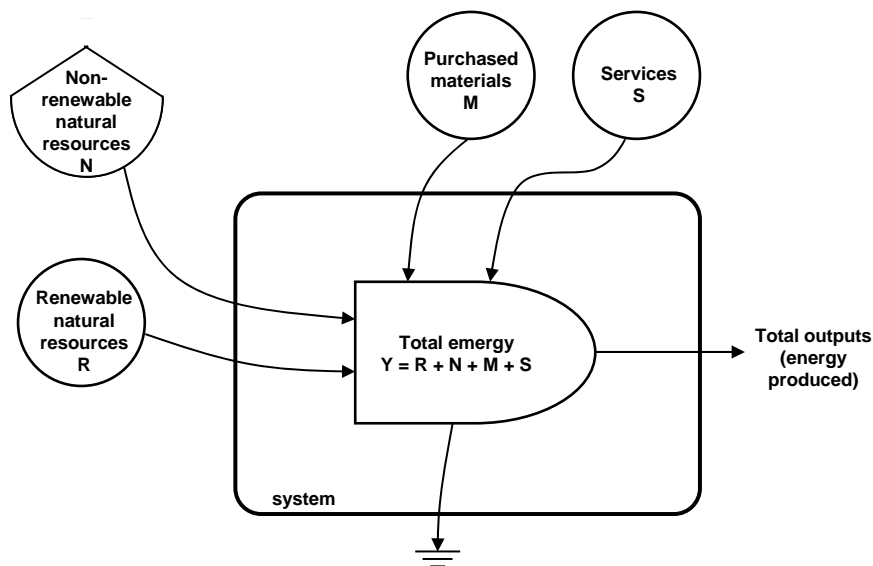
- La transformité qui correspond à l'*emergy* solaire utilisée par joule d'énergie disponible contenue dans le produit (exprimée en  $\text{sej.J}^{-1}$ )
- L'*emergy* spécifique qui correspond à l'*emergy* solaire utilisée par unité de masse de produit (exprimée en  $\text{sej.g}$  ou  $\text{kg}^{-1}$ )
- L'*emergy* par unité monétaire qui correspond l'*emergy* solaire nécessaire à la production d'une unité économique de produit (exprimée en  $\text{sej.unité monétaire}^{-1}$  e.g. € ou \$)
- L'*emergy* par unité de travail qui correspond à l'*emergy* solaire nécessaire à la fourniture d'un joule de travail physique directement dans un process.
- L'*empower* qui correspond au flux d'*emergy* solaire par unité de temps (exprimée en  $\text{sej.s}$  ou  $\text{mn}$  ou  $\text{an}^{-1}$ )

### 1.2.2. Application

L'application de la méthode *Emergy* est couramment décrite sous forme de trois étapes.

La première étape est la construction d'un diagramme énergétique du système (Figure 3). Ce diagramme illustre les limites du système, ses composantes principales, les relations entre ses différentes composantes et les sources d'*emergy*. Les différentes sources d'*emergy* sont regroupées en 4 types : les ressources naturelles renouvelables (*renewable natural resources, R*), les ressources naturelles non renouvelables (*non-renewable natural resources, N*), les matériaux achetés (*purchased materials, M*) et les services (*services, S*). Ce diagramme est

construit selon un symbolisme spécifique proposé par Odum (1996) où chaque symbole indique une gestion particulière de l'energy (source, consommateur, puit,...).



**Figure 3** Diagramme énergétique générique d'un système de production (d'après [Agostinho et al., 2008](#))

**La seconde étape** est la construction d'un tableau d'évaluation basé sur le diagramme précédemment établi. Ce tableau contient d'abord les quantités brutes des différents flux d'intrants exprimées dans leur propre unité. Sont ensuite indiqués les UEV représentant l'energy solaire requise pour générer une unité de chaque flux. Le tableau contient par la suite l'energy totale consommée pour chaque flux correspondant à la quantité brute multipliée par l'UEV correspondante. Une récente adaptation de la méthode consiste à ajouter des facteurs de renouvelabilité correspondant à la part d'energy renouvelable dans le flux d'energy totale ([Ulgiati et al., 1994](#); [Cavalett et al., 2006](#); [Agostinho et al., 2008](#)).

**La troisième étape** est le calcul des différents indicateurs. Six indicateurs sont couramment utilisés dans l'application de la méthode Energy (Tableau 2).

La Transformité (Tr) correspond au ratio de l'energy totale consommée par le système sur l'énergie disponible des produits (E). Elle fournit une mesure de l'efficacité de production ([Brown and Ulgiati, 2004](#)). Plus la transformité est élevée, moins le système est efficace.

La Renouvelabilité (%R) est la part d'energy renouvelable utilisé par le système sous forme de ressources naturelles (R), de matériaux achetés ( $M_R$ ) et de services ( $S_R$ ). Les systèmes avec une part de renouvelabilité élevée sont considérés comme plus durablement environnementalement ([Brown and Ulgiati, 2004](#)).

**Tableau 2** Indicateurs couramment calculés dans l'application de la méthode energy

| Indicateur                                 | unit         | Expression                          |
|--|--------------|-------------------------------------|
| Transformité ( <i>Tr</i> )                 | $seJ.J^{-1}$ | Y/E                                 |
| Renouvelabilité (%R)                       | %            | $100 \times (R + M_R + S_R) / Y$    |
| Energy Yield Ratio ( <i>EYR</i> )          | <i>sd</i>    | $Y / (M_N + S_N)$                   |
| Energy Investment Ratio ( <i>EIR</i> )     | <i>sd</i>    | $(M_N + S_N) / (R + N + M_R + S_R)$ |
| Environmental Loading Ratio ( <i>ELR</i> ) | <i>sd</i>    | $(M_N + S_N + N) / (R + M_R + S_R)$ |
| Energy Sustainability Index ( <i>ESI</i> ) | <i>sd</i>    | $EYR / ELR$                         |

*seJ.J<sup>-1</sup>*: solar emjoule par joule, %: pourcentage, *sd*: sans dimension

L'Energy Yield Ratio (EYR) est le ratio de l'energy totale utilisée par le système (Y) sur l'energy non-renouvelable utilisée sous forme de matériaux achetés ( $M_N$ ) et de services ( $S_N$ ). Cet indicateur mesure la capacité d'un processus à exploiter et rendre la ressource locale disponible en investissant dans des ressources extérieures (Agostinho et al., 2008). La valeur minimum de cet indicateur est 1 ce qui signifie que le processus restitue la même quantité d'energy entrante et qu'il n'est donc pas producteur d'energy. Le processus ne fait donc que transformer des ressources déjà existantes et ne participe à la création de richesse (Agostinho et al., 2008).

L'Energy Investment Ratio (EIR) correspond à l'energy non-renouvelable issue de l'économie ( $M_N$  et  $S_N$ ) divisée par l'energy issue des ressources locales (R et N) et de l'energy renouvelable issue de l'économie ( $M_R$  et  $S_R$ ). L'EIR évalue si un processus est un utilisateur efficace de l'energy naturelle ou renouvelable. Un EIR faible caractérise une faible utilisation des ressources disponibles sur le site et un recours plus important aux ressources payantes (Wilfart et al., 2012)

L'Environmental Loading Ratio (ELR) est le ratio de l'energy non renouvelable totale ( $M_N + S_N + N$ ) sur l'energy renouvelable totale ( $R + M_R + S_R$ ). L'ELR est considéré comme une mesure du stress exercé par un processus sur son environnement (Agostinho et al., 2008) considérant que plus la fraction d'energy renouvelable est faible plus la pression sur l'environnement est forte. Selon Brown and Ulgiati (2004), une valeur inférieure à 2 indique un impact faible sur l'environnement, des valeurs entre 2 et 10 indiquent un impact modéré et des valeurs supérieures à 10 indiquent que le système est à l'origine de dégradations environnementales élevées du fait de flux importants d'energy non renouvelable dans un environnement relativement restreint.

L'Emergy Sustainability Index (ESI) est le ratio de l'EYR sur l'ELR. L'ESI mesure la contribution potentielle du processus étudié à l'économie par unité de stress environnemental (Brown and Ulgiati, 2004). Une valeur élevée témoigne d'une bonne implication du processus dans l'économie globale à comparer de son impact environnemental.

## 2. Terrains d'étude et systèmes étudiés

### 2.1. Des territoires contrastés

Quatre territoires ont été choisis. Le choix a été principalement motivé par la recherche de contextes climatiques et socio-économiques contrastés et *in fine* de systèmes d'élevage offrant une diversité proche de celles mise en lumière par Seré and Steinfeld (1996). Les territoires retenus ont été le Mali Sud (SM) correspondant à la région périurbaine de Sikasso présentant des systèmes très peu mécanisés (11° 19' Nord, 5° 40' Ouest), l'Ile de la Réunion (RI), territoire français situé dans l'Océan Indien (21° 09' Sud, 55° 30' Est) présentant des systèmes très intensifs, et deux régions administratives situées à l'Ouest de la France métropolitaine, le Poitou-Charentes (PC) présentant des exploitations principalement en polyculture - élevage (46° 05' Nord, 00° 10' Est) et la Bretagne (BR) présentant des exploitations laitières de plus petite taille et généralement plus spécialisées (48° 00' Nord, 03° 00' Est).

Une des premières contraintes qui agit sur les systèmes et leurs pratiques est la contrainte climatique. En cela les quatre territoires présentant une diversité géographique et par conséquent pédoclimatique importante (Tableau 3).

**Tableau 3** Conditions pédoclimatiques moyennes dans les quatre territoires étudiés (SM : Mali Sud, RI : Ile de la Réunion, PC : Poitou-Charentes, BR : Bretagne)

|   | SM   | RI   | PC   | BR   |
|---|------|------|------|------|
| Pluviométrie annuelle (m)                         | 1,1  | 3,0  | 0,9  | 1,1  |
| Température (°C)                                  | 26   | 24   | 13   | 11   |
| Rayonnement solaire annuel (kWh.m <sup>-2</sup> ) | 2150 | 1750 | 1300 | 1150 |
| Evapotranspiration journalière (mm)               | 1,8  | 1,0  | 1,9  | 2,1  |

Le Mali Sud est représentatif de la région des savanes de l'Ouest africain. Le rayonnement solaire annuel est élevé (2150 kWh.m<sup>2</sup>) entraînant une température moyenne annuelle assez élevée (26°C). On observe deux saisons bien distinctes : une saison sèche de Décembre à Mai durant laquelle la température maximale peut atteindre plus de 35°C et une saison humide de Juin à Novembre durant laquelle la pluviométrie atteint les 1,1 m.an<sup>-1</sup>. L'Ile de la Réunion

présente un climat tropical ayant pour résultat des températures annuelles moyennes plutôt élevées (26°C), tout comme la pluviométrie (3,0 m.an<sup>-1</sup>) et le rayonnement solaire (1750 kWh.m<sup>-2</sup>). Le climat en Poitou-Charentes est océanique et représenté par des pluies (0,9 m.an<sup>-1</sup>) étalées de manière relativement uniforme sur l'année et une température moyenne de 13°C. Les conditions climatiques sont proches de celles que l'on retrouve en Bretagne bien que la pluviométrie soit légèrement plus élevée (1,1 m.an<sup>-1</sup>) alors que la température moyenne (11°C) et le rayonnement solaire (1150 kWh.m<sup>-2</sup>) sont légèrement plus faibles.

Le contexte socio-économique dans lequel s'inscrit l'activité d'élevage est également un facteur important dans la structuration des systèmes et de leurs pratiques. Dans la région périurbaine de Sikasso, l'activité d'élevage subit depuis quelques années une transformation importante similaire à toute la région d'Afrique de l'Ouest. Le réchauffement climatique et les épisodes de sécheresse de plus en plus nombreux ont entraîné ces dernières décennies un transfert géographique des éleveurs et de leurs troupeaux vers des zones plus propices à l'activité d'élevage (Pradère, 2007) ayant pour conséquence une saturation des terroirs locaux et en particulier des bas-fonds (Coulibaly, 2008). Cette migration a notamment eu pour conséquence l'apparition de nouveaux systèmes d'élevage intégrés à l'agriculture. Cette dynamique a été appuyée par la démographie croissante et l'urbanisation qui, accompagnée du relèvement du niveau de vie d'une partie de la population, a augmenté la demande en produits animaux de la ville dont le lait (Perrin, 2004 ; Pocard et al., 2005). Cependant, bien que cette nouvelle demande ouvre des perspectives économiques intéressantes pour l'activité d'élevage, les systèmes sont encore contraints par la difficulté économique d'accéder aux intrants industriels et à la mécanisation. Ainsi, si Pocard-Chapuis and Corniaux (2007) estiment que les éleveurs de la zone assurent près de 50% des besoins en produits laitiers des habitants de la ville, la concurrence de la poudre de lait importée est encore omniprésente.

La saturation des terres arables est également un facteur prédominant sur l'Ile de la Réunion. D'abord mis en place dans le cadre d'un maintien de la population dans les Hauts de l'Ile pour lutter contre l'urbanisation côtière (Guellec, 1993), l'activité d'élevage a rapidement vu ses surfaces disponibles pour la culture de fourrages limitée par le relief prononcé et la pression foncière importante liée au dynamisme des autres secteurs agricoles et de l'urbanisme. Face à la volonté politique de maintenir cette activité et d'atteindre l'autosuffisance laitière, le développement du secteur s'est maintenu grâce à l'aide financière et technique de l'Union Européenne permettant notamment l'import de concentrés commerciaux afin de pallier au manque de surfaces fourragères ce qui a favorisé le développement de systèmes très intensifs (D'Haese et al., 2007). Cependant, avec une



production dépassant difficilement les 20 millions de tonnes, le quota de production de 40 millions de tonnes initialement allouées à la Réunion dans le cadre de la réforme de la Politique Agricole Commune (PAC) en Europe n'a même jamais été atteint (Louhichi et al., 2004).

A l'inverse, les quotas laitiers mis en place dès 1984 ont fortement influencé les systèmes de l'Ouest de la France (Poitou-Charentes et Bretagne) tant dans leur dimension structurelle que leur productivité (Liénard et al., 1992). Leur future libéralisation en 2015 ne fera qu'augmenter les questions globales posées par la compétition forte des pays en développement et les enjeux environnementaux importants déjà omniprésents. Représentant plus d'un tiers de la production française (FranceAgriMer, 2011) qui elle-même représente un peu plus de 5% du lait mondial (Blaskó, 2012), les exploitations de l'Ouest sont principalement touchées par ces considérations. Cependant, ces considérations globales sont accompagnées de considérations environnementales locales aussi importantes qui ont pris sens récemment en Bretagne avec l'augmentation des apparitions d'algues vertes sur le littoral (Espagnol and Leterme, 2010).

## 2.2. Des systèmes laitiers contrastés

L'ensemble des contraintes ont et contribuent encore largement au développement de systèmes laitiers très contrastés dans chaque territoire (Tableau 4). Dans les systèmes du Mali Sud, la surface totale est principalement représentée par les surfaces fourragères (70%) qui sont en réalité des parcours naturels qui ne reçoivent aucun apport fertilisant à l'exception des effluents déposés lors du pâturage. Les cultures, qui représentent 30% en moyenne de la surface totale sont principalement à destination de l'alimentation humaine (maïs, mil, sorgho) avec parfois quelques cultures de ventes (patate douce, pomme de terre). La terre est travaillée manuellement par les hommes ce qui explique la main d'oeuvre élevée (4,3 UMO), avec l'aide d'animaux de labour. Compte tenu du coût économique élevé de la fertilisation minérale, la fertilisation de ces cultures est principalement basée sur les effluents du troupeau et les déchets ménagers (66%). Le nombre d'animaux est faible et le troupeau est composé d'animaux offrant une diversité d'âge assez importante bien que les vaches laitières en production (VL) représentent près de la moitié des animaux. Ces animaux sont principalement nourris par les résidus de cultures et le pâturage sur les parcours naturels. La quantité de concentrés distribués est faible illustrant un faible niveau d'intensification des troupeaux ayant pour résultant une faible production laitière annuelle (212 l.VL<sup>-1</sup>).

**Tableau 4** Description des systèmes laitiers étudiés sur les quatre territoires (SM: Mali Sud, RI: Ile de la Réunion, PC: Poitou-Charentes, BR: Bretagne)

| Territoire (nombre d'exploitations étudiées)  | SM (n=14)              | RI (n=30)                 | PC (n=48)                  | BR (n=38)                  |
|---|------------------------|---------------------------|----------------------------|----------------------------|
| Taille du troupeau (UBT ou UGB) <sup>a</sup>  | <b>32,8</b> (9,8-64,8) | <b>55,5</b> (24,0-131,2)  | <b>94,4</b> (27,9-220,0)   | <b>79,2</b> (38,0-125,5)   |
| Part des vaches en production dans le troupeau (%)  | <b>52</b> (37-100)     | <b>78</b> (57-100)        | <b>66</b> (56-98)          | <b>66</b> (51-82)          |
| Surface totale (ha)   | <b>36,5</b> (6,1-76,7) | <b>22,0</b> (2,5-72,0)    | <b>135,3</b> (30,0-378,3)  | <b>80,3</b> (28,6-200,0)   |
| Part des surfaces fourragères récoltées (%)   | <b>0</b> (0-0)         | <b>27</b> (20-100)        | <b>31</b> (0-90)           | <b>55</b> (0-60)           |
| Part des surfaces fourragères pâturées (%)  | <b>70</b> (10-100)     | <b>73</b> (0-80)          | <b>29</b> (0-100)          | <b>78</b> (40-100)         |
| Part des surfaces en cultures de vente ou destinées à l'alimentation (%)  | <b>30</b> (0-90)       | <b>0</b> (0-0)            | <b>40</b> (0-85)           | <b>22</b> (0-44)           |
| Chargement animal sur la surface totale (UBT ou UGB.ha <sup>-1</sup> )  | <b>1,0</b> (0,5-1,6)   | <b>4,4</b> (1,2-10,8)     | <b>0,8</b> (0,3-1,4)       | <b>1,1</b> (0,6-1,7)       |
| Chargement animal sur la surface fourragère (UBT ou UGB.ha <sup>-1</sup> )  | <b>2,4</b> (0,7-16,8)  | <b>4,4</b> (1,2-10,8)     | <b>1,5</b> (0,4-3,8)       | <b>1,4</b> (0,6-2,2)       |
| Unité main d'oeuvre   | <b>4,3</b> (2,6-9,8)   | <b>2,5</b> (1,3-4,5)      | <b>2,5</b> (1,0-4,5)       | <b>1,8</b> (1,0-3,5)       |
| Fertilisation minérale sur les cultures de vente ou destinées à l'alimentation (kgN.ha <sup>-1</sup> .an <sup>-1</sup> )  | <b>33</b> (6-57)       | -                         | <b>95</b> (0-197)          | <b>94</b> (0-161)          |
| Fertilisation organique sur les cultures de vente ou destinées à l'alimentation (kgN.ha <sup>-1</sup> .an <sup>-1</sup> ) | <b>64</b> (11-187)     | -                         | <b>22</b> (0-147)          | <b>23</b> (0-148)          |
| Fertilisation minérale sur les surfaces fourragères (kgN.ha <sup>-1</sup> .an <sup>-1</sup> )                             | -                      | <b>194</b> (30-1,022)     | <b>76</b> (0-220)          | <b>86</b> (16-344)         |
| Fertilisation organique sur les surfaces fourragères (kgN.ha <sup>-1</sup> .an <sup>-1</sup> )                            | -                      | <b>91</b> (0-383)         | <b>32</b> (0-360)          | <b>40</b> (0-93)           |
| Concentrés distribués (kg. UBT ou UGB <sup>-1</sup> .an <sup>-1</sup> )   | <b>123</b> (0-2600)    | <b>4672</b> (2,375-7,375) | <b>2,020</b> (338-3,649)   | <b>1,311</b> (663-2082)    |
| Biomasse produite sur les surfaces en herbe <sup>b</sup> (tMS.ha <sup>-1</sup> )  | <b>1,9<sup>b</sup></b> | <b>12,6</b> (6,2-24,4)    | <b>5,8</b> (3,9-9,0)       | <b>6,4</b> (5,5-7,5)       |
| Biomasse produite sur les surfaces ensilées <sup>c</sup> (tMS.ha <sup>-1</sup> )  | -                      | <b>22,6</b> (10,2-45,2)   | <b>12,8</b> (10,0-17,0)    | <b>13,4</b> (7,1-17,0)     |
| Rendement des surfaces en culture (t.ha <sup>-1</sup> )   | <b>1,6</b> (0,3-4,5)   | -                         | <b>6,0</b> (4,0-6,5)       | <b>8,0</b> (5,5-11,5)      |
| Production laitière (l.VL <sup>-1</sup> .an <sup>-1</sup> )   | <b>212</b> (56-813)    | <b>6082</b> (3,545-9,314) | <b>7,515</b> (4,627-9,719) | <b>7,012</b> (4,757-8,950) |

Les valeurs présentées sont des **moyennes (min-max)**

<sup>a</sup> UBT = Unité Bovin Tropical (1 UBT correspond à un bovin de 250 kg) et UGB = Unité Gros Bétail (1 UGB correspond à un bovin de 600 kg)

<sup>b</sup> La biomasse des surfaces en herbe peut-être pâturée, fauchée en vert ou récoltée en foin

<sup>c</sup> L'ensilage correspond à de l'ensilage d'herbe en RI et à l'ensilage maïs en PC et BR

La surface dédiée aux systèmes de production laitiers de l'île de la Réunion est totalement destinée aux cultures fourragères. Les exploitations ont aussi des cultures de vente, principalement sous forme de canne à sucre, mais qui n'ont pas été considérées car n'interférant pas avec la production laitière. Les fourrages produits sont majoritairement ensilés et distribués aux animaux qui sont également complétés avec des quantités de concentrés élevées ( $4672 \text{ kg.UGB}^{-1}.\text{an}^{-1}$ ) afin de répondre au chargement élevé ( $4,4 \text{ UGB.ha}^{-1}$ ). Les troupeaux restent d'importance moyenne et sont principalement composés de vaches laitières. Sur l'île, une majeure partie des génisses est vendue à la coopérative laitière locale qui les élève, les insémine et les revend aux éleveurs juste avant vêlage. Seule une partie minoritaire des éleveurs élèvent leurs propres génisses bien que cette pratique tende à se démocratiser. La fertilisation est relativement élevée ( $194 \text{ kgN.ha}^{-1}.\text{an}^{-1}$ ) afin d'atteindre le potentiel de production en biomasse élevé notamment sur les surfaces ensilées ( $22,6 \text{ tMS.ha}^{-1}.\text{an}^{-1}$ ) permis par les conditions locales favorables. Malgré un niveau d'apport de concentrés et des productions de biomasse sur les surfaces élevées, la production laitière peut être considérée comme moyenne ( $6082 \text{ l.VL}^{-1}.\text{an}^{-1}$ ).

En Poitou-Charentes, les systèmes de production laitiers ont des structures moyennes importantes ( $135,3 \text{ ha}$  de SAU et  $94,4 \text{ UGB}$ ). Les troupeaux sont composés pour deux tiers de vaches laitières, le restant du troupeau étant composé des animaux de renouvellement élevés sur l'exploitation. Les exploitations sont diversifiées avec une part élevée de cultures de vente (40%). Les ressources fourragères du troupeau sont issues pour approximativement la moitié (48%) du pâturage. Les chargements animaux sont modérés et mènent à des quantités de fertilisants organiques plutôt faibles en regard des besoins des surfaces ce qui conduit à des apports de fertilisants minéraux élevés ( $95 \text{ kgN.ha}^{-1}.\text{an}^{-1}$  sur les cultures et  $76 \text{ kgN.ha}^{-1}.\text{an}^{-1}$  sur les surfaces fourragères). La biomasse produite par les cultures fourragères relativement faible ( $5,8 \text{ tMS.ha}^{-1}.\text{an}^{-1}$  sur les pâturages et  $12,8 \text{ tMS.ha}^{-1}.\text{an}^{-1}$  sur les surfaces ensilées) et le recours à l'ensilage de maïs entraîne des apports importants de concentrés ( $2020 \text{ kg.V}^{-1}\text{L}.\text{an}^{-1}$ ) mais a pour principal conséquence une production de lait élevée ( $7515 \text{ l.VL}^{-1}.\text{an}^{-1}$ ).

Les systèmes de production laitiers de Bretagne présentent un fonctionnement proche des systèmes de Poitou-Charentes. Toutefois, les structures d'exploitation sont plus petites ( $80,3 \text{ ha}$  de SAU et  $79,2 \text{ UGB}$ ). Les surfaces de l'exploitation sont principalement représentées par des surfaces fourragères (78%), elles-mêmes principalement pâturées (70%). Si la fertilisation minérale sur les cultures est proche des exploitations de Poitou-Charentes ( $94 \text{ kgN.ha}^{-1}.\text{an}^{-1}$ ), la fertilisation minérale sur les surfaces fourragères est légèrement plus élevée ( $86 \text{ kgN.ha}^{-1}.\text{an}^{-1}$ ).

<sup>1</sup>.an<sup>-1</sup>). L'apport de concentrés est plus faible (1311 kg.VL.an<sup>-1</sup>) mais la production laitière annuelle moyenne reste tout de même élevée puisqu'elle atteint 7012 l.VL<sup>-1</sup>.

### 2.3. Une diversité au sein des territoires

Au delà de la diversité des territoires et des systèmes moyens caractérisés précédemment, il existe une variabilité des systèmes au sein de chaque territoire.

Au Mali Sud, [Coulibaly \(2008\)](#) a classé les exploitations laitières de la périphérie de Sikasso selon leur stratégie de production laitière (SPL) en 5 groupes. La SPL1 se caractérise par une production laitière proche de 70 l.VL<sup>-1</sup> par an malgré des troupeaux relativement importants pour la zone (35,7 UBT). Les chefs d'exploitation sont des agriculteurs avec des surfaces agricoles élevées (16,1 ha) pour lesquels l'élevage tient principalement une fonction d'épargne et dont l'alimentation est principalement basée sur les pâturages du terroir, l'apport quotidien de concentrés étant faibles (175 kg.VL<sup>-1</sup>.an<sup>-1</sup>). Bien que l'agriculture y soit également dominante, les exploitations de la SPL2 ont une trajectoire d'évolution vers un développement de l'activité laitière. La quantité de lait produite est ainsi plus importante (100 à 250 l.VL<sup>-1</sup>.an<sup>-1</sup>) malgré des surfaces plus faibles (7,3 ha) et des troupeaux élevés (33,1 ha). Cette quantité est notamment permise par une gestion raisonnée du pâturage, les quantités de concentrés apportés restant faibles (175 kg.VL<sup>-1</sup>.an<sup>-1</sup>). Malgré des productions de lait identiques à la SPL 2, les chefs d'exploitation de la SPL3 sont des éleveurs qui ont recours accru à l'apport d'aliments concentrés (450 kg.VL<sup>-1</sup>.an<sup>-1</sup>) pour nourrir le troupeau (35,5 UBT) afin de palier un manque de surfaces de cultures (2,7 ha) et donc de résidus disponibles pour le troupeau. La SPL4 correspond à des systèmes de production spécialisés innovants. Les exploitants sont des éleveurs avec un troupeau légèrement plus faible que les SPLs précédentes (29,9 UBT) mais qui ont atteint un niveau de production laitière annuelle élevé (entre 600 et 800 l.VL<sup>-1</sup>) notamment grâce à un apport accru d'aliments concentrés (623 kg.VL.an<sup>-1</sup>). L'activité agricole est somme toute toujours présente sur l'exploitation (11,0 ha). La SPL5 est également un système de production spécialisée dont le lait produit atteint près de 800 l.VL<sup>-1</sup>.an<sup>-1</sup>. Il se différencie de la stratégie précédente par la stabulation d'un troupeau de faible taille (9,8 UBT) nourri à l'auge notamment par l'apport de concentrés élevés (2600 kg.VL<sup>-1</sup>.an<sup>-1</sup>).

Sur l'île de la Réunion, [Alary et al. \(2002\)](#) ont proposé une classification des systèmes fortement influencée par la diversité climatique de l'île aboutissant à quatre zones principales de production. Dans les deux plaines centrales d'altitude de l'île (Plaine des Cafres et Plaine des Palmistes), les conditions favorables à la production fourragère du fait d'une pluviométrie

importante ( $3 \text{ m.an}^{-1}$ ) ont favorisé l'apparition de systèmes fourragers basés sur des graminées tempérées principalement récoltées sous forme d'ensilage balle ronde. On distingue cependant 3 tailles d'exploitations dans ces zones. On retrouve ainsi des grandes exploitations avec plus de 55 VL sur plus de 35 ha de terre dont au moins un tiers est utilisé en pâture. La complémentation quotidienne est élevée (+ de  $13 \text{ kg.VL}^{-1}$ ) tout comme les productions de lait ( $> 7000 \text{ l.VL}^{-1}.\text{an}^{-1}$ ). On retrouve également des exploitations de moindre taille (35 à 55 VL sur 15 à 35 ha) où la pâture est quasi absente. Les apports quotidiens de concentrés sont légèrement plus faibles ( $10$  à  $13 \text{ kg.VL}^{-1}$ ) et les productions mais les productions restent élevées ( $> 7000 \text{ l.VL}^{-1}.\text{an}^{-1}$ ). Enfin, des systèmes plus chargés, regroupant un troupeau d'une vingtaine d'animaux sur moins de 5 ha sont apparus à la fin des années 90 en raison de la pression foncière sur ces plaines. Ces exploitations importent une partie de leur affouragement et les apports de concentrés sont élevés (+ de  $13 \text{ kg.VL}^{-1}.\text{j}^{-1}$ ) pour des productions pourtant faibles (environ  $5000 \text{ l.VL}^{-1}.\text{an}^{-1}$ ). Dans les Hauts de l'Ouest, la faible pluviométrie ( $< 1 \text{ m.an}^{-1}$ ) et la difficile mécanisation des terres a conduit les systèmes vers une stratégie d'alimentation basée sur les espèces tropicales (pâturage de Kikuyu et complémentation fourragère à partir de foin de chloris et de résidus de canne à sucre). L'apport de concentrés reste tout de même élevé puisqu'il se situe entre 10 et  $13 \text{ kg.VL}^{-1}$  pour des productions faibles de moins de  $5000 \text{ l.VL}^{-1}$  par an. On retrouve dans le Sud Est de l'île (Plaine des Grègues et Hauts de St Joseph) des exploitations de faible taille (20 à 35 VL sur 9 ha en moyenne) mais présentant des chargements élevés ( $4.1 \text{ UGB.ha}^{-1}$ ). Le mode d'affouragement est principalement basé sur la fauche en vert quotidienne. Malgré ces chargements élevés, les apports de concentrés n'excèdent pas  $10 \text{ kg.VL}^{-1}.\text{j}^{-1}$  pour des productions s'élevant entre 5000 et  $6000 \text{ l.VL}^{-1}.\text{an}^{-1}$ .

Dans l'Ouest de la France, les systèmes de production laitiers de chacun des territoires peuvent être classés selon leur orientation technique et économique (OTEX). L'OTEX est une classification européenne permettant de comparer les productions agricoles de nature différente. Elle classe chaque exploitation en fonction de ses productions dominantes et de leur contribution à la marge brute standard de l'exploitation (Desbois, 2000). On retrouve ainsi des exploitations bovins lait spécialisées, bovins lait et viande, des exploitations en polyélevage ou encore des exploitations en polyculture – élevage. La seconde entrée de classification, couramment utilisée par l'Institut de l'Élevage, est basée sur l'utilisation de la surface fourragère des systèmes laitiers de plaine. La classification est basée sur la part de maïs ensilage dans la surface fourragère principale (SFP) et considère 3 types : les systèmes « herbagers » (moins de 10% de maïs ensilage dans la SFP), les systèmes « maïs-herbe »

(entre 10% et 30% de maïs ensilage dans la SFP) et les systèmes « maïs » (plus de 30% de maïs ensilage dans la SFP).

### 3. Collecte des données d'exploitation

Dans chacun des territoires, le choix des exploitations a été motivé par la volonté de s'appuyer sur des bases de données existantes.

Dans le cas du Mali Sud, une partie des données des 14 exploitations étudiées sont issues d'une précédente étude menée par [Coulibaly \(2008\)](#). Cette étude avait pour objectif d'évaluer l'impact de la commercialisation du lait sur les pratiques et les stratégies des éleveurs de la zone périurbaine de Sikasso au Mali. La récolte des données avait consisté pour cette étude en un suivi d'exploitation hebdomadaire sur la campagne agricole 2005-2006. Les données récoltées concernaient plus spécifiquement les données structurelles de l'exploitation, la conduite du troupeau, les productions du troupeau et la gestion du lait. Cette base de données a été complétée par une enquête sur chacune des exploitations menées en 2011 sur une période de 5 semaines. Les données complémentaires récoltées ont concerné principalement la gestion des cultures et les travaux menés sur l'exploitation. Une version du cahier d'enquête constitué pour les entretiens réalisés en 2011 est reportée en Annexe I.

Dans le cas de l'île de la Réunion, les données des 30 exploitations étudiées sont principalement issues d'un travail mené en 2008 et 2009 dans le but d'établir le bilan énergétique fossile des systèmes d'élevage de l'île ([Vayssières et al., 2010](#)). La récolte de données s'était appuyée à l'époque sur les comptes de gestion économique fournis par le CERFrance complétés par des enquêtes en exploitations.

Les données pour les systèmes de Poitou-Charentes et Bretagne sont issus de la base de données DIAPASON ([Charroin et al., 2005](#)) et concernent les années 2008 pour la Bretagne et 2008 et 2009 pour le Poitou-Charentes. Cette base a été constituée dans le cadre des « Réseaux d'Élevage pour le conseil et la prospective » mis en place à partir des années 80 pour fournir une description détaillée des systèmes d'élevage dans toutes les régions françaises. Basée sur une participation volontaire des éleveurs, la base concentre des données annuelles d'environ 1800 exploitations. Les données de la base ont été complétées par les différents travaux estimés à partir de références sur le travail fournies par la [Chambre d'Agriculture de Bretagne \(2006\)](#).

## 4. Analyse des données

Une analyse préliminaire a consisté à vérifier l'hypothèse précédemment émise dans la synthèse bibliographique (Chapitre II) sur la nécessité d'adaptation des facteurs de conversion des deux méthodes. Ce travail a été mené selon une analyse d'incertitude sur les coefficients énergétiques dans l'analyse énergétique fossile des territoires de la Réunion et du Poitou-Charentes (Chapitre IV.1).

Les deux méthodes adaptées à chacun des territoires ont ensuite été appliquées sur les systèmes laitiers choisis. Les résultats obtenus ont d'abord été comparés entre les différents territoires (Chapitre V). Cette comparaison a concerné les indicateurs moyens obtenus sur chacun des territoires. Une comparaison des indicateurs obtenues de l'analyse pluri-énergétique a ensuite été menée à l'intérieur du territoire Mali sous le prisme des différents types de SPL (Chapitre VI.1). Une comparaison menée conjointement sur les systèmes de Poitou-Charentes et de Bretagne et concernant les consommations énergétiques fossiles a ensuite été complétée par une analyse menée grâce à la méthode Data Envelopment Analysis (DEA) (Chapitre VI.2).

Des descriptions plus précises notamment sur l'analyse des variances des écarts sont indiquées dans les parties Matériel et Méthodes propres à chaque article constituant les chapitres de Résultats.

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## **Chapitre IV**

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# **FACTEURS DE CONVERSION**

Dans le chapitre précédent, la description des méthodes a confirmé la place importante des facteurs de conversion (coefficients énergétiques et Unit Emery Values) déjà supposée dans la synthèse bibliographique précédemment menée (Chapitre 2). Une des hypothèses émises au sujet de ces facteurs de conversion est la nécessité de les adapter aux conditions locales afin d'obtenir des résultats pertinents et reflétant au plus juste les réalités locales.

Ce chapitre analyse dans un premier temps les conséquences de l'incertitude des coefficients énergétiques fossiles sur la variation de l'analyse énergétique fossile des systèmes laitiers. Il met également en lumière l'importance de l'adaptation de ces coefficients aux conditions locales pour fournir des estimations de consommation d'énergie fossile pertinentes et ne pas biaiser les comparaisons entre territoires.

Cette conclusion est par la suite extrapolée à l'ensemble des facteurs de conversion des méthodes utilisées dans notre études soit l'ensemble des coefficients énergétiques de l'analyse pluri-énergétique (fossiles, bruts, liés au travail et solaires) et les Unit Emery Values pour la méthode Emery. Ce chapitre présente donc dans un second temps les valeurs retenues pour les différents facteurs de conversion utilisés dans notre étude (coefficients énergétiques et UEVs) et explicite leur mode de calcul.

## 1. Importance de l'adaptation des coefficients énergétiques fossiles<sup>3</sup>

### Comparative uncertainty analysis of energy coefficients in energy analysis of dairy farms from two French territories

#### *Analyse comparative de l'incertitude liée aux coefficients énergétiques dans l'analyse énergétique de systèmes laitiers issus de deux territoires français*

M. Vigne, O. Martin, P. Faverdin, J.L. Peyraud

Original Research Article - **Journal of Cleaner Production 37 (2012) 185-191**

### Résumé

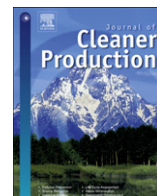
L'analyse énergétique fossile est une méthode courante d'évaluation environnementale des systèmes agricoles. Elle consiste à mesurer l'énergie fossile consommée directement sur l'exploitation ou indirectement pour produire les intrants. Son application est basée sur la somme des quantités brutes de chaque intrant multipliées par un coefficient énergétique fossile propre à chacun de ces intrants. Ce coefficient énergétique se doit de représenter au plus juste la consommation d'énergie fossile nécessaire à l'extraction des matières premières, la fabrication de l'intrant ou encore son transport. Cependant, la variation des valeurs trouvées dans la littérature pour différents coefficients énergétiques et la variabilité des contextes dans lesquels ils ont été utilisés questionnent la pertinence des estimations de consommation d'énergie fossile précédemment calculés. Afin d'évaluer les conséquences du choix des coefficients énergétiques sur les estimations de consommation d'énergie fossile et de proposer des améliorations pour une estimation plus précise de ces coefficients, cet article propose une analyse de l'incertitude et de sensibilité d'analyses énergétiques menées dans des systèmes laitiers de deux territoires français : le Poitou-Charentes (PC) et l'Ile de la Réunion (RI). Cette

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<sup>3</sup> Cette première partie correspond à un article scientifique accepté pour publication dans Journal of Cleaner Production auquel a été ajouté un résumé en français. Il a également donné lieu à 2 communications sous forme de poster :

- **Vigne, M., Peyraud, J.L., Lecomte, P., 2011.** *Impact du choix des coefficients énergétiques sur les résultats de l'analyse énergétique : Exemple de la consommation énergétique des élevages bovins laitiers réunionnais.* XVIIIème 3R Rencontres recherches Ruminants, 7-8 décembre 2011, Paris, France (Annexe I)
- **Vigne, M., Faverdin, P., Peyraud, J.L., 2012.** *Energy analysis of agricultural systems: Uncertainty associated to energy coefficients non-adapted to local conditions.* 8th International conference on Life Cycle Assessment in the Agri-Food sector, 1-4 October 2012, St Malo, France (Annexe II)

analyse a consisté en une simulation Monte Carlo basée sur 30 000 séries de coefficients énergétiques fossiles choisies aléatoirement à partir des valeurs minimum et maximum issues de la littérature. Les résultats obtenus montrent ainsi un intervalle de confiance à 95% s'étalant de 3,6 à 5,0 MJ.l de lait<sup>-1</sup> pour PC et de 5.8 à 8,2 MJ.l de lait<sup>-1</sup> pour RI ce qui représente des variations de valeur autour de la moyenne de 16% pour PC et 17% pour RI. Les risques d'erreur sont donc importants notamment dans le cas de comparaison de systèmes issus de différents territoires où les coefficients énergétiques de différents intrants peuvent varier par exemple en fonction de la distance de transport ou des technologies d'obtention. Ces résultats originaux mettent en lumière le besoin d'une méthode standardisée et clairement définie permettant de calculer des coefficients énergétiques fossiles adaptés aux conditions locales de chaque territoire étudié. Ceci permettrait de fournir des estimations précises et des comparaisons non biaisées des consommations d'énergie fossile de différents systèmes agricoles à travers le monde. Pour y parvenir, une investigation précise de l'origine des différentes matières premières utilisées pour la fabrication des intrants ainsi que des technologies utilisées est nécessaire. Cependant, de telles investigations peuvent s'avérer laborieuse et consommatrices de temps. Aussi, afin d'éviter l'adaptation de l'ensemble des coefficients, l'application de l'analyse énergétique devrait être associée à une analyse préalable de sensibilité permettant d'identifier les coefficients les plus sensibles sur lesquels devraient principalement se porter les efforts d'adaptation.



## Comparative uncertainty analysis of energy coefficients in energy analysis of dairy farms from two French territories

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### ARTICLE INFO

#### Article history:

Received 29 February 2012

Received in revised form

8 June 2012

Accepted 4 July 2012

Available online 25 July 2012

#### Keywords:

Energy analysis  
Agricultural systems  
Uncertainty

### ABSTRACT

Fossil energy analysis, also called cumulative energy demand, is a current method for environmental assessment of agricultural systems. It consists of assessing fossil energy directly consumed on the farm and indirectly consumed to produce farm inputs. Application of the method is based on the sum of the quantity of each farm input multiplied by its energy coefficient, which represents fossil energy use during the life cycle of the input, including extraction, manufacturing and disposal of the raw and auxiliary materials. The range of values for energy coefficients proposed in the literature and variability in their context of application challenges the confidence in estimates of fossil energy use.

To offer an initial representation of this uncertainty and to propose improvements for including uncertainty in energy coefficients, a fossil energy analysis completed by uncertainty and sensitivity analyses was applied to dairy farms from two differing French territories: Poitou-Charentes (PC) and Reunion Island (RI). Monte-Carlo simulation of 30,000 sets of coefficients randomly drawn from the ranges of values found in the literature shows a 95% confidence interval ranging from 3.6 to 5.0 MJ L<sup>-1</sup> of raw milk for PC and 5.8–8.2 MJ L<sup>-1</sup> of raw milk for RI. This represents a variation around the mean of ±16% for PC and ±17% for RI. This also highlights the need for a standardized and clearly defined method for calculating energy coefficients, especially regionally adapted ones, to accurately estimate fossil energy use of agricultural systems throughout the world.

Calculation of a more accurate energy coefficient could be associated with a preliminary sensitivity analysis performed with minimum and maximum values of energy coefficients from the literature to identify the most influential coefficients and adapt them to local conditions. This avoids time-consuming adaptation of all energy coefficients, but requires accurate information about life-cycle inputs. Since energy coefficients are not the only source of uncertainty in fossil energy analysis, however, other guidelines are provided, especially concerning data inputs.

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### 1. Introduction

Environmental impacts of livestock systems are a central issue for future development of the sector. To feed an increasing population, fossil energy use in agricultural systems has been increasing since the 1960s and the Green Revolution (Pimentel et al., 1973). Fossil energy use contributes to two environmental impacts: emission of greenhouse gases and depletion of natural resources. Efficient use of fossil energy is thus a valid concern for agricultural systems. Assessment of fossil energy use in agricultural systems is currently accomplished with fossil energy analysis methodology (e.g. Pimentel et al., 1973; Singh et al., 2002;

Tzivilakis et al., 2005; Veysset et al., 2010), also called cumulative energy demand (Kim and Dale, 2003; Huijbregts et al., 2010). Fossil energy analysis is based on the measurement of inputs consumed by the farm and transformed into a fossil-energy-use equivalent based on energy coefficients from the literature or calculated by researchers. In a preliminary study, more than 184 references were identified concerning application of fossil energy analysis on agricultural systems in the world through single-criterion analysis or multiple-criteria analysis such as life cycle assessment (Vigne et al., in press).

To estimate energy use accurately, energy coefficients must represent fossil energy use during the life cycle of an input, including fossil energy consumed during extraction, manufacturing and disposal of the raw and auxiliary materials, and must be adapted to current and local conditions of the area studied. In this sense, the literature offers a wide range of values for the same

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coefficient. For example, the energy coefficient for chemicals can range from 85 (Green, 1987) to 418 MJ kg<sup>-1</sup> of active matter (Pimentel, 1980). However, this variability does not seem linked only to the diversity of contexts. One can find different values for the same coefficient in the same context, such as diesel from Canada, which varies from 37.4 (McLaughlin et al., 2000) to 45.1 MJ L<sup>-1</sup> (Clements et al., 1995). Moreover, energy coefficients are lacking for many contexts (Liu et al., 2010) leading to the use of locally non-adapted energy coefficients. Consequently, the same coefficients have been used for different territories. For example, a fertilizer coefficient adapted from a Canadian context (Bhat et al., 1994) was used in Turkey (Canakci et al., 2005) and Iran (Mohammadi et al., 2008). The uncertainty associated with the choice of non-adapted energy coefficients from the literature has not yet been studied.

This study aims to offer an initial approach to estimate the uncertainty associated with energy coefficients and to propose methodological improvements for including it in future fossil energy analysis of agricultural systems. To reach this goal, fossil energy use was measured for specialized dairy farming systems in two contrasted French territories: Poitou-Charentes (PC), a temperate area situated in mainland France, and Reunion Island (RI), a tropical island situated in the Indian Ocean. Next, comparative uncertainty and sensitivity analyses were performed for the two territories.

## 2. Materials and methods

### 2.1. Description of the dairy production systems

Dairy production systems in RI have smaller mean herds than those in PC (Table 1). Moreover, the mean total area is considerably smaller in RI than in PC, although a mean of 40% of the area in PC is Cash-crops. The smaller area in RI is mainly due to lack of arable land associated with urban pressure. It results in a higher mean stocking rate for forage land in RI and the need for concentrate feeds to maintain an adequate level of productivity. The higher mean percentage of cows in RI is explained by specific management of heifers in these systems. In contrast to PC, where cow replacement is internal, female calves in RI are usually sold to agricultural technical institute, which breeds them and then returns them to farms after insemination. Management also differs on forage land; for example, although mean biomass production is higher in RI, less forage land is grazed than in PC, due to a preference for silage.

**Table 1**  
Description of dairy production systems in Reunion Island (RI) and Poitou-Charentes (PC).

| Territory  | PC (n = 42)               | RI (n = 30)              |
|--|---------------------------|--------------------------|
| Herd size (LU)   | <b>94.4</b> (27.9–220.0)  | <b>55.5</b> (24.0–131.2) |
| Percentage of cows   | <b>66</b> (56–98)         | <b>78</b> (57–100)       |
| Total area (ha)  | <b>135.3</b> (30.0–378.3) | <b>22.0</b> (2.5–72.0)   |
| Percentage of forage land  | <b>60</b> (15–100)        | <b>100</b> (100–100)     |
| Percentage of cash-crop land   | <b>40</b> (0–85)          | <b>0</b> (0–0)           |
| Stocking rate on total area (LU ha <sup>-1</sup> )                         | <b>0.8</b> (0.3–1.4)      | <b>4.4</b> (1.2–10.8)    |
| Stocking rate on forage land (LU ha <sup>-1</sup> )                        | <b>1.5</b> (0.4–3.8)      | <b>4.4</b> (1.2–10.8)    |
| Concentrate feed purchased (kg LU <sup>-1</sup> yr <sup>-1</sup> )         | <b>2020</b> (338–3649)    | <b>4672</b> (2375–7375)  |
| Percentage of grazing area on total area (dmnl)                            | <b>68</b> (26–100)        | <b>27</b> (0–58)         |
| Biomass production of forage land (tDM ha <sup>-1</sup> yr <sup>-1</sup> ) | <b>10.4</b> (5.4–16.4)    | <b>12.6</b> (6.2–24.4)   |
| Milk yield (L cow <sup>-1</sup> yr <sup>-1</sup> )                         | <b>7515</b> (4627–9719)   | <b>6082</b> (3545–9314)  |

Values given are **mean** (minimum–maximum).

LU: livestock units, dmnl: dimensionless, tDM: tons of dry matter.

### 2.2. Farm data

Farm data describe input consumption and production for one year. For RI they came from a 2007 survey of 30 dairy farms previously chosen to cover the structural and geographical variability described by Taché (2001) and were gathered by interviews. Farm data from PC came from the national DIAPASON database (Charroin et al., 2005) and concern 42 dairy farms in 2008.

### 2.3. Fossil energy analysis

Fossil energy analysis was conducted with the PLANETE method (Bochu, 2002) for PC dairy farms and with the PLANETE MASCAREIGNES method for RI dairy farms. PLANETE is a tool for energy analysis of agricultural systems in mainland France and nearby European contexts. PLANETE MASCAREIGNES is a version of PLANETE in which energy coefficients were adapted for RI (Thévenot et al., 2011). For processes that differed between mainland France and RI, energy coefficients were recalculated (e.g. fuel, electricity, concentrates and forages), unless data were lacking (e.g. water, livestock and veterinary costs). For inputs imported from mainland France, the energy cost of transport was added to the initial coefficients of PLANETE (e.g. seeds, fertilizer, agricultural equipment, buildings and chemicals).

Fossil energy use in this study is expressed in MJ L<sup>-1</sup> of raw milk produced. For each farm, fossil energy use is the sum of the quantity of each farm input (e.g. fuel, electricity, concentrates and fertilizers) multiplied by its energy coefficient:

$$\text{Fossil Energy Use (MJ)} = \sum C_i I_i \quad (1)$$

where  $C_i$  is the energy coefficient of each farm input  $i$ , and  $I_i$  is the quantity consumed for each farm input  $i$

### 2.4. Uncertainty analysis

To understand the impact of uncertainty in energy coefficients on mean energy use, uncertainty analysis was performed with Monte-Carlo methodology using the SIMLAB tool (Saltelli et al., 2004). The Monte-Carlo method, a stochastic approach, is useful for analyzing the response of a model to variation in input parameters (Rai and Krewski, 1998). Different values of parameters are simulated through a chosen model distribution, and propagation of this uncertainty on model output is analyzed.

In this study, the 61 initial inputs were first aggregated to obtain 28 groups of inputs (e.g. concentrate feeds, buildings and agricultural equipment). Then, 30,000 sets of energy coefficients were randomly generated. Each set contained a value for each of the 28 inputs randomly drawn from a uniform distribution between minimum and maximum values found in the literature (Table 2).

A uniform distribution was assumed because preliminary analysis of the value ranges (Table 2) showed that coefficient distributions did not have a defined shape. The full range of each coefficient was considered in each territory because the preliminary analysis did not indicate the most likely values in each region. Moreover, correlations were calculated between energy coefficients for diesel, electricity, N fertilizer, herbicides and materials from 20 studies. Since no significant correlations were observed, independence of the coefficients was assumed, and each was drawn randomly. For RI and PC, each farm was analyzed with each of the 30,000 sets to estimate the global uncertainty in model output resulting from uncertainty in energy coefficients. Uncertainty was expressed as a 95% confidence interval and variation from the mean.

**Table 2**

Minimum and maximum values of energy coefficients found in the literature for the 28 farm inputs.

| Inputs                 | Energy value (MJ unit <sup>-1</sup> ) |       | Unit             | References |      |
|------------------------|---------------------------------------|-------|------------------|------------|------|
|                        | Min.                                  | Max.  |                  | Min.       | Max. |
| Fuel                   | 35.90                                 | 56.31 | L                | [1]        | [2]  |
| Electricity            | 5.65                                  | 12.70 | kWh              | [3]        | [4]  |
| Water                  | 0.63                                  | 14.00 | m <sup>3</sup>   | [5]        | [6]  |
| N fertilizer           | 44.0                                  | 78.1  | kg N             | [7]        | [8]  |
| P fertilizer           | 7.03                                  | 17.40 | kg P             | [9]        | [8]  |
| K fertilizer           | 6.7                                   | 13.7  | kg K             | [10]       | [8]  |
| Manure                 | 3.8                                   | 18.3  | t                | [11]       | [12] |
| Herbicides             | 85                                    | 418   | kg active matter | [13]       | [14] |
| Insecticides           | 58.0                                  | 363.6 | kg active matter | [13]       | [14] |
| Fungicides             | 99                                    | 276   | kg active matter | [15]       | [3]  |
| Seeds                  | 9.40                                  | 12.08 | kg               | [16]       | [17] |
| Wheat                  | 2.68                                  | 4.03  | kg               | [18]       | [19] |
| Concentrate feeds      | 3.36                                  | 6.30  | kg               | [20]       | [3]  |
| Soybean meal           | 5.61                                  | 5.80  | kg               | [19]       | [21] |
| Bagasse                | 0.15                                  | 5.40  | kg               | [22]       | [23] |
| Sugarcane straw        | 0.2                                   | 0.3   | kg               | [21]       | [19] |
| Wheat straw            | 0.20                                  | 1.38  | kg               | [21]       | [25] |
| Hay                    | 0.7                                   | 1.9   | kg               | [19]       | [21] |
| Silage                 | 0.6                                   | 1.9   | kg               | [24]       | [25] |
| Heifer                 | 9.1                                   | 42.7  | kg               | [21]       | [22] |
| Animal buildings       | 590                                   | 4721  | m <sup>2</sup>   | [25]       | [21] |
| Storage buildings      | 790                                   | 1980  | m <sup>2</sup>   | [21]       | [21] |
| Agricultural equipment | 62.7                                  | 101.8 | kg               | [26]       | [21] |
| Tractor                | 80.2                                  | 138.0 | kg               | [27]       | [28] |
| Maize                  | 1.2                                   | 6.4   | kg               | [24]       | [21] |
| Cereal bran            | 0.1                                   | 0.2   | kg               | [24]       | [21] |
| Molasses               | 2.8                                   | 11.2  | kg               | [22]       | [29] |
| Milk powder            | 43.7                                  | 55.0  | kg               | [22]       | [22] |

[1] Refsgaard et al. (1998), [2] Binning et al. (1983), [3] Meul et al. (2007), [4] Fluck (1992), [5] Yilmaz et al. (2005), [6] Mrini et al. (2001), [7] Kaltschmitt and Reinhardt (1997), [8] Kitani (1999), [9] West and Marland (2002), [10] Mittal and Dhawan (1988), [11] Singh et al. (2002), [12] Guzmán and Alonso (2008), [13] Green (1987), [14] Pimentel (1980), [15] Mudahar and Hignett (1987), [16] Bonny (1986), [17] Pellizzi (1992), [18] Bonny (1993), [19] Sainz (2003), [20] Saunders and Barber (2007), [21] Risoud and Theobald (1997), [22] Thévenot et al. (2011), [23] Da Silva et al. (1978), [24] Koknaroglu (2010), [25] Wells (2001), [26] Mandal et al. (2002), [27] Sartori et al. (2005), [28] Tabar et al. (2010), [29] Nguyen and Haynes (1995) recalculated.

### 2.5. Sensitivity analysis

The objective of sensitivity analysis is to identify the energy coefficients that influence model predictions the most. Among many sensitivity analysis methods (Hamby, 1994), we chose the simple yet rigorous Standardized Regression Coefficient (SRC) because of the linearity of the model. SRC quantifies the linear effect of variability of each energy coefficient:

$$SRC = \sum_k \beta_x \frac{Y_x - \bar{Y}_x}{s_k} \quad (2)$$

where  $\beta_x$  is the regression coefficient of energy coefficient  $x$ ,  $Y_x$  is the average energy use,  $s_k$  is the standard deviation of energy coefficient  $x$ , and  $k$  is the number of sets of coefficients. A high SRC value indicates high influence of the energy coefficient on the model output, which could lead to large uncertainty in predictions.

## 3. Results and discussion

### 3.1. Uncertainty due to energy coefficients

Fossil energy analysis shows fossil energy use averaged  $4.6 \pm 1.0$  MJ L<sup>-1</sup> of raw milk in PC and  $7.9 \pm 1.1$  MJ L<sup>-1</sup> of raw milk in RI (Table 3).

**Table 3**

Fossil energy use per L of raw milk from Poitou-Charentes (PC) and Reunion Island (RI) dairy farms.

| Indicator                 | Energy use (MJ L <sup>-1</sup> of raw milk) |             |
|---------------------------|---|-------------|
|                           | PC (n = 42)                                 | RI (n = 30) |
| Mean                      | 4.6   | 7.9         |
| Standard deviation        | 0.4   | 0.7         |
| Minimum value among farms | 2.8   | 5.7         |
| Maximum value among farms | 8.3   | 9.3         |

Mean values of fossil energy use obtained from Monte-Carlo simulation of 30,000 sets of coefficients were  $4.3 (\pm 0.3)$  and  $7.0 (\pm 0.7)$  MJ L<sup>-1</sup> of raw milk, respectively, for PC and RI. Moreover, Monte-Carlo simulation of 30,000 sets of coefficients shows 95% confidence interval ranges from 3.6 to 5.0 MJ L<sup>-1</sup> of raw milk for PC and 5.8–8.2 MJ L<sup>-1</sup> of raw milk for RI (Fig. 1). This represents a variation around the mean of  $\pm 16\%$  for PC and  $\pm 17\%$  for RI and highlights the effect of uncertainty in energy coefficients on accurately expressing fossil energy use.

This uncertainty especially calls into question comparison of systems from different territories. Mean values of fossil energy use obtained with adapted energy coefficients are lower for PC than for RI (Table 3). This is mainly the consequence of using larger amounts of concentrate feeds in RI, which have higher energy costs than locally produced feeds. The average consumption profile of the farms in RI shows that more than half of energy use is represented by concentrate feeds (Table 4).

Concentrate feeds are imported from mainland France due to close economic links and the relatively large distance increases their energy cost. Twenty-eight percent of energy costs of concentrate feeds is due to their importation, giving them an energy coefficient of  $5.7$  MJ kg<sup>-1</sup>, which lies at the upper end of the range of literature values (Table 2). Nonetheless, the distribution obtained from Monte-Carlo simulation of 30,000 sets of coefficients (Fig. 1) shows that differences in energy use between dairy systems from RI and PC can even be minimal when considering higher values for PC and lower values for RI.

The effect of uncertainty in predicted values can also be illustrated when comparing dairy systems from different regions (e.g. different countries) (Fig. 2).

The lower bound of the 95% confidence interval for PC could place energy use of its dairy farms near that of Swedish farms (Cederberg and Mattsson, 2000); conversely, the upper bound is higher than the values for Belgian (Rabier et al., 2010) and Dutch farms (Bos et al., 2007). Similarly, energy use for RI dairy farms could be either less than those in Finland (Grönroos et al., 2006) and similar to Dutch dairy farms (Bos et al., 2007) or, conversely, much higher. This confirms the need for a standardized methodology to calculate energy coefficients, especially one that clearly defines system boundaries. This should result in locally adapted coefficients that provide more accurate predictions of fossil energy use.

### 3.2. How to decrease uncertainty in energy coefficients?

The standardized methodology for calculating energy coefficients should first include a clear definition of system boundaries in indirect energy assessment. The system boundaries debate is global to LCA and is mainly fed by an unclear description of the life cycle inventory in LCA standards of the International Organization for Standards (Tillman et al., 1994; Ekvall and Weidema, 2004; Suh et al., 2004). During the life cycle of an input, fossil energy can only concern non-renewable primary or indirect energy needed to produce raw materials. Different methods may lead to different



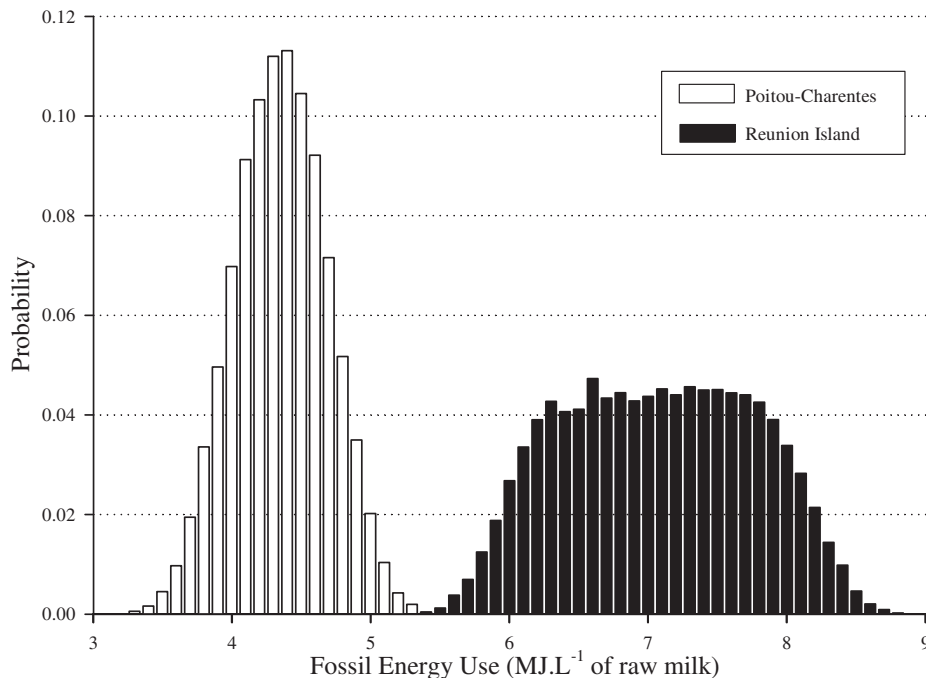


Fig. 1. Probability distribution of energy use for farms from Poitou-Charentes and Reunion Island calculated with 30,000 sets of energy coefficients.

values. For example, for crop production in Canada, Zentner et al. (2004) calculated that on-farm fuel use represents 17–22% of total fossil energy use. If only direct on-farm energy use were used to calculate energy coefficients for concentrated feed, for example, the exclusion of indirect energy use would omit around 80% of the total energy cost. In dairy systems such as those of RI, where large amounts of concentrate feeds are used, the impact of such a decision would be significant. The standardized methodology should also encourage consideration of the technologies used. For example, energy requirements for fertilizer production have decreased by at least 30% since 1983 (Pervanchon et al., 2002), which indicates that the type and age of technologies used should be considered. The mode of electricity production and its impact on energy coefficient values (Brown and Ulgiati, 2002) also argues for such investigation.

However, calculation of energy coefficients is time-consuming and requires accurate information about life-cycle inputs. In this sense, preliminary sensitivity analysis appears as an interesting way to facilitate such adaptation in highlighting energy coefficients that play a significant role in predicted fossil energy use of similar

livestock systems in different territories. SRCs obtained from the sensitivity analysis performed in this study for the different energy coefficients show that influential energy coefficients differ in the two territories (Table 5).

For PC dairy farms, most variability in total energy use seems due mainly to a combination of five inputs with medium SRCs (electricity, concentrate feeds, animal buildings, fuel and N fertilizer). For RI dairy farms, the coefficient for concentrate feeds was by far the most influential, due primarily to the high percentage of concentrate feeds in total energy use (Fig. 3). Unfortunately, similar links are more difficult to highlight for PC dairy farms.

The high sensitivity of energy use of RI dairy farms to a single input variable could explain why their probability distribution of energy use shows a plateau from 6.2 to 7.8 MJ L<sup>-1</sup> of raw milk (Fig. 1) and resembles a uniform distribution more than a Gaussian distribution (Skewness = -0.0002; Kurtosis = -0.95), in contrast to energy use of PC dairy farms (Skewness = 0.0002; Kurtosis = -0.27), which is influenced by several more independent coefficients. This confirms the importance of paying special attention to concentrate feeds in PLANETE MASCAREIGNES. While PLANETE proposes only two coefficients for feed concentrates per type of livestock system (e.g. dairy, pig), PLANETE MASCAREIGNES proposes a coefficient for each commercial concentrate feed, leading to twenty coefficients for RI dairy systems. These energy coefficients, calculated using compositions provided by the feed industry, range from 4.5 to 6.0 MJ kg<sup>-1</sup> of feed concentrate.

### 3.3. Others sources of uncertainty

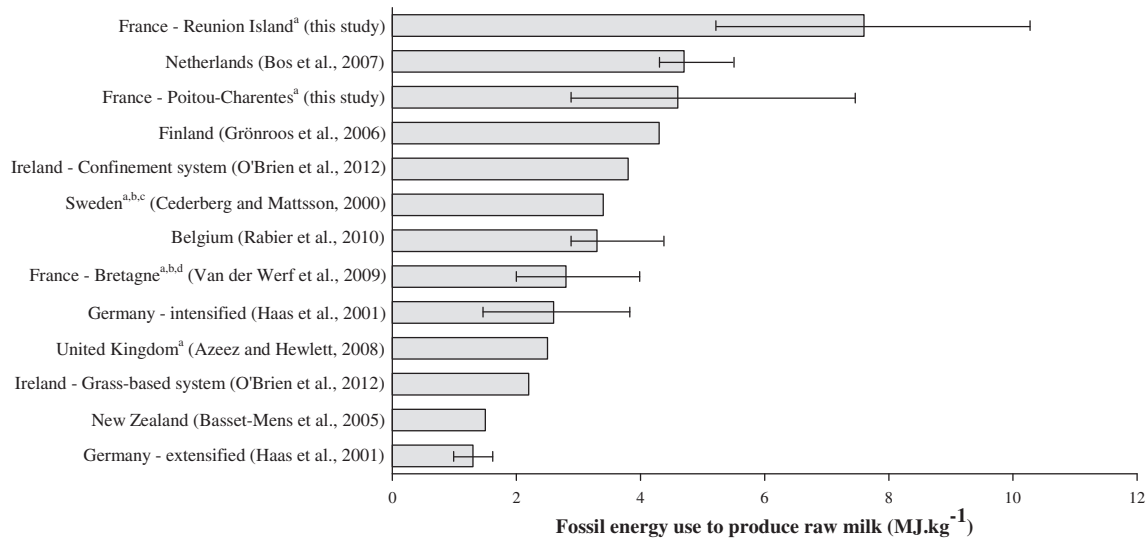
Previous results and discussion only illustrate uncertainty related to energy coefficients. Besides the need for a standardized methodology to calculate energy coefficients, estimating accurate values can be challenged by uncertainty in other factors of data collection or fossil energy analysis methodology. For example, how well the farms in each study represent the territory's dairy-farm diversity may be a large source of uncertainty. In this study, mean energy use had high variability, ranging from 2.8 to 8.3 MJ L<sup>-1</sup> of

**Table 4**  
Mean and standard error of fossil energy use per ha of land occupied for dairy farms of Poitou-Charentes (PC) and Reunion Island (RI).

| Input                  | PC (n = 42)                                    |                | RI (n = 30)                                    |                |
|------------------------|--|----------------|--|----------------|
|                        | Energy use <sup>a</sup> (MJ ha <sup>-1</sup> ) | % <sup>b</sup> | Energy use <sup>a</sup> (MJ ha <sup>-1</sup> ) | % <sup>b</sup> |
| Concentrate feed       | 9386 ± 1609                                    | 25             | 104,545 ± 22,632                               | 61             |
| Fuel                   | 7246 ± 541                                     | 19             | 15,044 ± 1753                                  | 9              |
| Electricity            | 6705 ± 787                                     | 18             | 12,498 ± 3244                                  | 7              |
| N fertilizer           | 4188 ± 420                                     | 11             | 5957 ± 420                                     | 3              |
| Animal buildings       | 2849 ± 185                                     | 7              | 5833 ± 190                                     | 3              |
| Agricultural equipment | 2419 ± 190                                     | 6              | 7789 ± 1004                                    | 5              |
| Tractor                | 1643 ± 120                                     | 4              | 3460 ± 611                                     | 2              |
| Heifer                 | -  | -              | 9445 ± 1373                                    | 5              |

<sup>a</sup> Mean ± standard error.

<sup>b</sup> Percentage of total energy use.



<sup>a</sup> Recalculated from an expected milk density of 1.03 kg.l<sup>-1</sup>  
<sup>b</sup> Recalculated from the formula for Energy Corrected Milk given by Sjauna et al. (1990)  
<sup>c</sup> Recalculated from an average content of Swedish milk of 4.34% fat and 3.37% protein (Lindmark-Mansson et al., 2003).  
<sup>d</sup> Recalculated from an average content of 4.05% fat and 3.48% protein for organic farms and 4.30% fat and 3.39% protein for conventional farms (Van der Werf et al., 2009)

**Fig. 2.** Comparison of fossil energy use (in MJ kg<sup>-1</sup> of raw milk) found in this study with references for conventional dairy farms from the literature (Error bars correspond to minimum and maximum values).

raw milk in PC and 5.7–9.3 MJ L<sup>-1</sup> of raw milk in RI. Similar ranges can be observed in other studies of dairy systems in which several farms have been analyzed (Fig. 2). Previous studies on energy use in RI (Vigne et al., 2008) have shown that observed variability is not significantly linked to simple structural (e.g. herd size, area) or geographic factors (e.g. geographic area, altitude). Similar results have been demonstrated in other studies of dairy systems (Rabier et al., 2010). Since variability in energy use is probably due to farm management, it seems difficult for a value built from regional or national statistics (Basset-Mens et al., 2005) or from one real farm (Cederberg and Mattsson, 2000) to represent such a variability. A large number of real farms are probably necessary to estimate average energy use. As in this study, an approach assessing several real farms (e.g. Van der Werf et al., 2009) most likely better represents the real diversity of farms and enable to calculate most accurate average value. Moreover, large farm sample sizes can decrease uncertainty in farm's data. Numerous studies have investigated uncertainty in parameters in life cycle analysis (LCA), and the need for accurate input data was highlighted in most (Heijungs, 1996; Weidema and Wesnæs, 1996; Steen, 1997; Maurice, 2000). Individual economic follow-up surveys can be interesting but also more time consuming.

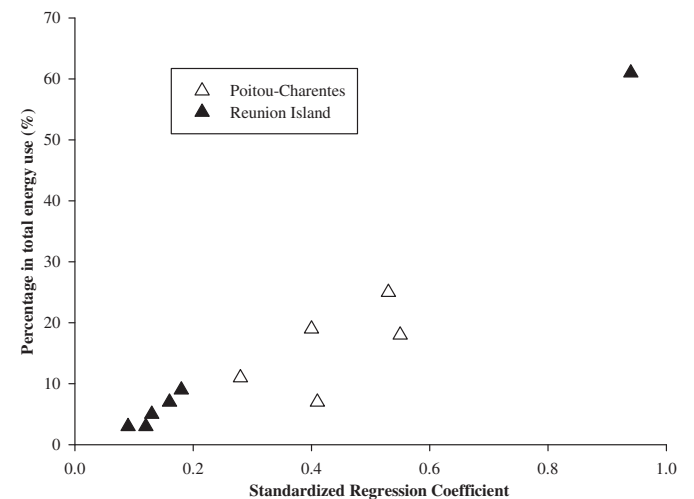
Once a representative survey is established, the choice of the studied year is important. Years differ in the two territories in our

study but have been chosen to represent a “standard” year in each territory, without unusual weather or socio-economic events. To assess the chosen year's representativeness, repeatability of data could be assessed. Since data were available for the year 2009 for 40 farms in PC, fossil energy use per L of raw milk for the two years were compared but had no significant difference ( $p = 0.35$ ). Studying similar years is useful, however, especially as fossil fuels become depleted, which impacts input prices and can lead to changes in farm management.

Concerning fossil energy analysis methodology, in addition to locally adapted energy coefficients, choice of allocation methods could play an important role. In the dairy studies cited previously, the allocation of environmental impacts to milk (when noted) ranges from 85% (Basset-Mens et al., 2006) to 91% (O'Brien et al.,

**Table 5**  
Standardized Regression Coefficients (SRC) of the most sensitive energy coefficients for Poitou-Charentes (PC) and Reunion Island (RI) dairy farms.

| Energy coefficients | SRC  |      |
|---------------------|------|------|
|                     | PC   | RI   |
| Electricity         | 0.55 | 0.16 |
| Concentrate feeds   | 0.53 | 0.94 |
| Animal buildings    | 0.41 | 0.12 |
| Fuel                | 0.40 | 0.18 |
| N fertilizer        | 0.28 | 0.09 |
| Heifers             | –    | 0.13 |



**Fig. 3.** Relation between the percentage of total fossil energy use of the most influential inputs of Poitou-Charentes and Reunion Island dairy farms and the Standardized Regression Coefficient sensitivity index.

2012), probably leading to small uncertainties. Cederberg and Mattsson (2000) applied four allocation methods (i.e., none, economic, biological, and system expansion) in LCAs of Swedish dairy systems, resulting in allocations of 85–100% of impacts to milk. When analyzing herds in which milk production has less importance (e.g., mixed systems), however, such a choice can be important.

#### 4. Conclusion

Fossil energy use from RI and PC dairy farms was respectively 7.9 and 4.6 MJ L<sup>-1</sup> of raw milk, and uncertainty analysis performed via 30,000 sets of randomly drawn energy coefficients estimated 95% confidence intervals from 3.6 to 5.0 MJ L<sup>-1</sup> of raw milk for PC milk and 5.8–8.2 MJ L<sup>-1</sup> of raw milk for RI milk. This represents a variation around the mean of ±16% and ±17%, respectively, and calls into question comparison of dairy systems from other territories. Such variations highlight the need for a standardized and well-defined method for calculation of energy coefficients that could be used to adapt energy coefficients regionally.

This method should include a clear definition of system boundaries in indirect energy assessment and encourage investigation of the technologies used. Moreover, while uncertainty is influenced by differing energy coefficients among territories, we propose performing a preliminary sensitive analysis using initial data inputs and a range of values for energy coefficients found in the literature. This would focus attention on the most influential coefficients and thereby avoid adapting all energy coefficients, which is time-consuming. However, for some territories, data on energy values of inputs are lacking, and life-cycle assessment might be difficult to define. In this case, a less accurate alternative could be to perform an uncertainty analysis similar to that in this study to calculate a confidence interval for energy use. In such a case, more detailed investigation of energy coefficients could help define valid ranges for each region to decrease confidence intervals.

Nonetheless, energy coefficients are not the only source of uncertainty in fossil energy analysis. Uncertainty in input data could decrease with large surveys of real farms and individual economic follow-up surveys based on representative years. Moreover, methodology-related uncertainty could decrease by selecting common allocation methods.

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## 2. Calcul des coefficients énergétiques

### 2.1. Coefficients énergétiques fossiles

Le coefficient énergétique fossile d'un intrant représente la quantité d'énergie fossile nécessaire à la production de ses matières premières, à sa fabrication ainsi qu'aux différentes étapes de son transport. Le tableau 1 reprend l'ensemble de ces coefficients utilisés. Concernant la Réunion, le Poitou-Charentes et la Bretagne, des bases de données regroupant des valeurs adaptées étaient disponibles dans la littérature et ont donc été valorisées. Ainsi, les valeurs utilisées sont issues de la méthode PLANETE MASCAREIGNES pour l'Ile de la Réunion (Thèvenot et al., 2011) et de la méthode Dia'terre® pour le Poitou-Charentes et la Bretagne (ADEME, 2011). Aucune donnée étant disponible dans la littérature pour le Mali Sud, les coefficients énergétiques fossiles ont été recalculés pour ce territoire. Toutefois, certains coefficients proviennent de la littérature lorsque les cycles de vie des intrants étaient difficiles à définir. Les différents modes de calcul et les références utilisées sont détaillés en Annexe VI.

**Tableau 1** Coefficients énergétiques retenus et correspondant à la consommation d'énergie fossile pour la production des intrants dans les quatre territoires étudiés (exprimés en MJ par unité de flux)

| Type de flux    | Flux                  | Unité          | SM     | RI    | PC    | BR    |
|-----------------|-----------------------|----------------|--------|-------|-------|-------|
| Energie directe | Essence               | l              | 41,56  | -     | -     | -     |
|                 | Fioul                 | l              | -      | 40,53 | 45,60 | 45,60 |
|                 | Gasoil                | l              | 42,36  | 40,53 | 45,70 | 45,70 |
|                 | Lubrifiants           | l              | -      | -     | 36,18 | 36,18 |
|                 | Electricité           | kWh            | 5,04   | 10,66 | 10,40 | 10,40 |
|                 | Gaz                   | m <sup>3</sup> | -      | 50,80 | 55,70 | 55,70 |
|                 | Huile Végétale Brute  | kg             | -      | -     | 12,40 | 12,40 |
| Eau             | Eau                   | m <sup>3</sup> | -      | 14,00 | 3,60  | 3,60  |
| Engrais         | Unité N               | kgN            | -      | 55,22 | 54,36 | 54,36 |
|                 | Unité P               | kgP            | -      | 18,15 | 9,80  | 9,80  |
|                 | Unité K               | kgK            | -      | 14,70 | 7,37  | 7,37  |
|                 | Complexe Céréales     | kg             | 10,59  | -     | -     | -     |
|                 | Complexe Coton        | kg             | 10,62  | -     | -     | -     |
|                 | Chaux                 | t              | -      | 0,70  | -     | -     |
|                 | Lisier                | m <sup>3</sup> | -      | 18,30 | 18,30 | 18,30 |
| Effluents       | Fumier                | t              | 84,00  | 8,90  | 8,90  | 8,90  |
|                 | Compost               | t              | -      | 51,50 | 51,50 | 51,50 |
|                 | Fum déposée céréales  | tMS            | 35,00  | -     | -     | -     |
|                 | Fum déposée bas-fonds | tMS            | 132,00 | -     | -     | -     |
|                 | Prairies Tempérées    | kg             | -      | 12,08 | 9,40  | 9,40  |
| Semences        | Prairies Tropicales   | kg             | -      | 11,08 | -     | -     |
|                 | Mais                  | kg             | 0,20   | -     | 0,95  | 0,95  |

**Tableau 1 (suite)**

| Type de flux     | Flux                    | Unité            | SM     | RI     | PC     | BR     |
|------------------|-------------------------|------------------|--------|--------|--------|--------|
|                  | Céréales                | kg               | -      | -      | 8,00   | 8,00   |
|                  | Mil                     | kg               | 1,25   | -      | -      | -      |
|                  | Riz                     | kg               | 8,00   | -      | -      | -      |
|                  | Niébé                   | kg               | 1,25   | -      | -      | -      |
|                  | Pomme de Terre          | kg               | 2,90   | -      | -      | -      |
|                  | Patate                  | kg               | 0,07   | -      | -      | -      |
|                  | Coton                   | kg               | 5,70   | -      | -      | -      |
| Phytosanitaires  | Phytosanitaires         | kgMA             | -      | -      | 282,00 | 282,00 |
|                  | Herbicides Emulsion     | kgMA             | -      | 414,00 | -      | -      |
|                  | Herbicides Poudre       | kgMA             | -      | 260,00 | -      | -      |
|                  | Herbicides Coton        | l                | 182,00 | -      | -      | -      |
|                  | Herbicides Céréales     | l                | 149,00 | -      | -      | -      |
|                  | Fongicides Emulsion     | kgMA             | -      | 267,00 | -      | -      |
|                  | Fongicides Poudre       | kgMA             | -      | 213,00 | -      | -      |
|                  | Insecticides Emulsion   | kgMA             | -      | 359,00 | -      | -      |
|                  | Insecticides            | l                | 32,00  | -      | -      | -      |
|                  | Travail                 | Travail Physique | MJ     | 0,20   | 0,73   | 0,73   |
| Travail Animal   |                         | MJ               | 0,03   | -      | -      | -      |
| Concentrés       | Coques de coton         | kg               | 0,79   | -      | -      | -      |
|                  | Graîne de coton         | kg               | 1,13   | -      | -      | -      |
|                  | Son de céréales         | kg               | 0,20   | -      | -      | -      |
|                  | Conc. type M49m         | kg               | -      | 5,03   | -      | -      |
|                  | Conc. type M49g         | kg               | -      | 5,75   | -      | -      |
|                  | Conc. type B45          | kg               | -      | 5,30   | -      | -      |
|                  | Conc. type B48          | kg               | -      | 5,75   | -      | -      |
|                  | Conc. type B82          | kg               | -      | 5,65   | -      | -      |
|                  | Conc. type B20          | kg               | -      | 5,56   | -      | -      |
|                  | Conc. type B22          | kg               | -      | 4,85   | -      | -      |
|                  | Conc. type SandiSolo    | kg               | -      | 6,49   | -      | -      |
|                  | Conc. type SandiLait    | kg               | -      | 6,23   | -      | -      |
|                  | Conc. type SandiEnergie | kg               | -      | 6,54   | -      | -      |
|                  | Conc. type SandiExcel   | kg               | -      | 6,11   | -      | -      |
|                  | Conc. type VL18         | kg               | -      | -      | 4,02   | 4,02   |
|                  | Tourteaux de Soja       | kg               | -      | -      | 5,76   | 5,76   |
|                  | Tourteaux de coton      | kg               | 0,97   | -      | -      | -      |
|                  | Luzerne Déshydratée     | kg               | -      | -      | 13,19  | 13,19  |
|                  | Pulpes de Betterave     | kg               | -      | -      | 3,02   | 3,02   |
|                  | Fourrages               | Bagasse          | kg     | -      | 0,15   | -      |
| Ensilage Herbe   |                         | kg               | -      | 1,86   | -      | -      |
| Ensilage Maïs    |                         | kgMS             | -      | -      | 1,70   | 1,70   |
| Foin             |                         | kgMS             | -      | 2,18   | 2,33   | 2,33   |
| Paille de Blé    |                         | kgMS             | -      | -      | 0,34   | 0,34   |
| Paille de Canne  |                         | kg               | -      | 636,80 | -      | -      |
| Paille de Riz    |                         | kg               | 0,27   | -      | -      | -      |
| Fanes de Niébé   |                         | kg               | 0,01   | -      | -      | -      |
| Fanes d'arachide |                         | kg               | 0,05   | -      | -      | -      |
| Résidus Céréales |                         | kgMS             | 0,09   | -      | -      | -      |
| Autres Aliments  | Résidus Bas-Fonds       | kgMS             | 0,33   | -      | -      | -      |
|                  | Poudre de lait          | kg               | -      | 45,98  | 43,3   | 43,3   |
| Animaux          | Mélasses                | kg               | -      | 2,81   | -      | -      |
|                  | Bœuf de Labour          | kg vif           | 0,80   | -      | -      | -      |
|                  | Taureaux                | kg vif           | 0,80   | -      | -      | -      |
|                  | Vaches                  | kg vif           | 0,80   | -      | -      | -      |

**Tableau 1** (suite)

| Type de flux    | Flux                      | Unité               | SM    | RI     | PC    | BR    |
|-----------------|---------------------------|---------------------|-------|--------|-------|-------|
| Bâtiments       | Veaux mâles               | kg vif              | 0,80  | -      | -     | -     |
|                 | Veaux femelles            | kg vif              | 0,80  | -      | -     | -     |
|                 | Génisses                  | kg vif              | 0,80  | 42,62  | -     | 9,08  |
|                 | Taurillons                | kg vif              | 0,80  | -      | -     | -     |
|                 | Bâtiment dur              | m <sup>2</sup>      | 31,60 | 84,86  | 31,56 | -     |
|                 | Stabulation libre         | m <sup>2</sup>      | -     | -      | -     | 31,56 |
|                 | Stabulation logettes      | m <sup>2</sup>      | -     | -      | -     | 42,03 |
|                 | Etable bois               | m <sup>2</sup>      | 0,00  | -      | -     | -     |
|                 | Etable banco              | m <sup>2</sup>      | 0,00  | -      | -     | -     |
|                 | Salle de Traitement       | m <sup>2</sup>      | -     | 84,86  | 56,17 | 56,17 |
|                 | Silo Couloir              | m <sup>2</sup>      | -     | -      | 11,75 | 11,75 |
|                 | Hangar à foin             | m <sup>2</sup>      | 31,60 | 22,57  | 38,56 | 38,56 |
|                 | Hangar en bois            | m <sup>2</sup>      | 0     | -      | -     | -     |
|                 | Hangar en banco           | m <sup>2</sup>      | 0     | -      | -     | -     |
| Bâtiments       | Fosse à lisier            | m <sup>3</sup>      | 21,48 | 8,186  | 27,94 | 27,94 |
|                 | Fosse sans consolidation  | m <sup>3</sup>      | -     | -      | -     | -     |
|                 | Fumière                   | m <sup>2</sup>      | -     | 10,17  | 11,87 | 11,87 |
|                 | Retenue collinaire        | m <sup>3</sup>      | -     | 16,68  | -     | -     |
|                 | Parc en bois              | m lin               | 0     | -      | -     | -     |
| Matériel        | Parc en fer barbelé       | m lin               | 0,11  | -      | -     | -     |
|                 | Tracteurs                 | kg.an <sup>-1</sup> | 95,70 | 98,60  | -     | 51,90 |
|                 | Automotrices              | kg.an <sup>-1</sup> | 83,50 | 86,10  | -     | 48,10 |
|                 | Travail du sol, Récolte   | kg.an <sup>-1</sup> | 99,20 | 101,80 | -     | 40,50 |
|                 | Epandeurs, Pulvérisateurs | kg.an <sup>-1</sup> | 95,40 | 98,00  | -     | 42,40 |
|                 | Véhicules                 | kg.an <sup>-1</sup> | 83,50 | 86,10  | -     | 48,10 |
|                 | Autres intrants           | kg.an <sup>-1</sup> | 95,40 | 98,00  | -     | 51,10 |
| Autres intrants | Sels et Minéraux          | €                   | 0,99  | 0,11   | 0,11  | 0,11  |
|                 | Frais Vétos               | €                   | 0,01  | 7,60   | 7,48  | 7,48  |
|                 | Frais d'Elevage           | €                   | 0,01  | 5,07   | 4,99  | 4,99  |
|                 | Plastiques                | Kg                  | -     | 94,68  | 87,00 | 87,00 |

## 2.2. Coefficients énergétiques bruts correspondant à l'énergie calorifique des produits animaux et végétaux<sup>4</sup>

Les coefficients énergétiques bruts des produits végétaux et animaux correspondent à leur énergie calorifique. Ils représentent donc la quantité de chaleur produite au cours de la combustion complète d'un gramme de composé organiques dans un calorimètre en présence d'oxygène. Les valeurs pour les différents produits végétaux sont issues des tables d'alimentation de l'INRA (INRA, 2007) pour la plupart des espèces tempérées, des tables d'alimentation tropicales actuellement mis en place (Feedipedia, 2012) ou de valeurs obtenues en laboratoire par le CIRAD pour les espèces tropicales. Les valeurs concernant les produits

<sup>4</sup> Aucune des exploitations étudiées dans les quatre territoires ne présentaient de production d'énergie renouvelable. En ce sens, les coefficients énergétiques bruts pour les différentes énergies renouvelables n'ont pas été calculés

animaux sont elles principalement extraites de la méthode PLANETE (Risoud et Théobald, 1999) à l'exception du lait dont la valeur en énergie brute a été recalculée sur chaque exploitation à partir de sa composition moyenne selon l'équation suivante :

$$\text{Energie brute du lait (MJ.l}^{-1}\text{)} = \frac{(TB \times 38,6 + TP \times 25,4 + 782,2)}{1000} \times d$$

où :

TB : Taux butyreux moyen (en g.kg<sup>-1</sup>),

TP : Taux protéique moyen (en g.kg<sup>-1</sup>),

d : densité du lait (estimée à 1,030 kg.l<sup>-1</sup>)

Les différents coefficients énergétiques bruts utilisés sont ainsi reportés dans le tableau 2.

**Tableau 2.** Coefficients énergétiques bruts des produits animaux et végétaux manipulés sur les exploitations pour les quatre territoires étudiés (exprimés en MJ par unité de produit)

| Type de Flux | Flux                                    | Unité            | ML    | RI    | PC    | BR    |       |
|--------------|---|------------------|-------|-------|-------|-------|-------|
| Grain        | Arachide                                | kg               | 10,55 | -     | -     | -     |       |
|              | Blé                                     | kg               | -     | -     | 15,80 | 15,80 |       |
|              | Coton                                   | kg               | 18,06 | -     | -     | -     |       |
|              | Maïs                                    | kg               | 16,14 | -     | -     | -     |       |
|              | Mil                                     | kg               | 16,46 | -     | -     | -     |       |
|              | Niébé                                   | kg               | 16,58 | -     | -     | -     |       |
|              | Riz                                     | kg               | 15,73 | -     | -     | -     |       |
|              | Sorgho                                  | kg               | 16,31 | -     | -     | -     |       |
| Tubercules   | Pomme de Terre                          | kg               | 3,35  | -     | -     | -     |       |
|              | Patate                                  | kg               | 4,52  | -     | -     | -     |       |
| Résidus      | Bagasse                                 | kg               | -     | 8,47  | -     | -     |       |
|              | Paille de Blé                           | kg               | -     | -     | 15,98 | 15,98 |       |
|              | Paille de Canne                         | kg               | -     | 16,31 | -     | -     |       |
|              | Paille de Maïs                          | kg               | 13,93 | -     | -     | -     |       |
|              | Paille de Sorgho                        | kg               | 18,36 | -     | -     | -     |       |
|              | Paille de Mil                           | kg               | 17,69 | -     | -     | -     |       |
|              | Paille de Riz                           | kg               | 13,87 | -     | -     | -     |       |
|              | Fanes d'Arachide                        | kg               | 17,92 | -     | -     | -     |       |
|              | Fanes de Niébé                          | kg               | 18,02 | -     | -     | -     |       |
|              | Fanes de PdT                            | kg               | 16,83 | -     | -     | -     |       |
|              | Fanes de Patate                         | kg               | 16,83 | -     | -     | -     |       |
|              | Tiges de Coton                          | kg               | 17,96 | -     | -     | -     |       |
|              | Résidus céréales pâturés à l'extérieur  | kgMS             | 13,80 | -     | -     | -     |       |
|              | Résidus bas-fonds pâturés à l'extérieur | kgMS             | 14,35 | -     | -     | -     |       |
|              | Ensilage                                | Ensilage d'Herbe | kg    | -     | 4,64  | -     | -     |
|              |   | Ensilage d'Herbe | kgMS  | -     | -     | 18,83 | 18,83 |
|              |   | Ensilage de Maïs | kgMS  | -     | -     | 18,63 | 18,63 |
|              |   | Brome            | kg    | -     | 3,45  | -     | -     |
|              |   | Chloris          | kg    | -     | 4,72  | -     | -     |
| Dactyle      |   | kg               | -     | 6,34  | -     | -     |       |
| Kikuyu       |   | kg               | -     | 3,79  | -     | -     |       |
| RGD          |   | kg               | -     | 4,91  | -     | -     |       |



**Tableau 2** (suite)

| Type de Flux   | Flux                      | Unité          | ML    | RI     | PC     | BR     |   |
|----------------|---------------------------|----------------|-------|--------|--------|--------|---|
| Foin           | Foin                      | kgMS           | -     | 17,607 | 18,50  | 18,50  |   |
| Fourrages Vert | Dactyle                   | kg             | -     | 3,34   | -      | -      |   |
|                | Kikuyu                    | kg             | -     | 2,22   | -      | -      |   |
|                | RGD                       | kg             | -     | 3,16   | -      | -      |   |
|                | Brome                     | kg             | -     | 3,43   | -      | -      |   |
|                | Chloris                   | kg             | -     | 4,58   | -      | -      |   |
|                | Prairies pâturées         | kgMS           | -     | -      | 18,41  | 18,41  |   |
| Concentrés     | Parcours naturels pâturés | kgMS           | 17,46 | -      | -      | -      |   |
|                | Coques de coton           | kg             | 14,66 | -      | -      | -      |   |
|                | Graine de coton           | kg             | 21,55 | -      | -      | -      |   |
|                | Luzerne Déshydratée       | kg             | -     | -      | 16,30  | 16,30  |   |
|                | Pulpes de Betterave       | kg             | -     | -      | 15,14  | 15,14  |   |
|                | Son de céréales           | kg             | 18,73 | -      | -      | -      |   |
|                | Tourteaux de coton        | kg             | 17,13 | -      | -      | -      |   |
|                | Tx de Soja                | kg             | -     | -      | 17,23  | 17,23  |   |
|                | Conc. type B20            | kg             | -     | 12,47  | -      | -      |   |
|                | Conc. type B22            | kg             | -     | 12,12  | -      | -      |   |
|                | Conc. type B45            | kg             | -     | 12,69  | -      | -      |   |
|                | Conc. type B48            | kg             | -     | 13,03  | -      | -      |   |
|                | Conc. type B82            | kg             | -     | 12,63  | -      | -      |   |
|                | Conc. type M49g           | kg             | -     | 12,91  | -      | -      |   |
|                | Conc. type M49m           | kg             | -     | 12,70  | -      | -      |   |
|                | Conc. type SandiEnergie   | kg             | -     | 12,93  | -      | -      |   |
|                | Conc. type SandiExcel     | kg             | -     | 12,11  | -      | -      |   |
|                | Conc. type SandiLait      | kg             | -     | 13,31  | -      | -      |   |
|                | Conc. type SandiLevure    | kg             | -     | 12,63  | -      | -      |   |
|                | Conc. type SandiSolo      | kg             | -     | 12,27  | -      | -      |   |
|                | Conc. type VL18           | kg             | -     | -      | 16,34  | 16,34  |   |
|                | Animaux                   | Bœuf de Labour | kg    | 9,19   | -      | -      | - |
|                |                           | Génisses       | kg    | 9,08   | 9,08   | -      | - |
| Taureaux       |                           | kg             | 9,19  | -      | -      | -      |   |
| Taurillons     |                           | kg             | 9,08  | -      | -      | -      |   |
| Vaches         |                           | kg             | 9,08  | 9,08   | -      | -      |   |
| Veaux femelles |                           | kg             | 6,11  | -      | -      | -      |   |
| Veaux mâles    |                           | kg             | 6,11  | -      | -      | -      |   |
| Effluents      | Compost                   | t              | -     | 345,31 | 345,31 | 345,31 |   |
|                | Fumier                    | t              | -     | 278,60 | 278,60 | 278,60 |   |
| Autres         |                           | kgMS           | 17,85 | -      | -      | -      |   |
|                | Lisier de bovin           | t              | -     | 68,67  | 68,67  | 68,67  |   |
|                | Mélasse                   | kg             | -     | -      | 11,02  | 11,02  |   |
|                | Poudre de Lait            | t              | -     | 22,66  | 22,66  | 22,66  |   |

### 2.3. Coefficients énergétiques liés au travail

Les coefficients énergétiques liés au travail représentent l'énergie dépensée lors d'une activité physique. Compte tenu de la simplification du travail qui se limite essentiellement à la conduite de tracteur, la traite et la manipulation manuelle des aliments ainsi qu'à l'absence de travail animal dans les systèmes de l'Ile de la Réunion, du Poitou-Charentes et de Bretagne,

les coefficients ont été standardisés pour ces territoires (Tableau 3) et sont issus de la littérature (Vaz et al., 2005).

**Tableau 3** Coefficients énergétiques liés au travail utilisés sur les systèmes de l’Ile de la Réunion, Poitou-Charentes et Bretagne (en MJ par heure de travail fourni)

| Travaux                                 | Unité | Homme | Femme |
|---|-------|-------|-------|
| Conduite d’un véhicule                  | h     | 0,636 | 0,509 |
| Traite                                  | h     | 0,864 | 0,691 |
| Distribution manuelle de l’alimentation | h     | 0,904 | 0,723 |
| Manipulation manuelle de la biomasse    | h     | 1,506 | 1,205 |
| Fauche manuelle                         | h     | 1,803 | 1,442 |

Dans le cas du Mali Sud, compte tenu de la diversité des travaux sur les exploitations, des personnes réalisant ces travaux et de la grande variabilité des coefficients présents dans la littérature, nous avons recalculé les coefficients pour les 33 travaux listés (Tableau 4).

**Tableau 4** Coefficients énergétiques liés au travail humain utilisés sur les systèmes du Mali Sud (exprimés en MJ par heure de travail fourni)

| Travaux                            | Unité | Homme | Femme | Enfant |
|------------------------------------|-------|-------|-------|--------|
| Conduite des animaux au pâturage   | h     | 0,650 | 0,520 | 0,390  |
| Conduite d'un véhicule             | h     | 0,650 | -     | -      |
| Buttage avec animaux               | h     | 0,754 | 0,603 | 0,452  |
| Distribution manuelle des aliments | h     | 0,754 | 0,603 | 0,452  |
| Transport avec moto                | h     | 0,754 | 0,603 | 0,452  |
| Pilage Poudre de Néré              | h     | -     | 0,645 | -      |
| Récolte des résidus                | h     | 0,806 | 0,645 | 0,484  |
| Traitement manuel                  | h     | 0,806 | 0,645 | 0,484  |
| Apport Complexe/Urée               | h     | 0,858 | 0,686 | 0,515  |
| Egrenage au moulin                 | h     | 0,858 | 0,686 | 0,515  |
| Implantation Patate                | h     | 0,858 | 0,686 | 0,515  |
| Nettoyage des parcs                | h     | 0,858 | 0,686 | 0,515  |
| Récolte des résidus paille         | h     | 0,858 | 0,686 | 0,515  |
| Semis avec animaux                 | h     | 0,858 | 0,686 | 0,515  |
| Transport avec animaux             | h     | 0,858 | 0,686 | 0,515  |
| Labour avec animaux                | h     | 0,910 | 0,728 | 0,546  |
| Nettoyage des champs               | h     | 0,910 | 0,728 | 0,546  |
| Récolte des grains                 | h     | 0,962 | 0,769 | 0,577  |
| Sarclage avec animaux              | h     | 0,962 | 0,769 | 0,577  |
| Traite                             | h     | 0,962 | 0,769 | 0,577  |
| Abreuvement des animaux            | h     | 1,014 | 0,811 | 0,608  |
| Apport Fumure organique            | h     | 1,066 | 0,853 | 0,639  |
| Pilage Céréales                    | h     | -     | 0,853 | -      |
| Récolte des patates                | h     | 1,066 | 0,853 | 0,639  |
| Récolte des PdT                    | h     | 1,170 | 0,936 | 0,702  |
| Arrosage                           | h     | 1,221 | 0,977 | 0,733  |
| Implantation PdT                   | h     | 1,221 | 0,977 | 0,733  |
| Sarclage manuel                    | h     | 1,273 | 1,019 | 0,764  |
| Transport à pied avec charge       | h     | 1,273 | 1,019 | 0,764  |
| Implantation du Riz                | h     | 1,377 | 1,102 | 0,826  |
| Buttage manuel                     | h     | 1,481 | 1,185 | 0,889  |
| Labour manuel                      | h     | 1,481 | 1,185 | 0,889  |
| Semis Manuel                       | h     | 1,481 | 1,185 | 0,889  |

Le recalcul de ces coefficients a obéi à une méthodologie en deux étapes. Tout d’abord, un degré de pénibilité considéré comme corrélé au niveau de dépense énergétique et similaire au Physical Activity Ratio proposé par [Loake \(2001\)](#) a été établi pour chacun des 33 travaux. Les valeurs de degré de pénibilité résultent d’enquêtes réalisées auprès de 4 chefs d’exploitation. L’enquête<sup>5</sup> consistait à classer les travaux selon une échelle indiquant le degré de pénibilité du travail de 1 (facile) à 5 (difficile). Lorsque le même degré de pénibilité était annoncé par au moins 3 des 4 chefs d’exploitation (cas de 11 travaux sur 33), la valeur affectée correspond à la valeur la plus prononcée. Dans les autres cas, nous avons considéré la moyenne des valeurs annoncées. Dans une seconde étape, le coefficient énergétique physique humain pour chaque travail a été calculée selon une valeur pondérée entre les valeurs minimales (0,703 MJ.h<sup>-1</sup> pour la conduite d’engins motorisés) et maximales (1,481 MJ.h<sup>-1</sup> pour le labour manuel) trouvées dans la littérature ([Passmore and Durnin, 1955](#)) correspondant à des degrés de pénibilité respectifs de 1 et 5. Les coefficients énergétiques physiques s’élèvent à 75% pour une femme et 85% pour un enfant de la valeur du coefficient pour un homme. Ces ratios ont été considérés à partir des besoins énergétiques journaliers moyens pour une femme et un enfant âgé de moins de 14 ans ([FAO and OMS, 1973](#)).

Les coefficients énergétiques liés au travail pour la traction animale sont issus de la littérature pour le transport ([Lawrence and Stibbards, 1990](#)) et le labour ([Fall et al., 1997](#)) et calculés pour les autres travaux selon le même ratio énergie dépensé que pour les valeurs humaines. Pour exemple, comme pour le travail humain, le coefficient énergétique animal pour le buttage s’élève à 83% de celui du labour. Les valeurs sont reportées dans le tableau 5.

**Tableau 5** Coefficients énergétiques liés au travail animal utilisé sur les systèmes du Mali Sud (exprimés en MJ par heure de travail fourni)

| Travaux   | Unité | Bovins             | Ânes               |
|-----------|-------|--------------------|--------------------|
| Buttage   | h     | 2,490              | -                  |
| Labour    | h     | 3,000              | -                  |
| Sarclage  | h     | 3,180              | -                  |
| Semis     | h     | 2,820              | -                  |
| Transport | km    | 0,416 <sup>a</sup> | 0,208 <sup>a</sup> |

<sup>a</sup> Recalculé selon une charge moyenne estimée de 160 kg pour les bovins et de 80kg pour les ânes

## 2.4. Coefficients énergétiques solaires

Les coefficients énergétiques solaires sont basés sur le rayonnement photosynthétiquement actif (Photosynthetically Active Radiation, PAR) correspondant à la part du rayonnement

<sup>5</sup> Une version originale de la feuille utilisée pour ces enquêtes est reportée en Annexe VII

solaire reçu réellement utilisée pour la photosynthèse. Il est communément considéré comme la part du rayonnement solaire dont les longueurs d'onde s'étendent de 400 à 700 nm. Varlet-Grancher et al. (1989) ont reporté dans une revue bibliographique que cette part pouvait varier de 46 à 51% selon le type d'appareillage utilisé pour la mesure ou l'espèce cultivée. Compte tenu du manque de données pour certains territoires sur la composition exacte de l'assolement et des espèces cultivées, une valeur simplifiée de 50% du rayonnement solaire global a été considéré (Bonnet and Combarous, 1996).

La valeur du rayonnement solaire global est issue de différentes bases de données ou logiciels, aucune mesure directe du rayonnement n'ayant été effectuée. La valeur pour le Mali Sud est issue de l'outil SolarGIS (<http://solargis.info>), celle de l'Ile de la Réunion provient des bases de données MétéoFrance (<http://climatheque.meteo.fr>) alors que les valeurs Poitou-Charentes et Bretagne sont issues de la base de données climatologiques « Climatik » de l'INRA (<https://intranet.inra.fr/climatik>) (Tableau 6).

**Tableau 6** Coefficients énergétiques solaires utilisé dans les quatre territoires

| <b>Territoire</b> | <b>Coefficient énergétique (<math>\times 10^7 MJ.ha^{-1}</math>)</b> |
|-------------------|--|
| Mali Sud          | 3.87   |
| Ile de la Réunion | 3.15   |
| Poitou-Charentes  | 2.32   |
| Bretagne          | 2.11   |

### 3. Calcul des Unit Emergy Values

Une partie des Unit Emergy Values (UEVs) sont issus de la base NEAD (National Environmental Accounting Database) (University of Florida, 2003). Basée sur des bilans émergétiques nationaux, cette base fournit des informations détaillées pour 134 pays et propose un certain nombre d'UEVs adaptées à chaque contexte. Elle représente en cela un intérêt particulier pour l'adaptation d'UEVs adaptées aux territoires. Cependant, cette base est encore incomplète notamment du fait de l'échelle d'analyse. Elle catégorise ainsi certaines ressources (e.g. production agricoles, métaux) et ne fournit donc pas d'UEV spécifiques à chaque ressource. De plus, l'Ile de la Réunion n'a pas été étudiée. Une autre partie des UEVs sont donc issus de références issues de la littérature et ont été choisies par rapprochement du contexte ou du type de ressources. Enfin une dernière partie des UEVs est issue de nos propres calculs à partir de bilans émergétiques spécifiques. Le tableau 6 reporte l'ensemble de ces UEVs par territoire. Les calculs plus précis des UEVs issus de nos propres calculs sont reportés en Annexe VIII.

**Tableau 6** Unit Energy Values (UEVs) utilisées sur les quatre territoires

| Item   | ML                     |                        |      | RI       |                      |      | PC/BR    |                      |      |
|--|------------------------|------------------------|------|----------|----------------------|------|----------|----------------------|------|
|  | UEV                    | Unité                  | Refs | UEV      | Unité                | Refs | UEV      | Unité                | Refs |
| <i>Ressources naturelles renouvelables</i>     |                        |                        |      |          |                      |      |          |                      |      |
| Rayonnement Solaire                            | 1.00E+00               | sej.J <sup>-1</sup>    | [1]  | 1.00E+00 | sej.J <sup>-1</sup>  | [1]  | 1.00E+00 | sej.J <sup>-1</sup>  | [1]  |
| Vent   | 2.52E+03               | sej.J <sup>-1</sup>    | [2]  | 2.52E+03 | sej.J <sup>-1</sup>  | [2]  | 2.52E+03 | sej.J <sup>-1</sup>  | [2]  |
| Rain   | 3.06E+04               | sej.J <sup>-1</sup>    | [2]  | 3.06E+04 | sej.J <sup>-1</sup>  | [2]  | 3.06E+04 | sej.J <sup>-1</sup>  | [2]  |
| <i>Ressources naturelles non-renouvelables</i> |                        |                        |      |          |                      |      |          |                      |      |
| Erosion  | 1.24E+05               | sej.J <sup>-1</sup>    | [3]  | 1.24E+05 | sej.J <sup>-1</sup>  | [3]  | 1.24E+05 | sej.J <sup>-1</sup>  | [3]  |
| Eau du sol                                     | 2.55E+05               | sej.J <sup>-1</sup>    | [4]  | 2.55E+05 | sej.J <sup>-1</sup>  | [4]  | 2.55E+05 | sej.J <sup>-1</sup>  | [4]  |
| <i>Intrants issus de l'économie</i>            |                        |                        |      |          |                      |      |          |                      |      |
| Eau réseau                                     | -                      |                        |      | 5.12E+05 | sej.g <sup>-1</sup>  | [5]  | 5.12E+05 | sej.g <sup>-1</sup>  | [5]  |
| Carburants                                     | 1.11E+05               | sej.J <sup>-1</sup>    | [6]  | 1.11E+05 | sej.J <sup>-1</sup>  | [6]  | 1.11E+05 | sej.J <sup>-1</sup>  | [6]  |
| Électricité                                    | 8.40E+04               | sej.J <sup>-1</sup>    | [7]  | 1.48E+05 | sej.J <sup>-1</sup>  | [7]  | 6.21E+04 | sej.J <sup>-1</sup>  | [7]  |
| Effluents                                      | 9.61E+12               | sej.kgMS <sup>-1</sup> | [7]  | 1.10E+12 | sej.kg <sup>-1</sup> | [7]  | 6.51E+11 | sej.kg <sup>-1</sup> | [7]  |
| Fertilisation N                                | 4.05E+13               | sej.kg <sup>-1</sup>   | [8]  | 4.08E+13 | sej.kg <sup>-1</sup> | [8]  | 4.05E+13 | sej.kg <sup>-1</sup> | [8]  |
| Fertilisation P                                | 3.70E+13               | sej.kg <sup>-1</sup>   | [8]  | 3.73E+13 | sej.kg <sup>-1</sup> | [8]  | 3.70E+13 | sej.kg <sup>-1</sup> | [8]  |
| Fertilisation K                                | 2.92E+12               | sej.kg <sup>-1</sup>   | [8]  | 3.26E+12 | sej.kg <sup>-1</sup> | [8]  | 2.92E+12 | sej.kg <sup>-1</sup> | [8]  |
| Urée   | 6.62E+12               | sej.kg <sup>-1</sup>   | [9]  | 6.96E+12 | sej.kg <sup>-1</sup> | [9]  | 6.62E+12 | sej.kg <sup>-1</sup> | [9]  |
| Herbicides                                     | 2.48E+13               | sej.kg <sup>-1</sup>   | [10] | 2.51E+13 | sej.kg <sup>-1</sup> | [7]  | 2.48E+13 | sej.kg <sup>-1</sup> | [10] |
| Fongicides                                     | 2.48E+13               | sej.kg <sup>-1</sup>   | [10] | 2.51E+13 | sej.kg <sup>-1</sup> | [7]  | 2.48E+13 | sej.kg <sup>-1</sup> | [10] |
| Insecticides                                   | 2.48E+13               | sej.kg <sup>-1</sup>   | [10] | 2.51E+13 | sej.kg <sup>-1</sup> | [7]  | 2.48E+13 | sej.kg <sup>-1</sup> | [10] |
| Semences de Coton                              | 68.03E+11 <sup>a</sup> | sej.kg <sup>-1</sup>   | [11] | -        |                      | [7]  | -        | sej.kg <sup>-1</sup> | [10] |
| Semences de Niébé                              | 4.28E+11 <sup>a</sup>  | sej.kg <sup>-1</sup>   | [7]  | -        |                      | [7]  | -        | sej.kg <sup>-1</sup> | [10] |
| Semences de Riz                                | 27.31E+11 <sup>a</sup> | sej.kg <sup>-1</sup>   | [7]  | -        |                      | [7]  | -        | sej.kg <sup>-1</sup> | [10] |
| Semences de Pomme de Terre                     | 7.12E+11 <sup>b</sup>  | sej.kg <sup>-1</sup>   | [7]  | -        |                      | [7]  | -        | sej.kg <sup>-1</sup> | [10] |
| Semences de Patate Douce                       | 5.96E+11 <sup>b</sup>  | sej.kg <sup>-1</sup>   | [7]  | -        |                      | [7]  | -        | sej.kg <sup>-1</sup> | [10] |
| Semences de Maïs                               | 17.88E+11 <sup>a</sup> | sej.kg <sup>-1</sup>   | [7]  | 1.82E+04 | sej.J <sup>-1</sup>  | [12] | 1.82E+04 | sej.J <sup>-1</sup>  | [12] |
| Semences de Mil                                | 24.96E+11 <sup>a</sup> | sej.kg <sup>-1</sup>   | [7]  | -        |                      | [7]  | -        | sej.kg <sup>-1</sup> | [10] |
| Semences de Sorgho                             | 32.49E+11 <sup>a</sup> | sej.kg <sup>-1</sup>   | [7]  | -        |                      | [7]  | -        | sej.kg <sup>-1</sup> | [10] |
| Semences de Blé                                | -                      |                        |      | 7.91E+04 | sej.J <sup>-1</sup>  | [13] | 7.91E+04 | sej.J <sup>-1</sup>  | [13] |
| Semences Prairies                              | -                      |                        |      | 2.26E+05 | sej.J <sup>-1</sup>  | [12] | 2.26E+05 | sej.J <sup>-1</sup>  | [12] |
| Coques de coton                                | 22.71E+12              | sej.kg <sup>-1</sup>   | [7]  | -        |                      | [7]  | -        | sej.kg <sup>-1</sup> | [10] |

<sup>a</sup>Basé sur la transforméité des grains, <sup>b</sup>Basé sur la transforméité des tubercules

References : [1] Odum(1996); [2] Odum et al. (2000); [3] Takahashi and Ortega (2010); [4] Bastianoni and Marchettini (2000); [5] La Rosa et al. (2008); [6] Brandt-Williams (2002); [7] Calcul personnel; [8] Cavalett et al. (2006); [9] Cuadra and Rydberg (2006); [10] Cavalett and Ortega (2009); [11] Batista et al. (2008); [12] Rótololo et al. (2007); [13] Dong et al. (2008); [14] Castellini et al. (2006); [15] Uligati et al. (1994); [16] Brown and Bardi (2001); [17] Cuadra and Rydberg (2006); [18] University of Florida (2003); [19] Ortega (1998)

Tableau 6 (suite)

| Item                                | ML        |                        |      | RI       |                      |      | PC/BR    |                        |      |
|-------------------------------------|-----------|------------------------|------|----------|----------------------|------|----------|------------------------|------|
|                                     | UEV       | Unité                  | Refs | UEV      | Unité                | Refs | UEV      | Unité                  | Refs |
| <i>Intrants issus de l'économie</i> |           |                        |      |          |                      |      |          |                        |      |
| Graine de coton                     | 28.38E+12 | sej.kg <sup>-1</sup>   | [71] | -        | -                    | -    | -        | -                      | -    |
| Tourteaux de coton                  | 4.11E+13  | sej.kg <sup>-1</sup>   | [71] | -        | -                    | -    | 1.82E+09 | sej.g <sup>-1</sup>    | [14] |
| Tourteaux de Soja                   | -         | -                      | -    | -        | -                    | -    | 1.51E+09 | sej.g <sup>-1</sup>    | [71] |
| Concentrés commerciaux              | -         | -                      | -    | -        | -                    | -    | -        | -                      | -    |
| B82                                 | -         | -                      | -    | 2.31E+09 | sej.g <sup>-1</sup>  | [71] | -        | -                      | -    |
| B48                                 | -         | -                      | -    | 2.49E+09 | sej.g <sup>-1</sup>  | [71] | -        | -                      | -    |
| B45                                 | -         | -                      | -    | 2.68E+09 | sej.g <sup>-1</sup>  | [71] | -        | -                      | -    |
| B22                                 | -         | -                      | -    | 2.85E+09 | sej.g <sup>-1</sup>  | [71] | -        | -                      | -    |
| B20                                 | -         | -                      | -    | 2.44E+09 | sej.g <sup>-1</sup>  | [71] | -        | -                      | -    |
| SandlExcel                          | -         | -                      | -    | 2.26E+09 | sej.g <sup>-1</sup>  | [71] | -        | -                      | -    |
| SandlEnergie                        | -         | -                      | -    | 2.27E+09 | sej.g <sup>-1</sup>  | [71] | -        | -                      | -    |
| SandlEuvre                          | -         | -                      | -    | 2.21E+09 | sej.g <sup>-1</sup>  | [71] | -        | -                      | -    |
| SandlSolo                           | -         | -                      | -    | 2.66E+09 | sej.g <sup>-1</sup>  | [71] | -        | -                      | -    |
| SandlLit                            | -         | -                      | -    | 2.73E+09 | sej.g <sup>-1</sup>  | [71] | -        | -                      | -    |
| M49 granulé                         | -         | -                      | -    | 2.53E+09 | sej.g <sup>-1</sup>  | [71] | -        | -                      | -    |
| M49 mash                            | -         | -                      | -    | 2.78E+09 | sej.g <sup>-1</sup>  | [71] | -        | -                      | -    |
| Pulpes de betteraves                | -         | -                      | -    | -        | -                    | -    | 9.64E+12 | sej.kg <sup>-1</sup>   | [15] |
| Son de céréales                     | 5.56E+12  | sej.kg <sup>-1</sup>   | [71] | -        | -                    | -    | -        | -                      | -    |
| Bagasse                             | -         | -                      | -    | 3.34E+11 | sej.kg <sup>-1</sup> | [71] | -        | -                      | -    |
| Luzerne déshydratée                 | -         | -                      | -    | -        | -                    | -    | 2.63E+12 | sej.kg <sup>-1</sup>   | [14] |
| Ensilage d'Herbe                    | -         | -                      | -    | 1.34E+12 | sej.kg <sup>-1</sup> | [71] | -        | -                      | -    |
| Ensilage de Maïs                    | -         | -                      | -    | -        | -                    | -    | 6.33E+11 | sej.kgMS <sup>-1</sup> | [71] |
| Foin                                | -         | -                      | -    | 1.34E+12 | sej.kg <sup>-1</sup> | [71] | 3.03E+08 | sej.g <sup>-1</sup>    | [14] |
| Paille de Canne                     | -         | -                      | -    | 2.66E+12 | sej.kg <sup>-1</sup> | [71] | -        | -                      | -    |
| Paille de Blé                       | -         | -                      | -    | -        | -                    | -    | 9.35E+11 | sej.kgMS <sup>-1</sup> | [71] |
| Paille de Riz                       | 9.10E+11  | sej.kg <sup>-1</sup>   | [71] | -        | -                    | -    | -        | -                      | -    |
| Fanes de Niébé                      | 32.11E+11 | sej.kg <sup>-1</sup>   | [71] | -        | -                    | -    | -        | -                      | -    |
| Fanes d'Arachide                    | 43.75E+11 | sej.kg <sup>-1</sup>   | [71] | -        | -                    | -    | -        | -                      | -    |
| Résidus de céréales                 | 5.83E+11  | sej.kg <sup>-1</sup>   | [71] | -        | -                    | -    | -        | -                      | -    |
| Résidus de bas-fonds                | 10.46E+11 | sej.kg <sup>-1</sup>   | [71] | -        | -                    | -    | -        | -                      | -    |
| Biomasse de Parcours                | 6.38E+11  | sej.kgMS <sup>-1</sup> | [71] | -        | -                    | -    | -        | -                      | -    |

<sup>a</sup>Basé sur la transformabilité des grains, <sup>b</sup>Basé sur la transformabilité des tubercules

References : [1] Odum(1996); [2] Odum et al. (2000); [3] Takahashi and Ortega (2010); [4] Bastianoni and Marchettini (2000); [5] La Rosa et al. (2008); [6] Brandt-Williams (2002); [7] Calcul personnel; [8] Cavallett et al. (2006); [9] Cuadra and Rydberg (2006); [10] Cavallett and Ortega (2009); [11] Batista et al. (2008); [12] Rótoló et al. (2007); [13] Dong et al. (2008); [14] Castellini et al. (2006); [15] Ugliati et al. (1994); [16] Brown and Bardi (2001); [17] Cuadra and Rydberg (2006); [18] University of Florida (2003); [19] Ortega (1998)

**Tableau 6 (suite)**

| Item                                | ML       |                        |      | RI       |                      |      | PC/BR    |                      |      |
|-------------------------------------|----------|------------------------|------|----------|----------------------|------|----------|----------------------|------|
|                                     | UEV      | Unité                  | Refs | UEV      | Unité                | Refs | UEV      | Unité                | Refs |
| <i>Intrants issus de l'économie</i> |          |                        |      |          |                      |      |          |                      |      |
| Mélasse                             | -        |                        |      | 9.57E+12 | sej.kg <sup>-1</sup> | [7]  | -        |                      |      |
| Poudre de Lait                      | -        |                        |      | 5.42E+13 | sej.kg <sup>-1</sup> | [7]  | 2.40E+13 | sej.kg <sup>-1</sup> | [7]  |
| Minéraux                            | 2.46E+09 | sej.g <sup>-1</sup>    | [2]  | 2.46E+09 | sej.g <sup>-1</sup>  | [2]  | 2.46E+09 | sej.g <sup>-1</sup>  | [2]  |
| Plastiques                          | 3.20E+12 | sej.kg <sup>-1</sup>   | [16] | 3.20E+12 | sej.kg <sup>-1</sup> | [16] | 3.20E+12 | sej.kg <sup>-1</sup> | [16] |
| Bâtiments - Banco                   | 5.21E+08 | sej.J <sup>1</sup>     | [7]  | -        |                      |      | -        |                      |      |
| Bâtiment - Bois                     | 8.19E+03 | sej.J <sup>1</sup>     | [9]  | -        |                      |      | -        |                      |      |
| Bâtiments - Béton                   | 1.54E+09 | sej.g <sup>-1</sup>    | [12] | 1.54E+09 | sej.g <sup>-1</sup>  | [12] | 1.54E+09 | sej.g <sup>-1</sup>  | [12] |
| Bâtiments - Acier                   | 1.13E+10 | sej.g <sup>-1</sup>    | [10] | 1.13E+10 | sej.g <sup>-1</sup>  | [10] | 1.13E+10 | sej.g <sup>-1</sup>  | [10] |
| Dépréciation du matériel            | 1.13E+10 | sej.g <sup>-1</sup>    | [10] | 1.13E+10 | sej.g <sup>-1</sup>  | [10] | 1.13E+10 | sej.g <sup>-1</sup>  | [10] |
| Animaux                             | 3.18E+13 | sej.kg <sup>-1</sup>   | [7]  | 2.92E+13 | sej.kg <sup>-1</sup> | [7]  | -        |                      |      |
| Services                            | -        |                        |      | -        |                      |      | -        |                      |      |
| Frais vétérinaires                  | 7.58E+10 | sej.FCFA <sup>-1</sup> | [18] | 2.89E+12 | sej.€ <sup>1</sup>   | [18] | 2.89E+12 | sej.€ <sup>1</sup>   | [18] |
| Travail Humain                      | 6.72E+05 | sej.J <sup>1</sup>     | [19] | 3.36E+06 | sej.J <sup>1</sup>   | [19] | 3.36E+06 | sej.J <sup>1</sup>   | [19] |
| Travail Animal                      | 6.94E+06 | sej.J <sup>1</sup>     | [7]  | -        |                      |      | -        |                      |      |

<sup>a</sup>Basée sur la transformé des grains, <sup>b</sup>Basée sur la transformé des tubercules

References : [1] Odum(1996); [2] Odum et al. (2000); [3] Takahashi and Ortega (2010); [4] Bastianoni and Marchettini (2000); [5] La Rosa et al. (2008); [6] Brandt-Williams (2002); [7] Calcul personnel; [8] Cavalett et al. (2006); [9] Cuadra and Rydberg (2006); [10] Cavalett and Ortega (2009); [11] Batista et al. (2008); [12] Rótoló et al. (2007); [13] Dong et al. (2008); [14] Castellini et al. (2006); [15] Ulgiati et al. (1994); [16] Brown and Bardi (2001); [17] Cuadra and Rydberg (2006); [18] University of Florida (2003); [19] Ortega (1998)

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## **Chapitre V**

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# **ANALYSE INTER-TERRITOIRE**

**A ce stade de l'étude nous disposons de deux méthodes génériques et potentiellement adaptées pour l'analyse d'un large gradient de systèmes de production laitiers présents à travers le monde. Dans ce chapitre, nous appliquons ces deux méthodes sur chacun des quatre territoires retenus afin de mieux cerner leurs intérêts et limites et d'analyser l'impact des différentes contraintes sur les modes de gestion de l'énergie au sein des systèmes de production laitiers.**

**L'application des deux méthodes sur les systèmes de production laitiers des quatre territoires confirme leurs potentialités pour l'analyse des différents flux d'énergie dans des systèmes laitiers présents à travers le monde. Elles mettent en évidence des modes de gestion des ressources très différents selon les territoires. Elles mettent notamment en lumière le très faible impact des systèmes du Mali Sud sur leurs ressources énergétiques fossiles (Analyse pluri-énergétique) ou globales (Emergy) grâce à un recours important à la traction animale ou humaine, à la valorisation par le troupeau de ressources naturelles à faible valeur agronomique et à la forte intégration entre cultures et élevage. Les deux méthodes montrent aussi que les systèmes de Bretagne sont relativement moins impactants que ceux de Poitou-Charentes et de l'Ile de la Réunion de par leur part élevée de pâturage dans l'alimentation des troupeaux. En revanche, si l'Analyse pluri-énergétique discrimine clairement les systèmes de la Réunion de ceux de Poitou-Charentes du fait de leur consommation très élevée en énergie fossile avec l'importation de concentrés, la méthode Emergy est moins catégorique et situe les systèmes de Poitou-Charentes au même niveau du fait d'une utilisation moins directe des ressources à travers l'ensilage maïs.**

## **1. Application de la méthode d'analyse pluri-énergétique sur les quatre territoires<sup>6</sup>**

**Pluri-energy analysis of livestock systems - a comparison of dairy systems in different territories**

***Analyse pluri-énergétique de système d'élevage – une comparaison de systèmes laitiers issus de différents territoires***

M. Vigne, J. Vayssières, P. Lecomte, J.L. Peyraud

*Original Research Article – Submitted in Journal of Environmental Management*

### **Résumé**

Une méthode générique appelée « analyse pluri-énergétique » est présentée dans cet article. Cette méthode consiste en i) la décomposition du système agricole en différentes composantes possédant chacune ses propres processus de conversion de l'énergie et ii) l'évaluation des flux d'énergie fossile, brute, liée au travail et solaire entrant dans le système, circulant dans le système entre les différentes composantes et sortant du système. La méthode a été appliquée sur des systèmes de production laitiers issus de quatre territoires : le Mali Sud (SM), un territoire insulaire français, l'Ile de la Réunion (RI), et deux régions métropolitaines françaises, le Poitou-Charentes (PC) et la Bretagne (BR). Ce choix de territoires avait pour but de comparer des systèmes de production laitiers contrastés, depuis les petits systèmes d'élevage familiaux que l'on trouve communément dans les pays en développement jusqu'à des systèmes fortement intensifiés des pays de l'OCDE. Les résultats de cette comparaison mettent en lumière différents modes de consommation de l'énergie et d'efficacité de son utilisation. Les systèmes de SM sont des systèmes à faibles intrants, principalement basés sur l'énergie solaire et liée au travail et mobilisant très peu d'énergie fossile pour produire du lait. La prise en compte de l'ensemble de l'énergie calorifique contenue dans les co-produits, incluant le lait, la viande et les effluents, met en avant la fonction principale du troupeau qui est la production de fertilisants organiques. A l'inverse, les systèmes de production de RI nécessitent une quantité importante d'énergie fossile pour produire du lait. Cette surconsommation est principalement le fait du développement de l'activité laitière dans un

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<sup>6</sup> Cette partie est présentée sous forme d'un article scientifique tel qu'il a été soumis dans Journal of Environmental Management auquel a été ajouté un résumé en français

contexte insulaire et donc de l'apport élevé de concentrés afin de pallier le manque de surfaces arables pour nourrir les animaux. Les systèmes de PC et BR présentent quant à elles des valeurs de consommation d'énergie fossile intermédiaires. L'efficacité d'utilisation de l'énergie fossile pour produire du lait est inférieure en PC du fait d'une proportion plus élevée de maïs ensilage dans la surface fourragère qu'en BR où les systèmes ont plus recours au pâturage. L'ensilage de maïs, bien que permettant la sécurisation du système fourrager dans une zone avec des risques importants de sécheresse, est plus consommateur en énergie fossile à travers la fertilisation minérale et les carburants nécessaires à la récolte. La comparaison entre les systèmes à faibles intrants de SM et les systèmes plus intensifiés de RI, PC et BR met en lumière l'effet positif de l'intensification sur la productivité et leur utilisation de l'énergie solaire de ces systèmes mais un effet négatif sur l'impact environnemental par unité de produit. Au final, la méthode d'analyse pluri-énergétique permet d'analyser finement les voies d'utilisation de l'énergie au sein des systèmes laitiers et est bien adaptée pour mettre en lumière des voies pour élaborer des systèmes d'élevage plus efficaces dans différents contextes.

**Mots Clés:** énergie, systèmes laitiers, Mali, France, Ile de la Réunion

### **Abstract**

A generic method called pluri-energy analysis is presented. This method consists in i) the decomposition of agricultural systems into productive components with their own energy conversion processes and ii) the assessment of fossil, gross, labor and solar energy flows entering the system, circulating in the system among the different components and leaving the system. The method was applied to compare smallholder low-input dairy production systems, which are common in developing countries, to the high-input systems encountered in OECD countries. The results of this comparison highlight different modes and energy efficiencies. Most dairy systems in South Mali (SM) are low-input systems. As these systems are primarily based on solar energy and labor energy, they do not require substantial fossil energy inputs to produce milk. Partitioning the total on-farm gross energy produced among animal co-products, including milk, meat and manure, highlights the major functions of herds that are managed to produce organic crop fertilization. Conversely, farms on Reunion Island (RI), which are intensive as a result of the lack of arable land, require a large amount of fossil energy to produce milk. This high level of use mainly occurs because of the development of the dairy sector in an island context where the amount of arable land is limited. Consequently,

milk production is based on large imports of concentrated feed with an associated high fossil energy cost. Farms in Poitou-Charentes (PC) and Bretagne (BR) show intermediate values of fossil energy use in milk production, similar to those found in the literature for common European systems. PC farms are less efficient than BR farms in terms of fossil energy use for milk production. This difference is mainly due to a higher proportion of maize silage in the forage area, which allows securing the forage production face to dryer climatic conditions but requires higher levels of fossil energy use due to mineral fertilization and mechanized harvests. This characterization differs from that of the grazing lands common on BR farms. Comparing the low-input systems represented by SM to the high-input systems represented by RI, PC and BR showed a positive effect related to productivity intensification and a negative effect related to environmental impacts per kg of product. As demonstrated in this study, the pluri-energy method is particularly relevant for the design of sustainable and intensified livestock systems.

**Keywords:** energy, dairy systems, Mali, France, Reunion Island

## I. INTRODUCTION

Agriculture gets the specific ability to transform solar energy into calorific energy, which is contained in biomass, through photosynthesis. Although solar energy is essentially an unlimited resource, the efficiency of its use is limited by the rhythm and intensity of use. Intensification efforts aim to increase the efficiency with which this resource is used and to increase productivity per unit area. Such efforts began with human and animal labor inputs, which represent the majority of small agricultural systems in developing countries. However, in industrialized countries, fossil energy and mechanization are increasingly used in place of human and animal labor (Pimentel et al., 1973; Leach, 1976; Fluck and Baird, 1980). Fossil energy use and the associated impacts on depletion of natural resources and global warming through CO<sub>2</sub> emissions are commonly assessed aspects of agricultural systems (Vigne et al., 2012a). Using fossil energy more efficiently is an important goal. The efficiency with which other forms of energy are used has also been investigated. The efficiency of solar energy use (Black and Ong, 2000; Noronha-Sannervik and Kowalik, 2003; Caviglia et al., 2004), commonly expressed as the amount of plant biomass per unit of intercepted radiation (in g.MJ<sup>-1</sup>), has been assessed to measure deviations from the potential maximum efficiency or to compare different types of production. Measuring the energy expended by draft animals is

useful in ensuring that the animals' nutrient requirements are being met (Fall et al., 1997; Brosh et al., 1998; Arieli et al., 2002). Similarly, humans' energy expenditures have been assessed to balance food requirements and energy expenditures, especially when there are concerns about malnutrition (Bleiberg et al., 1980, Singh et al., 1989). Loake (2001) highlighted the importance of assessing energy expenditures for social sustainability with regards to the health affects associated with high levels of energy expenditure and effort. Calorific energy measures have been widely used to explore the metabolism of animals and to assess the conversion of plant energy into animal products (Flatt, 1966; Estermann et al., 2001).

No studies in the literature have simultaneously assessed the contributions of different energy sources to the efficiency of livestock systems (Vigne et al., 2012a). Such an approach could offer a more precise explanation of the efficiency of fossil energy use by exploring the energy conversion rates of different processes involved in livestock production systems. Although approximately eighty percent of the world population depends on agriculture, including livestock, for their livelihood (United Nations, 2004), livestock systems in developing countries are often criticized because of their low levels of productivity. However, the number of studies that compare the fossil energy impact of these systems with that of intensive systems is limited and mainly focused on related CO<sub>2</sub> emissions (Steinfeld et al., 2006; Goodland and Anhang, 2009).

Dairy systems represent an interesting model for the development of a generic representation of energy flows within a livestock production system. They are common throughout the world in different forms, ranging from smallholder systems to intensive systems. They also represent a key economic activity in smallholder agricultural systems (FAO, 2009). Moreover, the demand for milk is expected to double in the coming decades in response to the increasing world population and life expectancies in developing countries (FAO, 2009). Thus, assessing current dairy systems and designing future intensified systems with limited environmental impacts are major challenges. This paper introduces a generic method of pluri-energy analysis that accounts for all the types of energy used in agricultural systems. The results from the application of this method to a wide range of dairy production systems, ranging from smallholder low-input systems in developing countries to high-input systems in OECD countries, are also presented.

## **II. MATERIALS AND METHODS**

## **2.1. Studied territories and production systems**

Systems that use different types of energy and that are located in four different territories were compared. The selected systems are representative of dairy production in each territory.

South Mali (SM) corresponds to the periurban region of Sikasso (11° 19' North, 5° 40' West) and is representative of the savannah area of Western Africa. This territory is characterized by high annual average temperatures (26°C) and two seasons: a dry period from December to May and a rainy season from June to November, with rainfall totaling approximately 1.1 m. Whereas these climatic conditions limit crop production, cash and food crops represent the total area of the production systems (Table 1). Human workforce completed by draft animals is larger than in other territories. Fertilization is mainly based on manure due to the high costs of mineral fertilization. The number of animals per farm is usually low, and animals are fed crop residues and graze on natural pasture. Few feed concentrates are distributed, indicating low levels of intensification and resulting in low milk yields (212 L.cow<sup>-1</sup>.yr<sup>-1</sup>). SM systems can be considered low-input systems.

Reunion Island (RI) is a French Island situated in the Indian Ocean (21° 09' South, 55° 30' East). Although its climate is tropical, with high annual average temperatures (24°C) and rainfall levels (3.0 m), contrasting climatic conditions are found among the island's regions. The humid eastern part is exposed to trade winds and receives approximately 3.0–6.0 m of rain per year, whereas the western part, which is protected by central mountains, receives less than 1.0 m of rain per year. The diversity of the geoclimatic conditions on the island has led to different livestock feeding strategies. At altitudes of less than 800 m, cultivated forage crops tend to be tropical, whereas at altitudes above 800 m, tropical and temperate species can be found. Forage crops are usually ensiled and subsequently distributed to animals (Table 1). Promotion of the dairy sector despite a lack of arable land has led to high livestock stocking rates and high levels of concentrate supplementation per cow. Large quantities of mineral fertilizers are used. Despite the high quantities of feed concentrates and mineral fertilizers, average milk yields are approximately 6,082 L.cow<sup>-1</sup>.yr<sup>-1</sup>, and RI systems can be considered high-input systems.

Poitou-Charentes (PC) is a French region situated in west of Metropolitan France (46° 05' North, 00° 10' East). The area has an oceanic climate, with rainfall distributed throughout the year (0.9 m) and moderate temperatures (13°C). This territory is characterized by larger farms with higher numbers of animals and larger areas (Table 1) than those of SM and RI. The farms are diversified, ranging from specialized dairy systems to mixed crop-livestock systems. Half of forage land is grazing area, while the other half is devoted to maize silage.



**Table 1**

Description of study farms from the four territories (SM: South Mali, RI: Reunion Island, PC: Poitou-Charentes, BR: Bretagne)

| Territory (number of farms studied)                                    | SM (n=14)              | RI (n=30)                  | PC (n=48)                  | BR (n=38)                  |
|--|------------------------|----------------------------|----------------------------|----------------------------|
| Herd size (LU)   | <b>32.8</b> (9.8-64.8) | <b>55.5</b> (24.0-131.2)   | <b>94.4</b> (27.9-220.0)   | <b>79.2</b> (38.0-125.5)   |
| Proportion of cows (%)   | <b>52</b> (37-100)     | <b>78</b> (57-100)         | <b>66</b> (56-98)          | <b>66</b> (51-82)          |
| Total area (ha)  | <b>36.5</b> (6.1-76.7) | <b>22.0</b> (2.5-72.0)     | <b>135.3</b> (30.0-378.3)  | <b>80.3</b> (28.6-200.0)   |
| Forage land (%)  | <b>70</b> (10-100)     | <b>100</b> (100-100)       | <b>60</b> (15-100)         | <b>78</b> (56-100)         |
| Cash and food crops (%)  | <b>30</b> (0-90)       | <b>0</b> (0-0)             | <b>40</b> (0-85)           | <b>22</b> (0-44)           |
| Livestock stocking rate for total area (LU.ha <sup>-1</sup> )          | <b>1.0</b> (0.5-1.6)   | <b>4.4</b> (1.2-10.8)      | <b>0.8</b> (0.3-1.4)       | <b>1.1</b> (0.6-1.7)       |
| Livestock stocking rate for forage land (LU.ha <sup>-1</sup> )         | <b>2.4</b> (0.7-16.8)  | <b>4.4</b> (1.2-10.8)      | <b>1.5</b> (0.4-3.8)       | <b>1.4</b> (0.6-2.2)       |
| Workforce (AWU)  | <b>4.3</b> (2.6-9.8)   | <b>2.5</b> (1.3-4.5)       | <b>2.5</b> (1.0-4.5)       | <b>1.8</b> (1.0-3.5)       |
| Proportion of grazing area in the total area (%)                       | <b>70</b> (10-100)     | <b>27</b> (0.00-0.58)      | <b>48</b> (0.26-1.00)      | <b>70</b> (0.50-0.90)      |
| Amount of mineral N on Cash and food crops (kgN.ha <sup>-1</sup> )     | <b>33</b> (6-57)       | -                          | <b>95</b> (0-197)          | <b>94</b> (0-161)          |
| Amount of manure N on Cash and food crops (kgN.ha <sup>-1</sup> )      | <b>64</b> (11-187)     | -                          | <b>22</b> (0-147)          | <b>23</b> (0-148)          |
| Amount of mineral N on Forage land (kgN.ha <sup>-1</sup> )             | -                      | <b>194</b> (30-1,022)      | <b>76</b> (0-220)          | <b>86</b> (16-344)         |
| Amount of manure N on Forage land (kgN.ha <sup>-1</sup> )              | -                      | <b>91</b> (0-383)          | <b>32</b> (0-360)          | <b>40</b> (0-93)           |
| Concentrate feeds (kg.LU <sup>-1</sup> )                               | <b>123</b> (0-365)     | <b>4,672</b> (2,375-7,375) | <b>2,020</b> (338-3,649)   | <b>1,311</b> (663-2082)    |
| Biomass production of grassland <sup>a</sup> (tDM.ha <sup>-1</sup> )   | <b>1.9<sup>b</sup></b> | <b>12.6</b> (6.2-24.4)     | <b>5.8</b> (3.9-9.0)       | <b>6.4</b> (5.5-7.5)       |
| Biomass production of silage land <sup>b</sup> (tDM.ha <sup>-1</sup> ) | -                      | <b>22.6</b> (10.2-45.2)    | <b>12.8</b> (10.0-17.0)    | <b>13.4</b> (7.1-17.0)     |
| Cereal yield (t.ha <sup>-1</sup> )                                     | <b>1.6</b> (0.3-4.5)   | -                          | <b>6.0</b> (4.0-6.5)       | <b>8.0</b> (5.5-11.5)      |
| Milk yield (L.cow <sup>-1</sup> )                                      | <b>212</b> (56-1,130)  | <b>6,082</b> (3,545-9,314) | <b>7,515</b> (4,627-9,719) | <b>7,012</b> (4,757-8,950) |

Values given are **mean** (min-max)

LU: Livestock Unit, AWU: Agricultural Workforce Unit, tDM: ton of Dry Matter, t: ton

<sup>a</sup>Biomass from grassland can be grazed or harvested through fresh green forage or hay<sup>b</sup>Silage is grass silage in RI and maize silage in PC and BR<sup>c</sup>Production of natural pasture has been estimated from [Penning de Vries and Djiteye \(1982\)](#)

Large amounts of mineral fertilizer are used. Concentrate supplementation rates are greater than 2000 kg.LU<sup>-1</sup>.yr<sup>-1</sup>, or approximately two times less than the RI rates, and average dairy production is relatively high (7,515 L.cow<sup>-1</sup>.yr<sup>-1</sup>).

Bretagne (BR) (48° 00' North, 03° 00' West) is also situated in west of Metropolitan France and has similar average climatic conditions to those of PC. Compared to the PC region, BR's farm and herd sizes are smaller (Table 1). Cash and food crops represent a lower proportion of the agricultural area because BR's dairy systems are more specialized. Forage land mainly consists of grazing area (70%). Fertilization levels are similar to those of PC systems, whereas the amount of biomass produced on grassland is higher. Concentrate supplementation rates are lower than those in PC, although milk production remains high (7,012 L.cow<sup>-1</sup>.yr<sup>-1</sup>). Both PC and BR's systems can be considered intermediate-input systems.

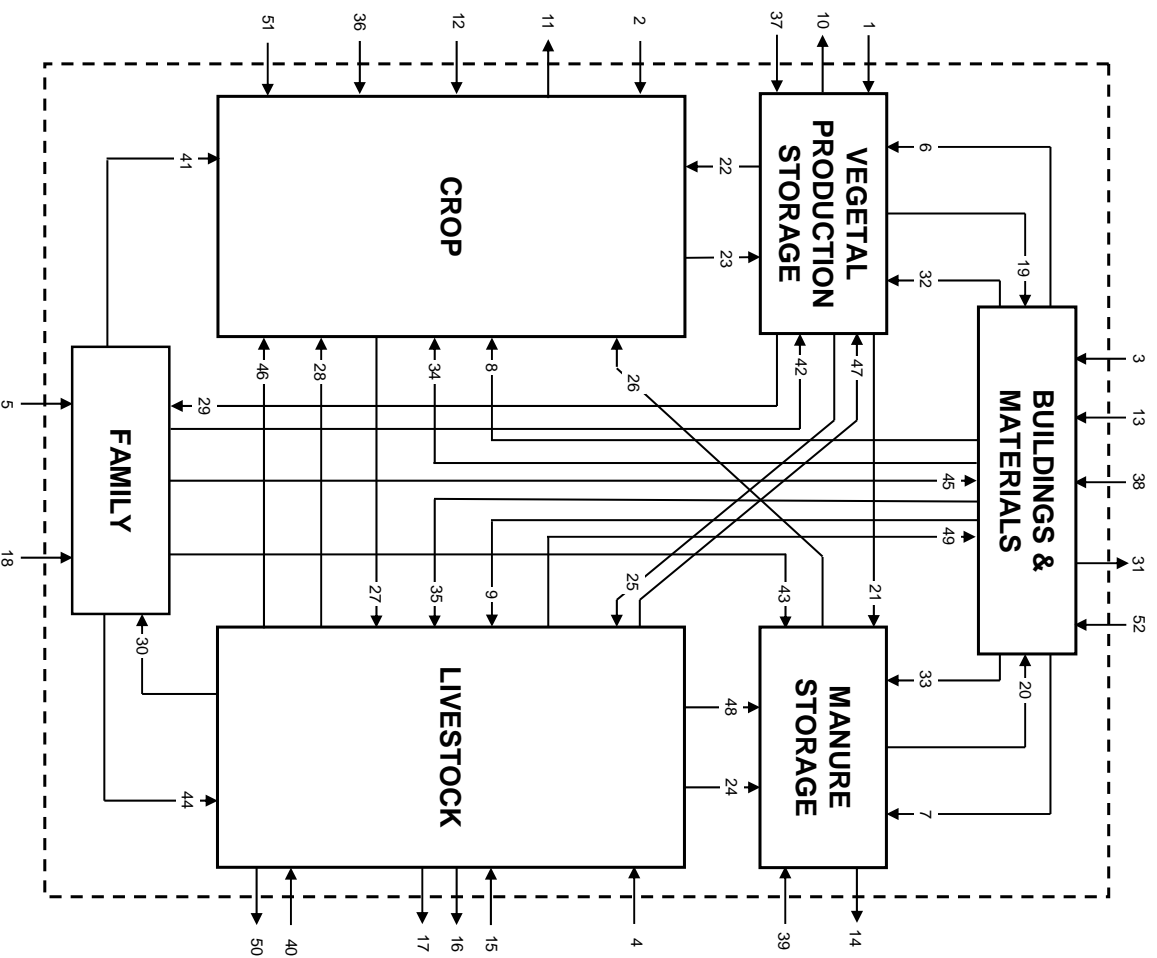
## **2.2. Principles and organization of the pluri-energy analysis method**

The pluri-energy analysis method is based on three basic principles, resulting in a generic conceptual framework of energy flows and use in an agricultural system. The method considers inputs, outputs and internal flows of energy and different types of energy (Figure 1).

The first principle accounts for the four types of energy used in agricultural systems: fossil energy, gross energy, energy from labor and solar energy. Fossil energy corresponds to fossil energy consumed directly on the farm (fuel, electricity and gas) or indirectly to produce crop inputs (fertilizer, seeds, chemicals and water), herd inputs (forage, concentrate feeds, veterinary costs and animal replacement) and agricultural equipment (materials and buildings). Gross energy is the calorific energy contained in animal and crop products and the renewable energy sources produced on farms as photovoltaic electricity. Labor energy corresponds to the physical energy expended on-farm by animal and human labor. Solar energy corresponds to the photosynthetically active radiation (PAR), which is the portion of solar radiation in the 400 to 700 nm wave band.

The second principle divides the agricultural system into subsystems. Six subsystems were identified: i) the material and building capital represented by materials and buildings on the farm, ii) the livestock, including the productive herd and draft animals, iii) the crops, iv) the plant production storage, v) the manure storage and vi) the family.

The third principle accounts for all energy flows entering the system, circulating in the system among different components and leaving the system. Fifty-two energy flows were identified (Figure 1).

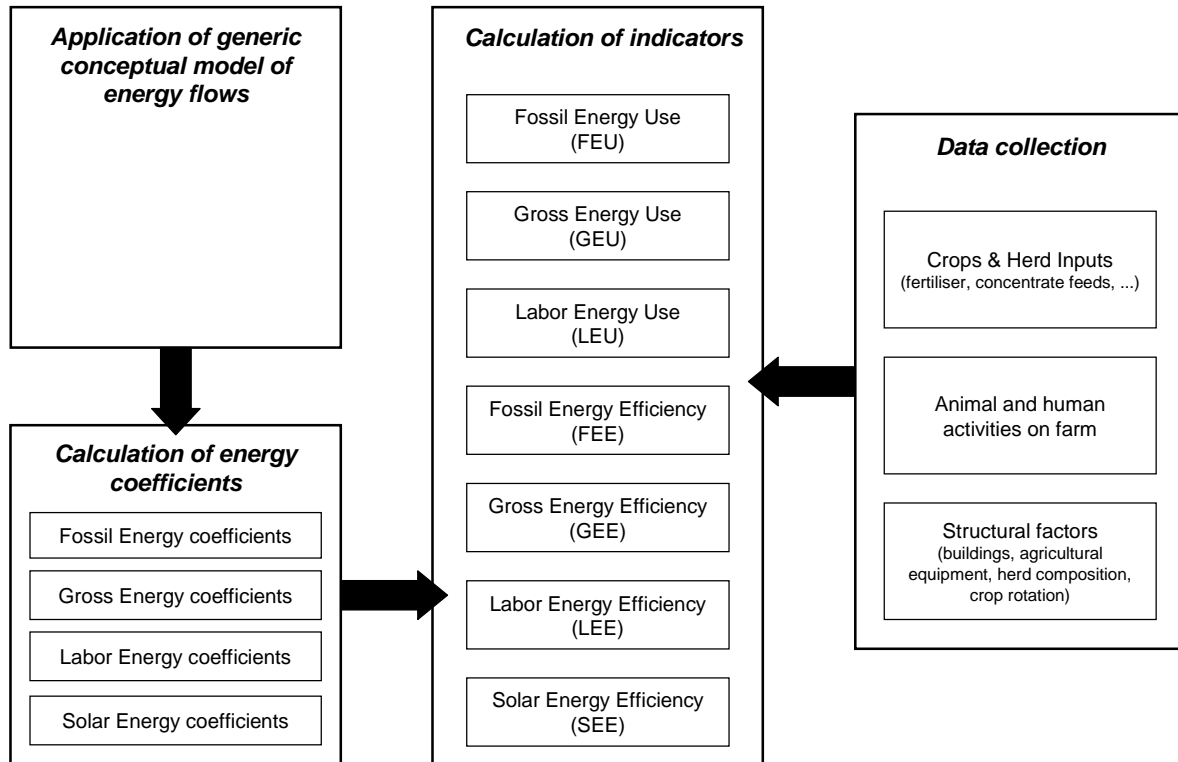


**Figure 1** Generic conceptual model of energy flows entering, circulating in and leaving a dairy system

- Fossil energy**
1. Plastics
  2. Crops inputs (fertiliser, herbicides, external manure,...)
  3. Materials, buildings and direct Energy (fuel, electricity, gas,...)
  4. Livestock inputs (concentrate feeds, forage, veterinary costs, ...)
  5. Family feeds to produce labor on farm
  6. Materials, buildings and direct energy used for vegetal production storage
  7. Materials, buildings and direct energy used for manure storage
  8. Materials, buildings and direct energy used for crops management
  9. Materials, buildings and direct energy used for livestock management
- Gross energy**
10. Vegetal products stored and given/sold
  11. Biomass from crops grazed by external livestock or harvested by other farms
  12. External manure spread or laid down during grazing
  13. Biomass imported for methanisation (vegetal products, manure, ...)
  14. Manure stored and given or sold
  15. Animal feeds (concentrate feeds and forages)
  16. Animal products given or sold
  17. Manure deposits during grazing on external crops
  18. Family feeds to produce labor on farm
  19. Biomass produced on farm for methanisation
  20. Manure produced on farm for methanisation
  21. Vegetal products produced on farm and used for bedding
  22. Vegetal products produced on farm and used as seeds
  23. Vegetal products produced on farm and stored
  24. Manure produced on farm and stored
  25. Vegetal products stored and distributed to the livestock
  26. Manure stored and spread on crops
  27. Biomass grazed from crops or harvested and distributed directly to livestock
  28. Manure deposit during grazing on crops
  29. Vegetal products stored and consumed by family
  30. Animal products consumed by family
  31. Renewable energies exported
  32. Renewable energies produced on farm and used for vegetal production storage
  33. Renewable energies produced on farm and used for manure storage
  34. Renewable energies produced on farm and used for crops management
  35. Renewable energies produced on farm and used for livestock management
- Labor energy**
36. External labor made on crops
  37. External labor made on vegetal production storage
  38. External labor made on buildings and materials
  39. External labor made on manure storage
  40. External labor made on livestock
  41. Family labor made on crops
  42. Family labor made on vegetal production storage
  43. Family labor made on manure storage
  44. Family labor made on livestock
  45. Family labor made on buildings and materials
  46. Animal labor made on crops
  47. Animal labor made on vegetal production storage
  48. Animal labor made on manure storage
  49. Animal labor made on material and buildings
  50. Animal labor made out of the farm
- Solar energy**
51. Useful solar radiation received by crops
  52. Useful solar radiation received by buildings to produce photovoltaic energy

## 2.3 Application of the pluri-energy analysis method

The application of the pluri-energy analysis method is organized in four successive steps (Figure 2).



**Figure 2** Steps of the application of pluri-energy analysis of dairy systems

### 2.3.1. Step 1: List the existing flows

The first step is to list the existing flows in the study system and to apply the generic conceptual model of energy flows (Figure 1) to the local agricultural system given the existing flows. The resulting model offers a first representation of a system's energy flows.

### 2.3.2. Step 2: Calculate locally adapted energy coefficients<sup>7</sup>

The second step is the calculation of locally adapted energy coefficients for inputs. Adapting the fossil energy coefficients for the different inputs is crucial. These coefficients can vary among the different territories based on factors such as the origin of the inputs or the techniques used to produce them; furthermore, the travel distance from the site of production to the site of use may differ. [Vigne et al. \(2012b\)](#) identified the contribution of uncertainty in existing energy coefficients to the global uncertainty of fossil energy use indicators and risks, thereby facilitating the comparison of systems. Locally adapted fossil energy coefficients can

<sup>7</sup> Le calcul de ces coefficients énergétiques est globalement exposés dans le chapitre IV et en annexe VI

be derived from the literature or recalculated by assessing the life cycle of the inputs. The fossil energy coefficients were recalculated for SM (Vigne et al., 2012c), derived using the Dia'terre® method for PC and BR (ADEME, 2011) and calculated from PLANETE MASCAREIGNES for RI (Thévenot et al., 2011).

The gross energy coefficients for crop and animal products were calculated based on the nutritive values of feeds for French (INRA, 2007), Tropical and Mediterranean (Tran et al., 2010) conditions. The gross energy coefficients for renewable energy sources were based on energy content.

Due to variability in the literature for similar contexts, the labor energy coefficients in SM were recalculated. A stress score similar to the Physical Activity Ratio (Loake, 2001), which is considered to be correlated with the level of physical energy expended during work, was established for each work activity. The scores were obtained through interviews with heads of household. These interviews aimed to classify work activities on a scale from 1 (easy) to 5 (difficult). When the same score was given by at least 75% of the heads of household, the announced value was confirmed. In other cases, the final scores were taken as the means of the announced values. Then, the energy coefficient for each work activity was weighted, with weights ranging between the minimum stress score value of 1 ( $0.703 \text{ MJ}\cdot\text{h}^{-1}$  for driving engine) and the maximum stress score value of 5 ( $1.481 \text{ MJ}\cdot\text{h}^{-1}$  for manual plowing) found in the literature (Passmore and Durmin, 1955). The labor energy coefficients from human labor in RI, PC and BR were taken from the literature (Vaz et al., 2005) and refer to tractor driving and milking. The energy coefficients for animal labor were calculated for SM. They were taken from the literature (Lawrence and Stibbards, 1990; Fall et al., 1997), or given the sparse data, were calculated using the same ratio as the human coefficients. For example, for human labor, the energy coefficient for mounding is 83% higher than that of plowing.

The solar energy coefficients are based on the Photosynthetically Active Radiation (PAR) in the solar spectrum. PAR is the proportion of total solar energy incident on the Earth's surface and available for photosynthesis. PAR is commonly considered to consist of wavelengths ranging from 400 to 700 nm. Varlet-Grancher et al. (1989) reported several values of PAR for different plant species. Due to a lack of data for several plant species present on the studied farms, a simplified value of 50% was used, as proposed by Bonnet and Combarrous (1996).

### **2.3.3. Step 3: Gather on-farm data**

The third step is the gathering of on-farm data and the transformation of this data into energy flows through the use of energy coefficients. Applications of the pluri-energy analysis

method require data on structural factors (e.g., total area, material equipment and buildings), crop management (e.g., area occupation, fertilization and crop yield), livestock management (e.g., herd size, feed and milk yield) and human and animal labor (e.g., type of activity and duration). Farm data for SM were partially derived from [Coulibaly \(2008\)](#) and completed through interviews with the head of household for each farm. Missing data primarily consisted of crop management information. The RI farm data were based on a survey to cover the variability described by [Taché \(2001\)](#). The data were taken from economic reports of each farm for 2007 and completed through interviews. The PC and BR farm data were taken from the national DIAPASON database ([Charroin et al. 2005](#)) and cover the years 2008 and 2009 for PC and 2008 for BR.

#### **2.3.4. Step 4: Calculate energy indicators**

The final step is the calculation of the total amount of energy used and produced and the establishment of indicators of energy conversion efficiencies. All indicators and equations are shown in Table 2. These indicators were calculated at the farm level and the crop (forage land and cash and food crops) and livestock level. Farm level is represented by the system defined in Figure 1. It consists in the whole-farm system containing crops, herd, materials and buildings and family. Materials and buildings considered are those used for crop and dairy activities, for vegetal production and manure storage and for production of renewable energies. Energy input is represented by flows 1 to 5 for fossil energy, flows 12, 13, 15 and 18 for gross energy, flows 36 to 40 for labor energy, and flows 51 and 52 for solar energy. Energy production corresponds to flows 10, 11, 14, 16, 17 and 31 for gross energy, and flow 50 for labor energy. Crop level has been divided into cash&food crops and forage land. Cash&Food is compound by arable lands to feed family and/or for commercial activities. Forage land is based on land used to feed animals, either managed land or untouched areas as natural pasture. Regarding the figure 1, energy input for crops corresponds to flows 2 and 8 for fossil energy, flows 12, 22, 26, 28 and 34 for gross energy, flows 41 and 46 for labor energy and flow 51 for solar energy. Energy production is only represented by gross energy (flows 11, 23 and 27). Livestock level corresponds to the herd and contains only animals. Regarding the figure 1, energy input corresponds to flows 4 and 9 for fossil energy, flows 15, 25, 27 and 35 for gross energy, and flows 40 and 44 for labor energy. No solar energy use is considered at this level. Energy production is represented by flows 16, 17, 24, 28 and 30 for gross energy and flows 46 to 50 for labor energy.

**Table 2**

Indicators and equations for calculations at the farm, crop and livestock levels

| Level      | Indicator                | Equation  |
|------------|--------------------------|---|
| Farm Level | Fossil energy use        | $FEU_{Farm} (MJ.ha^{-1}) = FE_{(1)} + FE_{(2)} + FE_{(3)} + FE_{(4)} + FE_{(5)} + FE_{(5)} + FE_{(6)} + FE_{(7)} + FE_{(8)} + FE_{(9)}$   |
|            | Gross energy use         | $GEU_{Farm} (MJ.ha^{-1}) = GE_{(12)} + GE_{(13)} + GE_{(15)} + GE_{(18)}$   |
|            | Labour energy use        | $LEU_{Farm} (MJ.ha^{-1}) = LE_{(36)} + LE_{(37)} + LE_{(38)} + LE_{(39)} + LE_{(40)}$   |
|            | Solar energy use         | $SEU_{Farm} (MJ.ha^{-1}) = SE_{(51)} + SE_{(52)}$   |
|            | Gross energy production  | $GEP_{Farm} (MJ.ha^{-1}) = GE_{(10)} + GE_{(11)} + GE_{(14)} + GE_{(16)} + GE_{(17)} + GE_{(31)} + GE_{(50)}$   |
|            | Fossil energy efficiency | $FEE_{Farm} (dmnl) = GEP_{Farm} / FEU_{Farm}$   |
|            | Gross energy efficiency  | $GEE_{Farm} (dmnl) = GEP_{Farm} / GEU_{Farm}$   |
|            | Labour energy efficiency | $LEE_{Farm} (dmnl) = GEP_{Farm} / LEU_{Farm}$   |
|            | Solar energy efficiency  | $SEE_{Farm} (dmnl) = GEP_{Farm} / SEU_{Farm}$   |
| Crop level | Fossil energy use        | $FEU_{Crop} (MJ.ha^{-1}) = FE_{(2)} + FE_{(8)} + (FE_{(4)} + FE_{(9)}) \times \frac{GE_{(28)} + LE_{(46)}}{GE_{(16)} + GE_{(17)} + GE_{(24)} + GE_{(28)} + GE_{(30)} + LE_{(46)} + LE_{(47)} + LE_{(48)} + LE_{(49)} + LE_{(50)}} \times$ |
|            |                          | $(1 + \frac{GE_{(26)}}{GE_{(24)}}) + FE_{(7)} \times \frac{GE_{(26)}}{GE_{(14)} + GE_{(20)} + GE_{(26)}}) + FE_{(5)} \times \frac{LE_{(41)}}{LE_{(41)} + LE_{(42)} + LE_{(43)} + LE_{(44)} + LE_{(45)}}$                                  |
|            | Labour energy use        | $LEU_{Crop} (MJ.ha^{-1}) = LE_{(36)} + LE_{(41)} + LE_{(46)}$   |
|            | Solar energy use         | $SEU_{Crop} (MJ.ha^{-1}) = SE_{(51)} + SE_{(52)} \times \frac{GE_{(34)}}{GE_{(31)} + GE_{(32)} + GE_{(33)} + GE_{(34)} + GE_{(35)}}$  |
|            | Gross energy production  | $GEP_{Crop} (MJ.ha^{-1}) = GE_{(11)} + GE_{(23)} + GE_{(27)}$   |
|            | Fossil energy efficiency | $FEE_{Crop} (dmnl) = GEP_{Cash\&Food} / FEU_{Cash\&Food}$   |
|            |                          |   |
|            |                          |   |
|            |                          |   |
|            |                          |   |

The number in the equation corresponds to the number of flows in Figure 1

**Table 2 (continued)**

| Level                    | Farm level   |
|--------------------------|--|
| Crop level               | $LEE_{Crop} (dmnl) = GEP_{Cash\&Food} / LEU_{Cash\&Food} \quad (15)$   |
| Solar energy efficiency  | $SEE_{Crop} (dmnl) = GEP_{Cash\&Food} / SEU_{Cash\&Food} \quad (16)$   |
| Livestock level          | $FEU_{Lvsstk} (MJ.LU^{-1}) = FE_{(4)} + FE_{(9)} + (FE_{(2)} + FE_{(8)}) \times \frac{GE_{(27)}}{GE_{(11)} + GE_{(23)} + GE_{(27)}} \times \left( 1 + \frac{GE_{(25)}}{GE_{(10)} + GE_{(19)} + GE_{(22)} + GE_{(25)}} \right) + (FE_{(1)} + FE_{(6)}) \times \frac{GE_{(25)}}{GE_{(10)} + GE_{(19)} + GE_{(22)} + GE_{(25)}} + FE_{(5)} \times \frac{LE_{(44)}}{LE_{(41)} + LE_{(42)} + LE_{(43)} + LE_{(44)} + LE_{(45)}} \quad (17)$ |
| Gross energy use         | $GEU_{Lvsstk} (MJ.LU^{-1}) = GE_{(15)} + GE_{(25)} + GE_{(27)} + GE_{(29)} \quad (18)$   |
| Labour energy use        | $LEU_{Lvsstk} (MJ.LU^{-1}) = LE_{(40)} + LE_{(44)} + (LE_{(36)} + LE_{(41)} + LE_{(46)}) \times \frac{GE_{(27)}}{GE_{(11)} + GE_{(23)} + GE_{(27)}} \times \left( 1 + \frac{GE_{(25)}}{GE_{(10)} + GE_{(19)} + GE_{(22)} + GE_{(25)}} \right) + (LE_{(37)} + LE_{(42)} + LE_{(47)}) \times \frac{GE_{(25)}}{GE_{(10)} + GE_{(19)} + GE_{(22)} + GE_{(25)}} \quad (19)$   |
| Solar energy use         | $SEU_{Lvsstk} (MJ.LU^{-1}) = SE_{(51)} \times \frac{GE_{(27)}}{GE_{(11)} + GE_{(23)} + GE_{(27)}} \times \left( 1 + \frac{GE_{(25)}}{GE_{(10)} + GE_{(19)} + GE_{(22)} + GE_{(25)}} \right) + SE_{(52)} \times \frac{GE_{(35)}}{GE_{(31)} + GE_{(32)} + GE_{(33)} + GE_{(34)} + GE_{(35)}} \quad (20)$   |
| Gross energy production  | $GEP_{Lvsstk} (MJ.LU^{-1}) = GE_{(11)} + GE_{(23)} + GE_{(27)} \quad (21)$   |
| Fossil energy efficiency | $FEE_{Lvsstk} (dmnl) = GEP_{Lvsstk} / FEU_{Lvsstk} \quad (22)$   |
| Gross energy efficiency  | $GEE_{Lvsstk} (dmnl) = GEP_{Lvsstk} / GEU_{Lvsstk} \quad (23)$   |
| Labour energy efficiency | $LEE_{Lvsstk} (dmnl) = GEP_{Lvsstk} / LEU_{Lvsstk} \quad (24)$   |
| Solar energy efficiency  | $SEE_{Lvsstk} (dmnl) = GEP_{Lvsstk} / SEU_{Lvsstk} \quad (25)$   |

The number in the equation corresponds to the number of flows in Figure 1



At each level, the total energy use was calculated by summing all flows of energy for the different types of energy. At the crop level, energy from animal manure was calculated by allocating energy among the different animal products. A similar energy allocation process was used at the livestock level to calculate the energy from the forage and feeds consumed by the herd. The energy produced at each level is the amount of gross energy produced by the system. In this method, internal flows (e.g., gross energy from crops produced on-farm and consumed by the herd at the farm level or milk directly fed to at the livestock level) are not accounted for in energy production. Efficiency indicators are calculated at each level from the ratio of gross energy produced and the amount of energy use. Energy used and produced is expressed in megajoules per hectare ( $\text{MJ}\cdot\text{ha}^{-1}$ ) at the farm and crop levels and in megajoules per Livestock Unit ( $\text{MJ}\cdot\text{LU}^{-1}$ ) at the livestock level. The efficiency indicators are dimensionless.

#### 2.4. Statistical analysis

Mean values were calculated for each variable in each territory. Due to the small number of farms for SM and RI, statistical comparisons of the means were not informative. A multivariate approach was used to overcome such difficulties and to ensure suitable comparisons of variables among the four territories. Statistical analysis was conducted through a principal component analysis (PCA), using the R software v 2.15.0 (R Development Core Team, 2008) in order to conduct spatial classifications of the farms. PCA was performed using whole energy use indicators described in table 2 with the exception of  $\text{SEU}_{\text{Crop}}$  and  $\text{GEU}_{\text{Lvstk}}$  since they were closely related to respectively  $\text{SEU}_{\text{Farm}}$  and  $\text{GEU}_{\text{Farm}}$ .

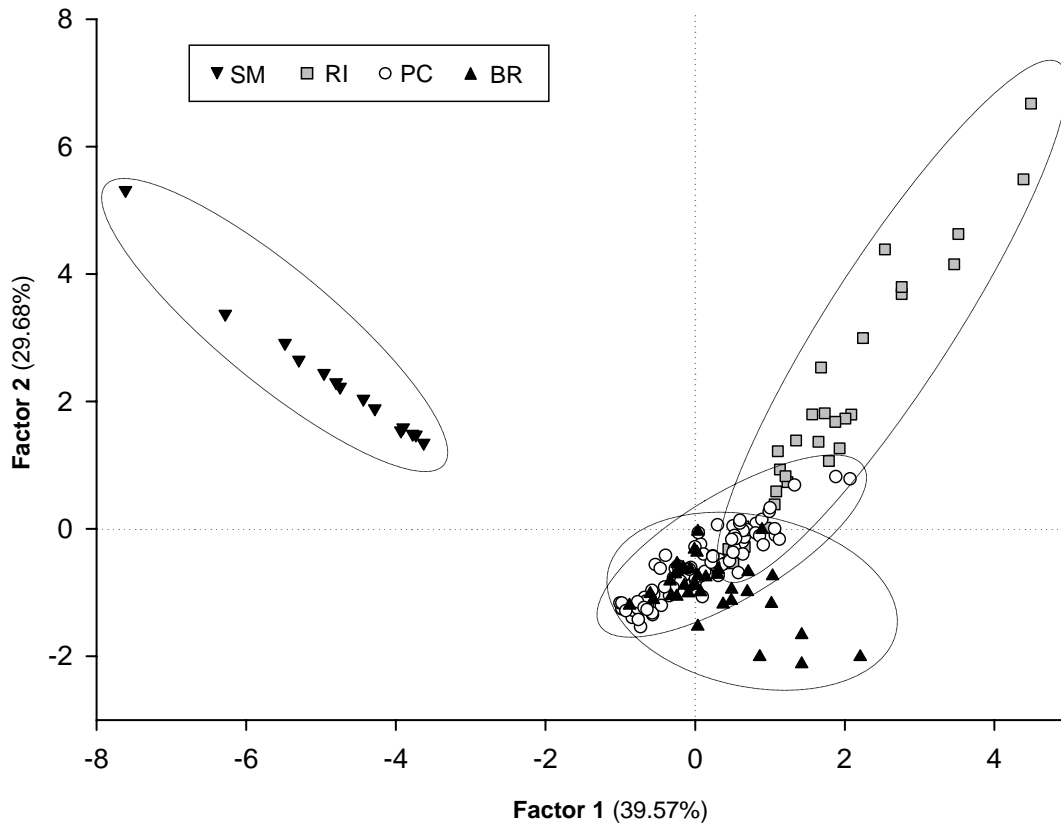
### III. RESULTS

#### 3.1. Principal Component Analysis

Because they had eigenvalues greater than 1, only the two first principal components, Factors 1 and 2, were retained. Moreover, they explained respectively 39.6% and 29.7% of the total variance whereas Factors 3 to 9 represents the 30.8% remaining, each one representing less than 10.0%. Factor 1 had high loading for  $\text{LEU}_{\text{Crop}}$  (-0.88) and  $\text{LEU}_{\text{Lvstk}}$  (-0.79) and for  $\text{FEU}_{\text{Lvstk}}$  (0.72). Factor 2 revealed a close association between  $\text{FEU}_{\text{Farm}}$  (0.77) and  $\text{SEU}_{\text{Farm}}$  (0.77).

The corresponding individual factor map for the first two principal component analyses shows that SM farms are located far from other farms (Figure 3). The majority of RI farms are clearly differentiated from farms in other territories while there were large variations between

RI farms. Differentiation between PC and BR farms is less obvious. However, the PC confidence ellipse only partly covers the BR confidence ellipse which enables to highlight differences between farms from the two territories. The four territories can be graphically identified; as a result, the average values were considered to be different.

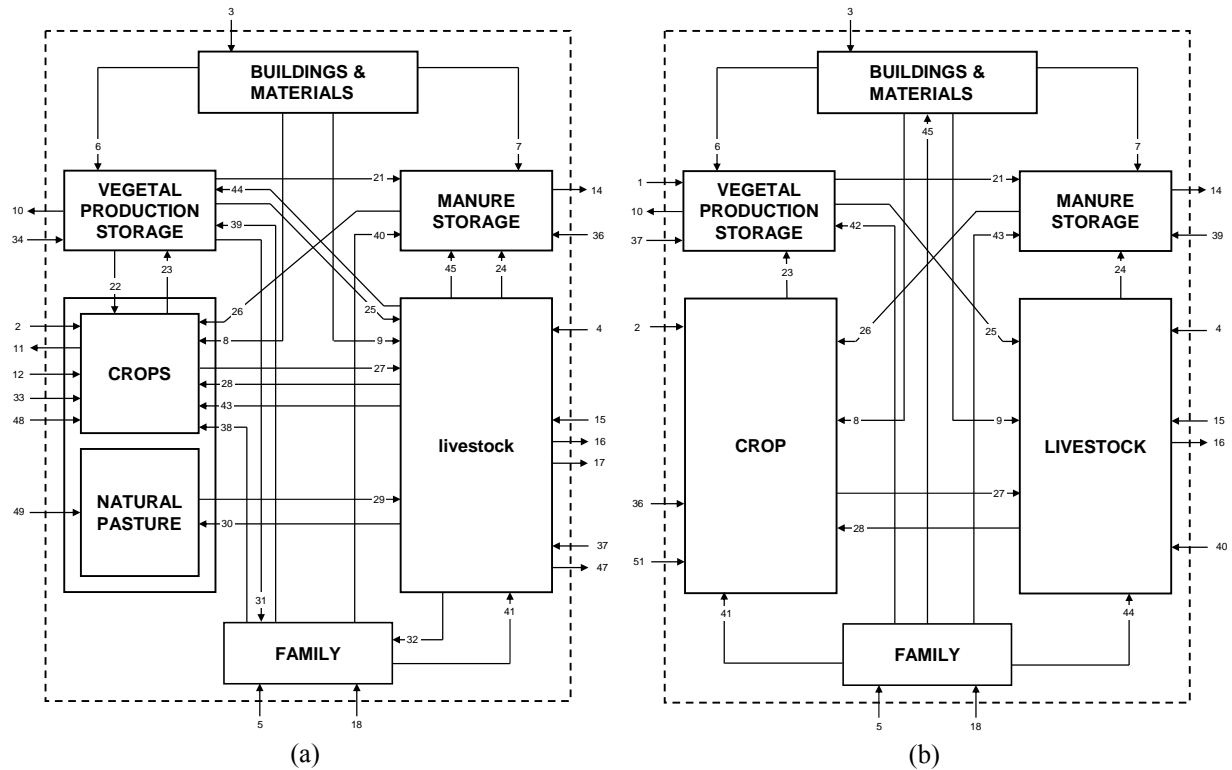


**Figure 3** Principal Component Analysis (PCA) on energy indicators for farms from the four territories (SM: South Mali, RI: Reunion Island, PC: Poitou-Charentes, BR: Bretagne)

### 3.2. Conceptual models of energy flows

Applying the generic conceptual model to the four territories produced an inventory of energy flows in the systems and resulted in two specific conceptual models: one for SM and a similar conceptual model for RI, PC and BR (Figure 4). With reference to the generic conceptual model (Figure 1), some flows related to the production of non-renewable energy sources were not considered because they were not observed on the studied farms. SM farms are described with forty-one energy flows, while farms from the other territories are described with only thirty-one energy flows. Therefore, SM resulted in a more complex conceptual model. SM's additional energy flows originated from the presence of communal natural pasture, draft animals, the reuse of crop products as seeds and the consumption of residual crops by external herds. Autoconsumption of meat and milk by members of the farm was not

considered for the RI, PC and BR farms because these flows represent less than 1% of the total meat and milk produced on these farms, whereas they represent up to 20% of the meat and milk produced on SM farms. No crop products are consumed on RI, PC and BR farms, whereas the consumption of crop products ranges from 25% to 95% on SM farms.



**Figure 4** Generic conceptual model of energy flow of dairy systems applied to household farms from South Mali (a) and intensified farms from Reunion Island, Poitou-Charentes and Bretagne (b)

### 3.3. Energy indicators and flows

The average results for the indicators in each territory and at the different levels are presented in Table 3.

#### 3.3.1. Energy uses

At the farm level, huge differences appear between the territories. The SM systems use very few fossil energy and gross energy per ha but use high amount of labor energy and solar energy compared to the farm in the three other territories. The reverse is observed for RI farms. The  $FEU_{Farm}$  value for SM is approximately 30 times lower than the values for PC and BR and 170 times lower than for RI. The  $GEU_{Farm}$  value for RI is more than 700 times greater than for SM farms and approximately 25 times greater than for the PC and BR farms.

**Table 3**  
Results of pluri-energy analysis at the farm, crop and livestock levels for four territories (SM: South Mali, RI: Reunion Island, PC: Poitou-Charentes, BR: Bretagne)

| Level   | Type of indicators | Indicators   | SM    | RI    | PC    | BR    |
|---|--------------------|--|-------|-------|-------|-------|
| Farm  | Use                | Fossil Energy Use ( $FEU_{Farm}$ ) ( $\times 10^3 MJ.ha^{-1}$ )                | 1.0   | 170.8 | 29.2  | 25.7  |
|   |                    | Gross Energy Use ( $GEU_{Farm}$ ) ( $\times 10^3 MJ.ha^{-1}$ )                 | 9.8   | 776.1 | 31.5  | 30.0  |
|   |                    | Labor Energy Use ( $LEU_{Farm}$ ) ( $MJ.ha^{-1}$ )                             | 1,716 | 366   | 38    | 25    |
|   |                    | Solar Energy Use ( $SEU_{Farm}$ ) ( $\times 10^7 MJ.ha^{-1}$ )                 | 77.4  | 62.7  | 46.1  | 40.0  |
|   |                    | Gross Energy Produced ( $GEP_{Farm}$ ) ( $\times 10^3 MJ.ha^{-1}$ )            | 13.2  | 67.2  | 71.8  | 44.8  |
| Production Efficiency   | Efficiency         | Fossil Energy Efficiency ( $FEE_{Farm}$ ) ( $dmml$ )                           | 14.1  | 0.4   | 2.6   | 1.8   |
|   |                    | Labor Energy Efficiency ( $LEE_{Farm}$ ) ( $dmml$ )                            | 16    | 213   | 3,038 | 1,098 |
|   |                    | Solar Energy Efficiency ( $SEE_{Farm}$ ) ( $\times 10^{-3}$ )                  | 0.9   | 2.2   | 3.1   | 2.3   |
|   |                    | Fossil Energy Use ( $FEU_{Forage}$ ) ( $\times 10^3 MJ.ha^{-1}$ )              | 0     | 39.8  | 15.1  | 7.7   |
| Forage land <sup>a</sup>  | Use                | Labor Energy Use ( $LEU_{Forage}$ ) ( $MJ.ha^{-1}$ )                           | 0     | 12    | 4     | 4     |
|   |                    | Gross Energy Produced ( $GEP_{Forage}$ ) ( $\times 10^3 MJ.ha^{-1}$ )          | 32.9  | 125.8 | 141.3 | 137.0 |
|   |                    | Fossil Energy Efficiency ( $FEE_{Forage}$ ) ( $dmml$ )                         | -     | 3.7   | 12.7  | 20.5  |
|   |                    | Labor Energy Efficiency ( $LEE_{Forage}$ ) ( $\times 10^3$ )                   | -     | 14.7  | 41.3  | 40.5  |
|   |                    | Solar Energy Efficiency ( $SEE_{Forage}$ ) ( $\times 10^{-3}$ ) ( $dmml$ )     | 0.5   | 4.1   | 6.1   | 6.9   |
| Cash&Food crops   | Use                | Fossil Energy Use ( $FEU_{Cash\&Food}$ ) ( $\times 10^3 MJ.ha^{-1}$ )          | 0.7   | -     | 22.3  | 15.7  |
|   |                    | Labor Energy Use ( $LEU_{Cash\&Food}$ ) ( $MJ.ha^{-1}$ )                       | 471   | -     | 4.7   | 4.2   |
|   |                    | Gross Energy Produced ( $GEP_{Cash\&Food}$ ) ( $\times 10^3 MJ.ha^{-1}$ )      | 29.6  | -     | 108.6 | 118.2 |
|   |                    | Fossil Energy Efficiency ( $FEE_{Cash\&Food}$ ) ( $dmml$ )                     | 38.6  | -     | 8.4   | 6.8   |
|   |                    | Labor Energy Efficiency ( $LEE_{Cash\&Food}$ ) ( $\times 10^3$ )               | 0.9   | -     | 22.5  | 24.5  |
| Livestock   | Use                | Solar Energy Efficiency ( $SEE_{Cash\&Food}$ ) ( $\times 10^{-3}$ ) ( $dmml$ ) | 2.5   | -     | 4.7   | 5.7   |
|   |                    | Fossil Energy Use ( $FEU_{Lvsstk}$ ) ( $\times 10^3 MJ.LLU^{-1}$ )             | 0.5   | 43.4  | 30.9  | 21.5  |
|   |                    | Fossil Energy Use ( $FEU_{Lvsstk}$ ) ( $MJ.L^{-1}$ )                           | 0.1   | 6.6   | 4.9   | 3.6   |
|   |                    | Gross Energy Use ( $GEU_{Lvsstk}$ ) ( $\times 10^3 MJ.LLU^{-1}$ )              | 43.2  | 209.0 | 146.4 | 143.2 |
|   |                    | Labor Energy Use ( $LEU_{Lvsstk}$ ) ( $MJ.LLU^{-1}$ )                          | 202   | 45    | 35    | 41    |
| Production Efficiency   | Efficiency         | Solar Energy Use ( $SEU_{Lvsstk}$ ) ( $\times 10^7 MJ.LLU^{-1}$ )              | 3.38  | 1.02  | 2.05  | 1.71  |
|   |                    | Gross Energy Produced ( $GEP_{Lvsstk}$ ) ( $\times 10^3 MJ.LLU^{-1}$ )         | 9.7   | 16.6  | 21.6  | 21.2  |
|   |                    | Fossil Energy Efficiency ( $FEE_{Lvsstk}$ ) ( $dmml$ )                         | 26.2  | 0.5   | 0.8   | 1.1   |
|   |                    | Gross Energy Efficiency ( $GEE_{Lvsstk}$ ) ( $dmml$ )                          | 0.26  | 0.17  | 0.15  | 0.16  |
|   |                    | Labor Energy Efficiency ( $LEE_{Lvsstk}$ ) ( $dmml$ )                          | 16    | 366   | 568   | 463   |
| Solar Energy Efficiency ( $SEE_{Lvsstk}$ ) ( $\times 10^{-3}$ ) | 1.0                | 2.4  | 1.3   | 1.2   |       |       |

<sup>a</sup>Forage lands are natural pasture for SM and forage crops for RI, PC and BR

The  $LEU_{Farm}$  value for SM farms is roughly 5 times higher than that of RI farms and up to 57 times higher than that of PC and BR farms. The  $SEU_{Farm}$  value for SM farms is 23% higher than that of SM farms, and 80% higher than that of PC and BR farms.

At the forage and crop levels, the  $FEU_{Forage}$  and  $LEU_{Forage}$  values are null for the SM systems. The  $FEU_{Forage}$  value for RI is 2.6 times greater than that of PC which is in turn 2 times greater than that of BR farms. The  $LEU_{Forage}$  value for RI farm is 3 times greater than that of PC and BR farms. There is no cash&food crops in RI farms. The  $FEU_{Cash\&Food}$  value is 42% greater for PL than that of BR farms whereas value for the SM farms is very low. The  $LEU_{Cash\&Food}$  value is at the highest for the RI farms where it is approximately 100 times greater than for the PC and BR farms.

At the livestock level, SM farm consume very few fossil energy and gross energy, but and they are high labor energy and solar energy users. The greatest  $FEU_{Lvstk}$  value is in RI farm. This value, expressed per LU unit is 40% greater than that of PC farms which is in turn 45% greater than that of BR farms. Similar trends are observed when the  $FEU_{Lvstk}$  value are expressed per litre of milk,. The  $GEU_{Lvstk}$  value for SM farms is approximately 5 times lower than that for RI and 3 times lower than the values for PC and BR farms. The  $LEU_{Lvstk}$  value is 4.5 times greater for SM farms than for RI farms and 5 to 6 times greater than that for BR and PC farms. The  $SEU_{Lvstk}$  value is 3.3 times greater than that for RI ( $1.02 \times 10^{-7}$  MJ.LU-1), 2 times greater than that for BR farms and 65% greater for SM farms.

### 3.3.2. Energy production

The  $GEP_{Farm}$  per unit area is not very different for PC and RI farms but value are much lower for BR farms the lowest values being observed for the SM farms.  $GEP_{Farm}$  for PC farms is 60% and 5.4 times higher than for BR and SM farms respectively. The  $GEP_{Forage}$  values are similar for RI, BR and PC farm while the value for ML is 4.2 time less for SM farms. The  $GEP_{Cash\&Food}$  values are similar for BR and PC farms, while the value for SM farms is markedly lower. No value exists for RI farms. The  $GEP_{Lvstk}$  value is very similar for PC and BR farms, the value for RI farm is 30% lower whereas values for SM farms are 2.2 times less.

### 3.3.3. Energy efficiencies

At the farm level, the  $FEE_{Farm}$  value is higher than 1 in almost all situations with the noticeable exception of the RI farms, thus the gross energy produced in these farms is lower than the fossil energy required to produced milk, meat and crops. The highest values are recorded for SM farms where the efficiency is up to 6 times higher than for PC and BR farms. Conversely, the  $LEE_{Farm}$  value is the lowest for SM farms, the value for RI farms is more than ten times greater, whereas the values for BR and PC (3,038) are substantially larger. The

$SEE_{\text{Farm}}$  value is lowest for SM farms and greatest for PC farms, RI and BR farms having similar intermediate values (2.2 and 2.3, respectively).

At the crop level, the greatest  $FEE_{\text{Forage}}$  value is for BR farms and the lowest are for RI farms while PC farm are intermediate. No  $FEE_{\text{Forage}}$  and  $LEE_{\text{Forage}}$  values are available for SM farms and no  $FEE_{\text{Cash\&Food}}$ ,  $LEE_{\text{Cash\&Food}}$  and  $SEE_{\text{Cash\&Food}}$  values are available for RI farms. The greatest  $FEE_{\text{Cash\&Food}}$  value is for SM farms which is 6 to 7 times higher than for PC and BR farms.  $LEE_{\text{Forage}}$  is similar for PC and BR farms and 2.7 times higher than for RI farms.  $LEE_{\text{Cash\&Food}}$  is also similar for PC and BR farms while very low value are obtained for SM farms.

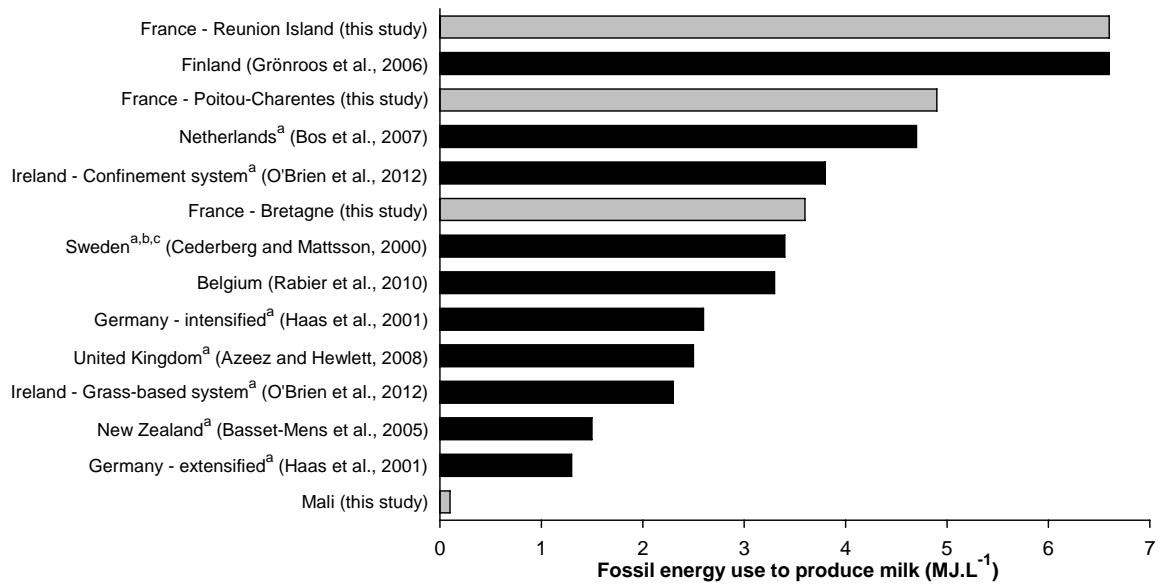
At the livestock level, the  $FEE_{\text{Lvstk}}$  is far greater for SM farms than for the farms in the others territories. Indeed  $FEE_{\text{Lvstk}}$  is lower than 1 for RI and PC farms and hardly higher than 1 for BR farms. The  $GEE_{\text{Lvstk}}$  value is also the greatest for SM farms. The values for the other territories are similar and almost 50% lower than for SM farms. On the contrary  $LEE_{\text{Lvstk}}$  is far lower for the SM farms. The  $SEE_{\text{Lvstk}}$  values is 2 times higher for SM farms than for farms in the thress others territories ware efficiency are numerically similar.

## IV. DISCUSSION

### 4.1. The pluri-energy analysis allows a comprehensive description of energy use in various dairy systems

In our study, fossil energy use to produce milk is very variable between territories and in the range of values previously reported in the literature (Figure 5). It should be noted that value for RI farms are similar to the highest values previously reported whereas value for SM farm are the lowest never reported. Beyond relative comparisons, applying the pluri-energy analysis method enabled a comprehensive description of very different dairy systems and produces precise explanations for efficiency and inefficiency.

For SM, the difficulty of accessing fossil energy inputs, especially through mechanization and mineral fertilizers, is counter-balanced by the large amounts of labor energy in the systems. Therefore fossil energy efficiencies for livestock and farm level are very high but labor efficiency is low in comparison to systems of others territories. This shift reduces the conversion rate of solar energy into both animal and crop products, as illustrated by low solar energy efficiency and high  $FEE_{\text{Farm}}$  and  $FEE_{\text{Lvstk}}$  values.



<sup>a</sup> Recalculated from an expected milk density of 1.03 kg.L<sup>-1</sup>

<sup>b</sup> Recalculated from the formula for Energy Corrected Milk given by Sjaunja et al. (1990)

<sup>c</sup> Recalculated from an average content of Swedish milk of 4.34% fat and 3.37% protein (Lindmark-Mansson et al., 2003).

<sup>d</sup> Recalculated from an average content of 4.05% fat and 3.48% protein for organic farms and 4.30% fat and 3.39% protein for conventional farms (Van der Werf et al., 2009)

**Figure 5** Comparison of energy use obtained in this study with results for dairy systems in the literature

Moreover, limited access to feed supplements leads to low  $FEU_{Lvstck}$  values, expressed per LU or  $MJ.l^{-1}$ . The multiple functions obtained from the livestock, particularly from manure, result in relatively high  $GEP_{Lvstck}$  values and low  $FEU_{Lvstck}$  values, expressed in  $MJ.l^{-1}$ , as compared to references for dairy systems in the literature (Figure 5). In RI, socioeconomic constraints play a key role in dairy and energy management systems, leading to high rates of fossil energy use in the production of milk (Figure 5). The development of the dairy sector is promoted by financial and technical support from the European Union to maintain populations in the highlands and to improve the island's food self-sufficiency, which is still below 40% for milk. The limited availability of arable land is a critical factor in animal feeding, and as a result, imports of concentrate feeds are significant, with high levels of  $GEU_{Lvstck}$  imported to feed herds. Due to the indirect fossil energy costs of producing and importing concentrate feeds, these practices increase  $FEU_{Lvstck}$  values. While land is mainly dedicated to sugarcane and meat production, dairy systems are rarely based on grazing (Table 1). Scarce grasslands are intensively exploited, with four to six cuttings per year. This process leads to high mechanization costs and results in  $FEU_{Forage}$  values that are three times greater than those for PC and BR, despite high forage yields. High  $FEU_{Lvstck}$  values are mainly explained by the large quantities of concentrate feeds distributed to lactating cows. Although

they are situated in countries with more similar socioeconomic and climatic conditions, the energetic performances for Cash&crops are rather similar between PC and BR but the PC and BR systems show some differences in the energy indicators for livestock and whole farm levels. For PC, the  $FEE_{L\text{vstck}}$  and  $FEE_{\text{forage}}$  values are lower than those for BR. In PC, the use of maize silage, which is partially associated with the presence of irrigation to secure forage systems (Amigues et al., 2006), has increased at the expense of grazing. This forage system requires higher fossil energy inputs compared to grazing based on harvest costs and protein supplementation. Because systems based on grazing lands are less common in PC, the average value for  $FEE_{\text{Forage}}$  is lower. The higher fossil energy cost associated with higher concentrated feed imports due to low yields affects the  $FEE_{L\text{vstck}}$  values.

#### 4.2. Intensification and efficiency of energy use

The specialization of livestock systems tends to simplify natural ecosystems (Swift et al., 1996; Izac and Sanchez, 2001) by replacing ecosystem functions with external and industrialized inputs. This shift decreases interactions among the components of a system. This is illustrated in our study by a decrease in the number and diversity of internal energy flows in high-input systems (RI, PC, BR) compared to low-input smallholder systems (SM). In OECD countries, the specialization of dairy systems has been accompanied by the intensification of agricultural systems through mechanization and the generalization of input use. This phenomenon is often perceived as a management strategy for increasing technical and economical efficiency (Simpson and Conrad, 1993; Reinhard et al., 1999; Alvarez et al., 2008). In our study, the effects of intensification on the productivity of agricultural lands were large, as shown by the amount of gross energy produced per unit area for RI, PC and BR farms compared to SM farms (Table 4).

The efficiency of solar radiation capture is notably increased by intensification. In our study, the  $SEE_{\text{Cash\&Food}}$  and  $SEE_{\text{Forage}}$  values are at least 2 to 8 times greater for high-input systems (RI, PC, BR) than the corresponding values for low-input systems (SM). Even if the effects of severe climatic conditions and the limited use of inputs on biomass production in SM are difficult to distinguish, agronomists often associate the insufficient use of mineral fertilizers or other nutrient inputs (Tittonell et al., 2009) with low rates of productivity. Values of  $SEE_{\text{Cash\&Food}}$  in our study ranges from  $2.5 \times 10^{-3}$  to  $5.7 \times 10^{-3}$  and  $SEE_{\text{Forage}}$  values ranging from  $0.5 \times 10^{-3}$  to  $6.9 \times 10^{-3}$ , the results obtained in our study are similar to current values observed at the field scale in Britain (Monteith, 1977) and the US (Heaton et al., 2008). Potential gains for solar energy use efficiency are important when considering the maximum



efficiency of solar energy conversion rate into gross energy given by [Zhu et al. \(2008\)](#) of  $43.0 \times 10^{-3}$  for C3 photosynthesis and  $60.0 \times 10^{-3}$  for C4 photosynthesis. Moreover, as demonstrated by [Conelly \(1992\)](#) and [Kennedy \(2000\)](#), mechanization enables reductions in human and animal labor and increases its efficiency in the production of food. In our study,  $LEE_{Crop}$  and  $LEE_{Lstck}$  values are approximately 25 times greater in PC and BR than in SM. For SM farms, labor energy investments in livestock yield low calorific benefits for crop activities. This calculation could misrepresent the nutritional requirements of animals if the predominant economic and agronomic interests fail to consider manure.

Intensification can also have a negative effect on system efficiency if resources (e.g., feed concentrates or mineral fertilizers) are not well managed. In this case, an inverse relationship between productivity and sustainability can be observed ([Viglizzo and Roberto, 1998](#), [Basset-Mens et al., 2009](#)). In our study, among intensive systems, the efficiency of fossil energy use at the farm and livestock levels is lower for the most intensive system of RI farms. These results show that the most intensive systems are less resilient to fossil energy price variations.

Despite low rates of fossil energy use on crops and low energy conversion rates of solar energy into gross energy by crops, fossil energy efficiency of SM farms is high for all components. These results contrast with the dominant image of cattle from extensive livestock systems as contributors to land use problems, air and water pollution, water depletion and biodiversity losses ([Steinfeld et al., 2006](#)). Globally, this finding contrasts with conclusions regarding the contribution of low-input systems to global warming ([FAO, 2010](#)) as compared to industrialized systems. The capacity of traditional low-input ruminant systems to convert plant biomass that has no direct value for humans or monogastric species into food has been documented by [Coughenour et al. \(1985\)](#) for nomadic pastoral systems in Kenya and by [de Ridder and Wagenaar \(1986\)](#) for traditional livestock systems in Botswana.

The intensification of extensive systems is crucial for the advancement of developing countries. Because the world's human population may increase to 9.2 billion by 2050, the global demand for animal products will increase over the next several decades. Large increases in milk production, which have been associated with increases in life expectancy, have been observed in developing countries ([FAO, 2009](#)). In OECD and North American countries, agricultural yields are already high, and the land available for agriculture has been fully exploited ([Paillard et al., 2010](#)). Thus, the challenge of livestock intensification is particularly relevant for developing countries. Governance of the livestock sector should be strengthened to ensure that its development is environmentally sustainable. The pluri-energy analysis method proposed in this paper can be used to support the sustainable intensification

of world livestock systems and clearly shows that large margins of progress do exist. [Herrero et al. \(2010\)](#) stated that the intensification of systems in developing countries will require a closer integration of livestock and crop production systems to improve productivity rather than a systematic use of inputs as in the classical intensification pathways observed in OECD countries that may be not appropriate ([Waithaka et al., 2006](#); [Tittonell et al., 2009](#)). The pluri-energy analysis method can represent and quantify the relationship between crop and livestock activities.

### **4.3. Methodological strengths and limitations of the pluri-energy analysis method**

To provide comprehensive descriptions of each system, the pluri-energy method analysis utilizes four methodological approaches: accounting for all types of energy, considering internal flows, considering manure as a product and delimiting the system to encompass all components operating in the agricultural system.

#### **4.3.1. Accounting for all types of energy**

The accounting of all energy types enables the efficiency of energy use to be measured during the main biological processes of the agricultural system. These processes include i) the transformation of solar energy at the crop level into metabolizable energy via photosynthesis and ii) the transformation of non-useful energy (cellulose) into digestible energy for humans at the livestock level. This accounting facilitates an in-depth description of the systems and highlights explanatory factors.

However, the pluri-energy analysis method proposes an unequal accounting of indirect energy. It is generally assumed that both direct and indirect fossil energy must be taken into account to calculate fossil energy use efficiency. However, assessing the indirect solar energy and labor energy needed to produce farm inputs is helpful in understanding transfers of the environmental impacts associated with solar energy and the social impacts associated with labor energy. In this sense, the method could consider two accounting levels corresponding to two levels of analysis. The first level would be similar to the method described in this study: direct and indirect fossil energy and other direct energy sources would be considered to explore the efficiency of indirect and direct fossil energy use while transforming direct solar energy at the crop level and direct gross energy at the livestock level. The second level would consist of accounting for all direct and indirect energy sources to analyze common social and environmental impact transfers. For indirect labor energy, quantification could be based on social Life Cycle Analysis ([Dreyer et al., 2006](#)), especially with the simple assessment of the Life Cycle Working Time ([Wolf et al., 2002](#)). The accounting of indirect solar energy is

possible based on Emergy synthesis (Odum, 1996). Emergy is defined as the available energy of a certain kind, usually quantified in solar-energy, which has been used directly or indirectly to make a product or provide a service. This allows for accounting on a common basis all the inputs that contributed to the construction of a product, including environmental ones. In this sense, as pointed out by Vigne et al. (2012a), it gets interest similarly to pluri-energy analysis to achieve the holistic assessment of all energy forms in an agricultural system especially face to recent improvements in the methodology (Bastianoni and Marchettini, 2000; Cavalett et al., 2006; Ju and Chen, 2011). Applying emergy synthesis on the same panel of dairy systems could enable to highlight respective and common interest in such a way.

#### **4.3.2. Considering internal flow of energy**

Considering internal flows provides information on the different productive components within a system and highlights the origins of differences in energy efficiency. This approach allows comparisons of similar production systems in different territories, accounting for variable livestock and crop components of systems. The method makes it possible to compare systems that differ in the proportion of crop and animal products and the total gross energy produced. For example, the importance of cash and food crops for PC farms leads to higher  $FEE_{Farm}$  values in comparison to BR farms although fossil energy efficiency for forage land and for livestock are lower. The decomposition of the internal flows into different components requires allocating the different energy uses among different products. Several modes of allocation have been proposed: economic allocation, mass allocation, protein allocation, energy allocation, biological allocation and system expansion (Cederberg and Mattsson, 2000; Eide, 2002; Hospido et al., 2003; de Vries and de Boer, 2010; Dollé et al., 2011). A lack of economic data in some territories prevented the use of economic allocation. Biological allocation is relevant for comparing different ratios between meat and milk in livestock production systems, but it is more difficult to implement when considering crop products. In our study, the choice of energy allocation was motivated by the global scope of the method and the focus on energy flows. Furthermore, a comparison of the effects of the energy, protein and mass allocation methods on  $FEU_{Lvstk}$  values was conducted and no differences were observed (personal communication). Therefore, it is assumed that the use of energy allocation was sufficient for our purposes.

#### **4.3.3. Considering manure as a product**

Accounting for manure as a product of the herd also increases the genericity of the method. The aim of intensive livestock systems is primarily to generate income for the livestock holder and to produce food calories for human consumption. In extensive mixed crop-

livestock systems, the roles of the herd are to store capital, to supply manure as a fertilizer and to provide draft power for crops (Randolph et al., 2007; Herrero et al., 2010). The proportion of manure in the total gross energy produced at the farm and livestock levels for the four territories confirms these roles (Table 4).

**Table 4**

Proportion of the different products in total gross energy produced for the four territories at the farm and livestock levels

| Level     | Products         | ML | RI | PC | BR |
|-----------|------------------|----|----|----|----|
| Farm      | Vegetal products | 66 | 0  | 54 | 64 |
|           | Milk             | 3  | 96 | 43 | 34 |
|           | Meat             | 4  | 3  | 3  | 3  |
|           | Manure           | 27 | 1  | 0  | 0  |
| Livestock | Milk             | 2  | 86 | 82 | 84 |
|           | Meat             | 3  | 3  | 6  | 6  |
|           | Manure           | 95 | 11 | 12 | 10 |

As shown in Table 5, not accounting for manure could significantly increase  $FEU_{L_{vstck}}$  values, expressed in  $MJ.l^{-1}$ , and consequently increase the environmental costs of milk. Failing to consider manure especially penalizes the production of milk in SM due to the importance of manure to the total  $GEP_{L_{vstck}}$ . In intensive livestock systems, accounting for manure energy might be worthwhile for methane production.

**Table 5**

$FEU_{L_{vstck}}$  values (in  $MJ.l^{-1}$ ) for the four territories (SM: South Mali, RI: Reunion Island, PC: Poitou-Charentes, BR: Bretagne), with or without the accounting of manure as a herd product

|                                  | SM  | RI  | PC  | BR  |
|----------------------------------|-----|-----|-----|-----|
| $FEU_{L_{vstck}}$ with manure    | 0.1 | 6.6 | 3.6 | 4.9 |
| $FEU_{L_{vstck}}$ without manure | 2.9 | 7.4 | 4.1 | 5.3 |
| Significativity <sup>a</sup>     | *** | **  | *   | *   |

<sup>a</sup>ns = p-value>0.05, \*\*\* = 0.05<p-value<0.01), \*\* = 0.01<p-value<0.001, \*\*\* = p-value<0.001

#### 4.3.4. Definition of the spatial boundaries of the system

Plentinger and Penning de Vries (1996) stated that there are few methods that can be used to compare fossil energy use for different agricultural production systems. Similarly, the number of methods that have been proposed to compare fossil energy use for similar agricultural production systems in different territories is limited. Comparisons are extremely sensitive to the choice of scale and the boundaries of the analysis (Dalgaard et al., 2001). The pluri-energy analysis method tends to surpass these limits by proposing a generic conceptual

model and basic principles for defining the spatial boundaries to analyze and compare mixed dairy systems and other specialized and non-specialized systems.

Defining the spatial boundaries of a system and decomposition tend to encompass all components operating in the agricultural system. The cut-off criteria in the proposed method are based on the levels of direct interactions among farm components and between the farmer and others. While the inclusion of farm crops within the system boundaries is not debatable, considering natural pasture (communal lands), such as on-farm land, is questionable. For SM, up to 70% of the total used area is represented by natural pasture and not accounting for them could result in  $FEU_{Farm}$  values that are more than two times greater than their actual values. Natural pasture may be considered as indirect land used to produce feed that is unavailable on farms; this definition resembles land outside the farm that is needed to produce imported concentrated feed because these lands are not owned by the farmer. However, the farm herd interacts with these lands directly during grazing and farmers collectively manage these lands. Moreover, these lands represent an important feed resource for livestock in many systems in developing countries (Herrero et al., 2010). The accounting of lands that are indirectly used is therefore important even though the amount of biomass is limited. Not accounting for these lands could lead to misinterpretations of indicators expressed per hectare. With high  $SEE_{Lvsstk}$  values, RI farms appear to be the most efficient converters of solar energy into livestock products. This finding is mainly due to high livestock rates resulting from a lack of land and a high dependence on non-farm lands. The definition of system boundaries can help to separate direct and indirect crops based on the distinction between farm lands that are managed by the farmer and non-farm lands that are indirectly used by the farmer but regarding which he does not make any decisions. This approach is similar to the ecological footprint methodology (Wackernagel and Rees, 1996).

## **V. CONCLUSION**

In this study, an original method for the environmental assessment of dairy systems was developed. The pluri-energy analysis method is based on four types of energy used in a system, fossil, gross, labor and solar energy, considers internal flows and delimits the system to encompass all components operating in the agricultural system and facilitates an in-depth description of the systems and highlights explanatory factors. The application of this method to four dairy systems located in contrasting territories enabled a comparison of the different modes of energy use between smallholder low-input systems (SM) and the high-input systems

(RI, PC and BR) as those encountered in OECD countries. The climatic and socioeconomic factors that affect management practices and the efficiency of fossil energy use were analyzed. SM farms are mainly based on solar and labor energy but they are particularly efficient in the conversion of fossil energy into gross energy (feed and food). These results counterbalance the dominant image of cattle from extensive livestock systems as contributors to land use problems, air and water pollution, water depletion and biodiversity losses and demonstrate their capacity to convert plant biomass that has no direct value for humans or monogastric species into high nutritional human food.

These differences in energy efficiency raise questions regarding the sustainable intensification of livestock production systems in the world that is needed to respond to increasing demands for animal products. The method proposed in this paper enables to describe functioning of agro-ecosystems could be useful for designing agricultural systems both highly productive and efficient to valorize the different energy sources, especially fossil energy.

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## 2. Application de la méthode emergy sur les quatre territoires<sup>8</sup>

**Emergy evaluation at different levels of contrasting dairy systems from low-input smallholder systems to high-input intensive systems**

***Evaluation émergétique de systèmes laitiers contrastés issus de différents territoires analysés à différents niveaux d'échelle***

M. Vigne, J.L. Peyraud, M. Corson, A. Wilfart

*Original Research Article* – **Soumis dans Journal of Environmental Management**

### **Résumé**

La méthode Emergy a été appliquée sur différents systèmes de production laitiers : des systèmes familiaux à faibles intrants du Mali Sud (SM), des systèmes mobilisant des quantités d'intrants intermédiaires de deux régions métropolitaines françaises, le Poitou-Charentes (PC) et la Bretagne (BR), et des systèmes très intensifs à haute quantité d'intrants issus d'un territoire insulaire français, l'Ile de la Réunion. Ces systèmes ont été étudiés à trois niveaux d'échelle : à l'échelle de l'exploitation qui inclue l'atelier laitier et les surfaces de cultures, à l'échelle de l'atelier lait en considérant le troupeau laitier et les surfaces fourragères et à l'échelle du troupeau laitier incluant seulement les animaux. Les résultats obtenus montrent que les systèmes du SM sont de faibles consommateurs d'emergy à tous les niveaux d'échelle mais que la part des ressources naturelles dans cette emergy totale est élevée. Malgré des ressources consommées de faibles qualités agronomiques (résidus de culture et parcours naturels), l'efficacité de leur utilisation est proche de l'efficacité d'utilisation des intrants industriels observable dans les systèmes industriels de RI, PC et BR. De plus, les systèmes de SM apparaissent plus durable environnementalement. L'application de la méthode emergy met également en lumière des spécificités entre les trois autres territoires. Les systèmes de RI et PC apparaissent moins efficaces pour transformer les ressources utilisées et moins durables environnementalement que les systèmes de BR. Ceci semble dû principalement aux choix de stratégies d'alimentation différentes pour répondre aux contraintes socio-climatiques propres à chaque territoire. Au-delà des différences entre système qu'elle permet de mettre en lumière, l'application de la méthode Emergy à différents niveaux d'échelle montre également un

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<sup>8</sup> Cette partie est présentée sous forme d'un article scientifique soumis dans Journal of Environmental Management auquel a été ajouté un résumé en français

intérêt particulier. Si l'analyse à l'échelle globale apparaît utilisée pour évaluer la contribution globale du système son environnement, le niveau d'échelle correspondant à l'atelier lait permet de comparer des systèmes sous l'angle d'un même produit, même dans le cas de panier de production très différents comme ceux étudiés ici. De plus, l'analyse à l'échelle du troupeau permet de se concentrer sur les pratiques de gestion du troupeau et évite les débats sur la définition des limites du système.

### **Abstract**

Emergy accounting (EmA) was applied to a range of dairy systems, from low-input smallholder systems in South Mali (SM), to intermediate-input systems in two regions of France, Poitou-Charentes (PC) and Brittany (BR), to high-input systems on Reunion Island (RI). These systems were studied at three different levels: whole-farm (dairy system and cropping system), dairy-system (dairy herd and forage land), and herd (animals only). Dairy farms in SM used the lowest total emergy at all levels and was the highest user of renewable resources. Despite the low quality of resources consumed (crop residues and natural pasture), efficiency of their use was similar to that of industrialised inputs by intensive systems in RI, PC and BR. In addition, among the systems studied, SM dairy farms lay closest to environmental sustainability, contradicting the usual image of high environmental impact of cattle production in developing countries. EmA also revealed characteristics of the three intensive systems. Systems from RI and PC had lower resource transformation efficiency and higher environmental impacts than those from BR, due mainly to feeding strategies that differed due to differing socio-climatic constraints. Application of EmA at multiple levels revealed the importance of a multi-level analysis. While the whole-farm level assesses the overall contribution of the system to its environment, the dairy-system level is suitable for comparison of multi-product systems. In contrast, the herd level focuses on herd management and bypasses debates about definition of system boundaries by excluding land management. Combining all levels highlights the contribution of livestock to the global agricultural system and identifies inefficiencies and influences of system components on the environment.

## **I. INTRODUCTION**

Climate change and pollution have led to global concern about environmental impacts of human activities. Livestock farming is primary among these societal challenges. It is currently held responsible for 18% of greenhouse gas emissions of the planet (Steinfeld et al., 2006).

Since the global human population will potentially increase to 9.2 billion by 2050 (United Nations, 2007), and with increasing numbers of people in middle classes in developing countries, global demand for animal products will increase (FAO, 2009). In this sense, assessing livestock systems and increasing their production without increasing their environmental impact is a major challenge.

Many methods have been used to assess environmental impacts of livestock systems. Most concern life cycle analysis (de Vries and de Boer, 2010) or ecological footprint (Berg et al., 1996; Kautsky et al., 1997; van der Werf et al., 2007; Kissinger and Rees, 2009). The concept of energy accounting (EmA) has existed for several years (Castellini et al., 2006; Cavalett et al., 2006; Rótolo et al., 2007; Xi and Qin, 2009; Li et al., 2011; Zhang et al., 2011). EmA is defined as the available energy of a certain kind that has been used, directly or indirectly, to make a product or provide a service (Odum, 1996). It is usually quantified in solar-energy equivalents and expressed as solar emJoules (seJ). This allows for accounting on a common basis all the inputs that contributed to the construction of a product, including environmental ones that are considered “free” in energy or life cycle analyses. EmA is used to measure environmental stress, especially when estimating long-term sustainability in natural-resource management (Ulgiati and Brown, 1998).

Increasing demand for animal products particularly concerns milk, whose production is expected to double between 2000 and 2050 (Steinfeld et al., 2006). Milk production occurs throughout the world in a variety of forms, from extensive smallholder systems with low inputs to confinement systems with high inputs. In most cases, milk production represents the central economic activity of farms with a dairy subsystem (FAO, 2009). Assessing and comparing contrasting dairy production systems is an important goal. Thus, the main aim of this study was to perform EmA on such a range of dairy-production systems: low-input smallholder systems in South Mali; intermediate-input systems in two regions of France (Poitou-Charentes and Brittany), and a high-input system on Reunion Island. Moreover, few livestock systems have been assessed with EmA (Vigne et al., 2012), in particular dairy systems (Bastianoni and Marchettini, 2000; Brandt-Williams, 2002). This paper discusses the utility of assessing multiple farming system levels and the suitability of recent improvements in energy methodology for doing so for livestock systems.

## II. MATERIALS AND METHODS

### 2.1. Description of the territories and dairy-production systems

South Mali (SM) corresponds to the peri-urban region of Sikasso (11° 19' N, 5° 40' W) and is representative of western African savannah. The local climate has a relatively high mean temperature and two seasons: a dry season from December-May and a rainy season from June-November, during which precipitation averages 1.1 m (Table 1).

**Table 1**

Mean climate in the four territories (SM: South Mali, RI: Reunion Island, PC: Poitou-Charentes, BR: Bretagne)

|   | SM   | RI   | PC   | BR   |
|---|------|------|------|------|
| Annual precipitation (m)                      | 1.1  | 3.0  | 0.9  | 1.1  |
| Annual temperature (°C)                       | 26   | 24   | 13   | 11   |
| Annual solar radiation (kWh.m <sup>-2</sup> ) | 2150 | 1750 | 1300 | 1150 |

The area contains approximately 70% of natural pasture and 30% of Cash&Food crops (Table 2). To cultivate Cash&Food crops, human labour is completed by draft animals. Fertilisation is based for a large part (66%) on manure, mainly due to the high cost of mineral fertilisers. Cattle herds are usually small and composed of local bovines and zebus from a wide diversity of ages and types (e.g., calves, dairy cows, draft cows, bulls) fed by crop residues and grazing on natural pasture. Few feed concentrates are distributed, illustrating the low intensification of herds, which results in low milk yield (212 l.cow<sup>-1</sup>). SM systems can be considered low-input systems.

Reunion Island (RI) is a French territory in the Indian Ocean (21° 09' S, 55° 30' E) with a tropical climate. It has relatively high mean temperature and precipitation (Table 1) but localised mesoclimates. For example, the eastern part of the island is exposed to trade winds and is humid (3.0–6.0 m of precipitation per year), whereas the western part, protected by the central mountains, receives less than 1.0 m of precipitation per year. This diversity of terrain and climate has led to different feeding strategies. Under 800 m of altitude, forage crops cultivated are tropical, whereas over this limit, tropical and temperate species are associated (Barbet-Massin et al., 2004). Herds mainly consist of Holstein Friesian and mean size is 55.5 LU. Produced forages are mainly ensiled and distributed to animals (Table 2). Lack of arable land has led to a high stocking rate (4.4 LU.ha<sup>-1</sup>) and high supplementation of feed concentrates (4,672 kg.LU<sup>-1</sup>). The mean mineral fertilisation rate is high (194 kg N.ha<sup>-1</sup>) to optimise biomass production. High quantities of concentrates and mineral fertilisers make RI systems high-input systems.

**Table 2**  
Mean (and minimum-maximum) characteristics of studied farms in the four territories (SM: South Mali, RI: Reunion Island, PC: Poitou-Charentes, BR: Bretagne)

| Territory ( <i>number of farms studied</i> )            | SM ( <i>n=14</i> )     | RI ( <i>n=30</i> )       | PC ( <i>n=48</i> )        | BR ( <i>n=38</i> )       |
|---|------------------------|--------------------------|---------------------------|--------------------------|
| Herd size (LU)  | <b>32.8</b> (9.8-64.8) | <b>55.5</b> (24.0-131.2) | <b>94.4</b> (27.9-220.0)  | <b>79.2</b> (38.0-125.5) |
| Dairy cows in herd (%)                                  | <b>52</b> (37-100)     | <b>78</b> (57-100)       | <b>66</b> (56-98)         | <b>66</b> (51-82)        |
| Usable agricultural area (UAA) (ha)                     | <b>36.5</b> (6.1-76.7) | <b>22.0</b> (2.5-72.0)   | <b>135.3</b> (30.0-378.3) | <b>80.3</b> (28.6-200.0) |
| Forage-crop area in UAAC (%)                            | <b>70</b> (10-100)     | <b>100</b> (100-100)     | <b>60</b> (15-100)        | <b>78</b> (56-100)       |
| Non-forage crop area in UAA (%)                         | <b>30</b> (0-90)       | <b>0</b> (0-0)           | <b>40</b> (0-85)          | <b>22</b> (0-44)         |
| Overall farm stocking rate (LU.ha <sup>-1</sup> )       | <b>1.0</b> (0.5-1.6)   | <b>4.4</b> (1.2-10.8)    | <b>0.8</b> (0.3-1.4)      | <b>1.1</b> (0.6-1.7)     |
| Forage-crop area stocking rate (LU.ha <sup>-1</sup> )   | <b>2.4</b> (0.7-16.8)  | <b>4.4</b> (1.2-10.8)    | <b>1.5</b> (0.4-3.8)      | <b>1.4</b> (0.6-2.2)     |
| Human workforce (AWU)                                   | <b>4.3</b> (2.6-9.8)   | <b>2.5</b> (1.3-4.5)     | <b>2.5</b> (1.0-4.5)      | <b>1.8</b> (1.0-3.5)     |
| Grazing area in UAA (%)                                 | <b>0</b> (0-0)         | <b>27</b> (0-58)         | <b>48</b> (26-100)        | <b>70</b> (50-90)        |
| Mineral N on Cash&Food crops (kg N.ha <sup>-1</sup> )   | <b>33</b> (6-57)       | -                        | <b>95</b> (0-197)         | <b>94</b> (0-161)        |
| Organic N on Cash&Food crops (kg N.ha <sup>-1</sup> )   | <b>64</b> (11-187)     | -                        | <b>22</b> (0-147)         | <b>23</b> (0-148)        |
| Mineral N on forage crops (kg N.ha <sup>-1</sup> )      | -                      | <b>194</b> (30-1022)     | <b>77</b> (0-220)         | <b>41</b> (0-93)         |
| Organic N on forage crops (kg N.ha <sup>-1</sup> )      | -                      | <b>91</b> (0-383)        | <b>52</b> (0-260)         | <b>86</b> (16-344)       |
| Concentrate feeds (kg.LU <sup>-1</sup> )                | <b>123</b> (0-365)     | <b>4672</b> (2375-7375)  | <b>2020</b> (338-3649)    | <b>1311</b> (663-2082)   |
| Grassland production (t DMF.ha <sup>-1</sup> )          | <b>1.9<sup>b</sup></b> | <b>12.6</b> (6.2-24.4)   | <b>5.8</b> (3.9-9.0)      | <b>6.4</b> (5.5-7.5)     |
| Silage production <sup>a</sup> (t DM.ha <sup>-1</sup> ) | -                      | <b>22.6</b> (10.2-45.2)  | <b>12.8</b> (10.0-17.0)   | <b>13.4</b> (7.1-17.0)   |
| Cereal yield (t.ha <sup>-1</sup> )                      | <b>1.6</b> (0.3-4.5)   | -                        | <b>6.0</b> (4.0-6.5)      | <b>8.0</b> (5.5-11.5)    |
| Milk yield (L.cow <sup>-1</sup> )                       | <b>212</b> (56-1130)   | <b>6082</b> (3545-9314)  | <b>7515</b> (4627-9719)   | <b>7012</b> (4757-8950)  |

LU: Livestock Unit (1 LU = 250 kg of animal body weight for SM and 500 kg for RI, PC and BR), AWU: Agricultural Workforce Unit corresponding to the number of persons usually working on farms, DM: dry matter

<sup>a</sup> Grass silage in RI and maize silage in PC and BR

<sup>b</sup> Estimated from Penning de Vries and Djiteye (1982)



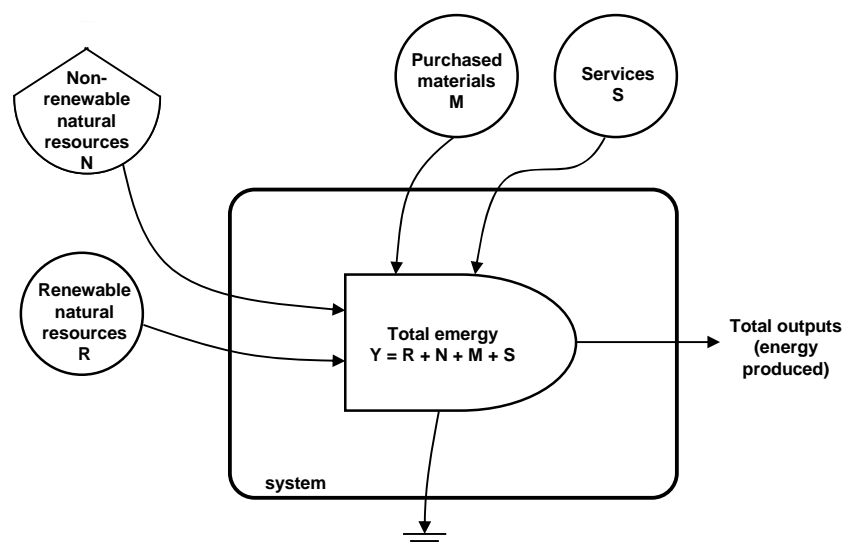
Poitou-Charentes (PC) is a region in western France (46° 05' N, 00° 10' E) with an oceanic climate characterised by precipitation distributed throughout the year and a moderate mean temperature (Table 1). It has relatively large farms with relatively large herds (94.4 LU), mainly Holstein Friesian and Normande breeds (Table 2). Farms are diversified, ranging from specialised dairy systems to mixed crop-livestock systems. The mean proportion of grazing area in total farm area is relatively high (48%), but a low mean stocking rate leads to low availability of manure and thus a relatively high mean quantity of mineral fertiliser applied (77 kgN.ha<sup>-1</sup>). Grassland biomass production is relatively low, but mean distribution of feed concentrates exceeds 2,000 kg.LU<sup>-1</sup>, which leads to high milk production (7,515 l.cow<sup>-1</sup>).

Britanny (BR) (48° 00' N, 03° 00' W) is also located in western France and has a climate similar to that of PC (Table 1). Dairy farms are smaller, however, with fewer animals (Table 2). Crops are less common because dairy systems are more specialised. Mineral fertilisation on forage land is lower to that in PC (41 kgN.ha<sup>-1</sup>), while grassland biomass production is higher. Milk production is relatively high (7,012 l.cow<sup>-1</sup>), but distribution of feed concentrates is low (1,311 kg.LU<sup>-1</sup>). Consequently, in this study, both PC and BR systems can be considered intermediate-input systems.

## 2.2. Application of emergy accounting

Detailed description of emergy methodology is given by [Odum \(1996\)](#) and others ([Ulgiati and Brown, 1998](#); [Brown and Ulgiati, 2004](#)). However, application of EmA can be simplified into three steps.

The first step is drawing an energy system diagram of processes (Figure 1).



**Figure 1** System diagram of a generic production system (from [Agostinho et al., 2008](#))

This diagram illustrates boundaries of the system, main components and their relationships and energy sources. The energy sources are aggregated into renewable natural resources (R), non-renewable natural resources (N), purchased materials (M) and services (S). Diagrams follow a specific language (Odum, 1996), and each symbol has a meaning (e.g., bullets represent “production”, hexagons represent “consumers”).

The second step is the construction of an evaluation table based on the diagram that contains flows of energy inputs and outputs expressed in raw units. Inputs are then associated with unit energy values (UEV), which represent the amount of the solar energy, expressed in  $seJ.raw\ unit^{-1}$  (Brown and Ulgiati, 2004), required to generate each flow.

UEV are also called energy intensities (Brown and Buranakarn, 2003) or solar transformities (Odum, 1996) when expressed in  $seJ.J^{-1}$ . Finally, each input flow is multiplied by its specific UEV to calculate its energy content, and energy inputs into the system are added together to calculate total energy input. Each energy input also has an associated renewability factor (Agostinho et al., 2008), which corresponds to the proportion of renewable energy sources in its energy flow. UEV and renewability factors come from the literature or are recalculated through local energy evaluation (Appendix B<sup>9</sup>). Finally, the third step is the calculation of energy ratios, such as those used in this study (Table 3).

**Table 3**  
Energy ratios calculated in this study

| Indicator                                  | Unit         | Expression                          |
|--|--------------|-------------------------------------|
| Transformity of milk ( <i>Tr</i> )         | $seJ.L^{-1}$ | $Y / \text{milk quantity}$          |
| Renewability (% <i>R</i> )                 | %            | $100 \times (R + M_R + S_R) / Y$    |
| Energy Yield Ratio ( <i>EYR</i> )          | unitless     | $Y / (M_N + S_N)$                   |
| Energy Investment Ratio ( <i>EIR</i> )     | unitless     | $(M_N + S_N) / (R + N + M_R + S_R)$ |
| Environmental Loading Ratio ( <i>ELR</i> ) | unitless     | $(M_N + S_N + N) / (R + M_R + S_R)$ |
| Energy Sustainability Index ( <i>ESI</i> ) | unitless     | $EYR / ELR$                         |

*seJ: solar emJoule*

Transformity of milk corresponds to the total energy inputs (Y) needed to produce one litre of milk. Total energy was allocated between products according to the energy allocation proposed by Bastianoni and Marchettini (2000). Transformity represents the energy efficiency of production (Brown and Ulgiati, 2004), with higher values indicating greater need for environmental resources for the process or product. Renewability (%*R*) is the percentage of renewable energy used by the system; systems with high renewability are

<sup>9</sup> Dans ce manuscrit, les UEVs se trouvent en Chapitre IV.3 alors que les facteurs de renouvelabilité se trouvent en Annexe IX

considered closer to being environmentally sustainable (Brown and Ulgiati, 2004). Emergy Yield Ratio (*EYR*) is the ratio of total emergy inputs divided by the emergy of non-renewable inputs from purchased materials and services. *EYR* measures of the ability of a process to exploit and make local resources available by investing in outside resources (Agostinho et al., 2008). Emergy Investment Ratio (*EIR*) corresponds to the ratio of non-renewable emergy inputs from the economy to emergy inputs from nature and renewable emergy inputs from the economy. *EIR* evaluates how well a process uses invested emergy, compared to alternative uses for the same resources (Brown and Ulgiati, 2004). Environmental Loading Ratio (*ELR*) is the ratio of total non-renewable emergy inputs to total renewable-emergy inputs; it assesses the carrying capacity of a production system (Brown and Ulgiati, 1997) and can be considered a measure of ecosystem stress (Agostinho et al., 2008). Finally, Emergy Sustainability Index (*ESI*), the ratio of *EYR* to *ELR*, measures the potential contribution of a resource or process to the economy per unit of environmental loading (Brown and Ulgiati, 2004).

In our calculations, only the largest contributor of renewable natural resources was considered when calculating emergy ratios, since renewable resources are co-products of the same phenomenon, i.e., sunlight reaching the biosphere (Odum, 1996). EmA was applied to a representative dairy farm for each territory (construction described below) at three levels: whole-farm (dairy system and cropping system), dairy-system (dairy herd and forage land), and herd (animals only).

### 2.3. Data sources

Farm data included structural factors (e.g., usable agricultural area, herd size), crop management (e.g., fertilisation, crop yield), livestock management (e.g., concentrate feeds, milk yield) and human and animal labour. SM farm data came from Coulibaly (2008) and interviews with heads of farm households. RI farm data came from 2007 individual economic report and interviews. PC and BR farm data (2008-2009 and 2008, respectively) came from the national DIAPASON database (Charroin et al. 2005). Data about soil and climate in the four territories came from soil and climate databases and tools: BDAT (<http://bdat.gissol.fr>), Climatik (<https://intranet.inra.fr/climatik>), SolarGIS (<http://solargis.info>) and Climathèque (<http://climatheque.meteo.fr>).

## III. RESULTS

### 3.1. Emergy evaluation at the whole-farm level

Construction of system diagrams at whole-farm level for the four territories resulted in three different system diagrams (Figure 2): one each for SM, RI and the French continental farms (PC and BR). Total energy input was by far highest in RI ( $596.45\text{E}+14 \text{ seJ}\cdot\text{ha}^{-1}$ ) and lowest in SM ( $65.56\text{E}+14 \text{ seJ}\cdot\text{ha}^{-1}$ ), with PC and BR in-between (132.61 and  $108.08\text{E}+14 \text{ seJ}\cdot\text{ha}^{-1}$ , respectively) (Table 4).

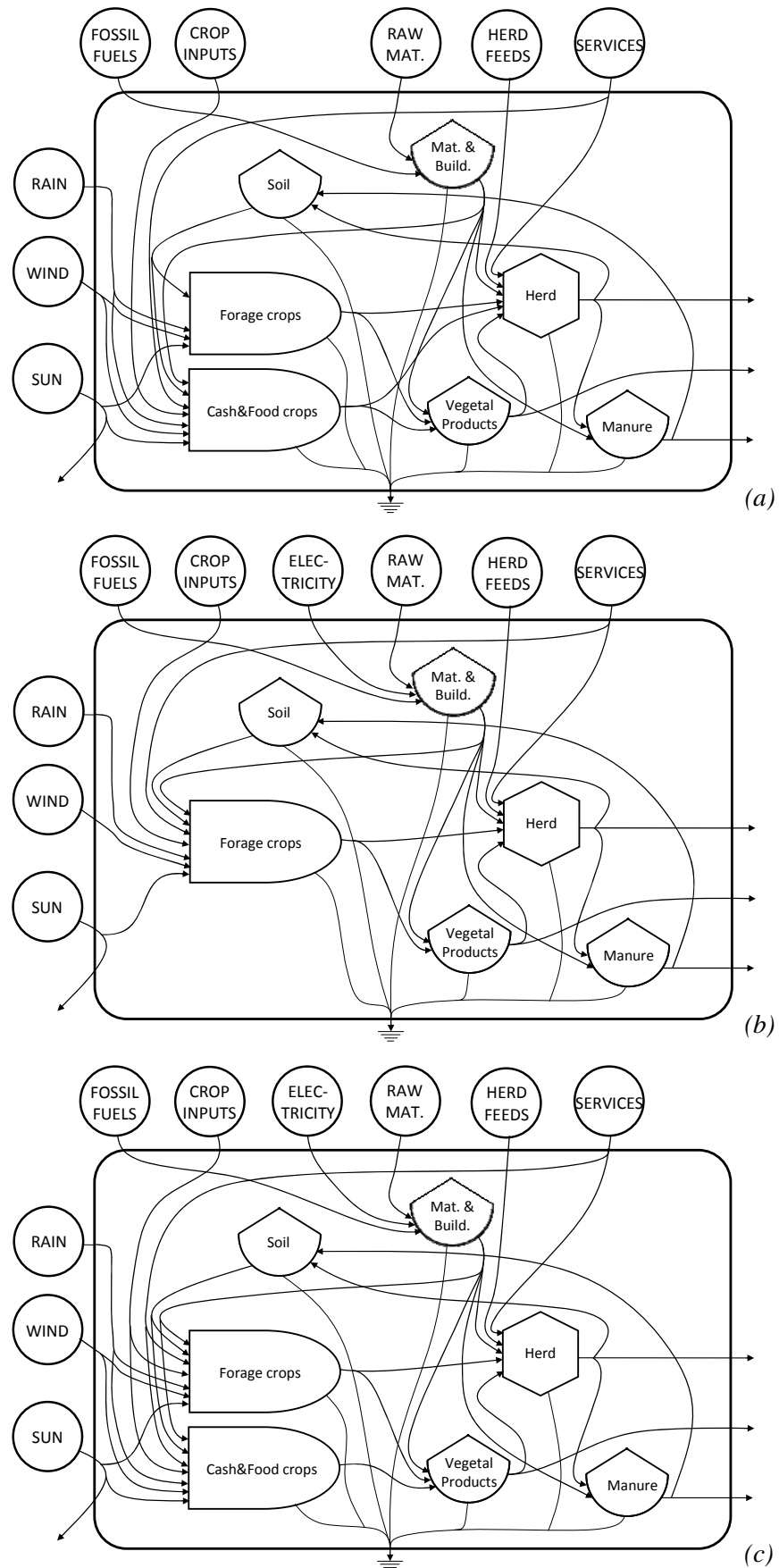
**Table 4**

Energy flow in the four territories (SM: South Mali, RI: Reunion Island, PC: Poitou-Charentes, BR: Bretagne) at the whole-farm level ( $\times 10^{14} \text{ seJ}\cdot\text{ha}^{-1}$ )

| Note                                       | Item                   | SM           |      | RI            |      | PC            |      | BR            |      |
|--|------------------------|--------------|------|---------------|------|---------------|------|---------------|------|
|  |                        | Energy       | %    | Energy        | %    | Energy        | %    | Energy        | %    |
| <i>Natural renewable resources (R)</i>     |                        |              |      |               |      |               |      |               |      |
| 1  | Sunlight               | 0.57         | -    | 0.48          | -    | 0.37          | -    | 0.32          | -    |
| 2  | Rain                   | 15.36        | 24.2 | 37.71         | 6.3  | 13.79         | 10.4 | 13.90         | 12.9 |
| 3  | Wind                   | 1.35         | -    | 0.57          | -    | 0.33          | -    | 0.23          | -    |
| <i>Non-renewable natural resources (N)</i> |                        |              |      |               |      |               |      |               |      |
| 4  | Erosion                | 1.91         | 2.9  | 27.84         | 4.7  | 0.56          | 0.4  | 0.56          | 0.5  |
| 5  | Water                  | 0.01         | <0.1 | 0.30          | <0.1 | 1.25          | 0.9  | 0.31          | 0.3  |
| <i>Materials (M)</i>                       |                        |              |      |               |      |               |      |               |      |
| 6  | Fuel                   | 0.02         | <0.1 | 15.06         | 2.5  | 7.02          | 5.3  | 6.19          | 5.8  |
| 7  | Electricity            | 0.00         | 0.0  | 3.69          | 0.6  | 6.82          | 5.2  | 6.84          | 6.4  |
| 8  | N Fertiliser           | 3.10         | 4.9  | 34.61         | 5.8  | 43.50         | 33.0 | 20.24         | 18.8 |
| 9  | P Fertiliser           | 2.61         | 4.1  | 10.73         | 1.8  | 7.13          | 5.4  | 1.65          | 1.5  |
| 10   | K Fertiliser           | 0.13         | 0.2  | 0.93          | 0.2  | 0.36          | 0.3  | 0.11          | 0.1  |
| 11   | Manure                 | 7.07         | 11.1 | 4.17          | 0.7  | 10.11         | 7.7  | 13.62         | 12.7 |
| 12   | Chemicals              | 0.11         | 0.2  | 0.10          | <0.1 | 0.18          | 0.1  | 0.10          | 0.1  |
| 13   | Plastics               | 0.00         | 0.0  | 0.62          | 0.1  | 1.32          | 1.0  | 1.07          | 1.0  |
| 14   | Feed concentrates      | 25.46        | 40.0 | 300.92        | 50.5 | 20.80         | 15.8 | 19.53         | 18.1 |
| 15   | Milk powder            | 0.00         | 0.0  | 9.56          | 1.6  | 1.41          | 1.1  | 0.40          | 0.4  |
| 16   | External pasture       | 1.82         | 2.9  | 0.00          | 0.0  | 0.00          | 0.0  | 0.00          | 0.0  |
| 17   | Forages                | 0.04         | <0.1 | 57.67         | 9.7  | 3.19          | 2.4  | 3.43          | 3.2  |
| 18   | Animals                | 1.25         | 2.0  | 41.05         | 6.9  | 0.00          | 0.0  | 0.00          | 0.0  |
| 19   | Minerals               | 0.20         | 0.3  | 0.02          | <0.1 | 0.02          | <0.1 | 0.04          | <0.1 |
| 20   | Seeds                  | 0.18         | 0.3  | 2.12          | 0.4  | 0.76          | 0.6  | 1.42          | 1.3  |
| 21   | Machinery depreciation | 0.08         | 0.1  | 8.16          | 1.4  | 1.99          | 1.5  | 2.55          | 2.4  |
| 22   | Buildings - Wood       | <0.01        | <0.1 | 0.00          | 0.0  | 0.00          | 0.0  | 0.00          | 0.0  |
| 23   | Buildings - Mud        | <0.01        | <0.1 | 0.00          | 0.0  | 0.00          | 0.0  | 0.00          | 0.0  |
| 24   | Buildings - Concrete   | 0.10         | 0.2  | 9.98          | 1.7  | 3.80          | 2.9  | 5.38          | 5.0  |
| 25   | Buildings - Steel      | 0.02         | <0.1 | 8.36          | 1.4  | 3.86          | 2.9  | 3.33          | 3.1  |
| <i>Services (S)</i>                        |                        |              |      |               |      |               |      |               |      |
| 26   | Veterinary costs       | 2.32         | 3.7  | 17.51         | 2.9  | 3.17          | 2.4  | 5.50          | 5.1  |
| 27   | Human labour           | 1.63         | 2.6  | 4.29          | 0.7  | 0.87          | 0.7  | 1.36          | 1.3  |
| 28   | Animal labour          | 0.22         | 0.3  | 0.00          | 0.0  | 0.00          | 0.0  | 0.00          | 0.0  |
| <b>Total energy (Y)</b>                    |                        | <b>65.56</b> |      | <b>596.45</b> |      | <b>132.61</b> |      | <b>108.08</b> |      |
| <i>Outputs (O)</i>                         |                        |              |      |               |      |               |      |               |      |
| 29   | Milk                   | 238          | 1.1  | 44,026        | 95.8 | 12,305        | 13.8 | 16,651        | 37.5 |
| 30   | Meat                   | 315          | 1.5  | 1,526         | 3.3  | 964           | 1.1  | 1,280         | 2.9  |
| 31   | Manure                 | 1782         | 8.6  | 416           | 0.9  | 5             | <0.1 | 0             | 0.0  |
| 32   | Vegetal products       | 18370        | 88.7 | 0             | 0.0  | 75,717        | 85.1 | 26,528        | 59.7 |

Footnotes given in appendix A1<sup>10</sup>

<sup>10</sup> Dans ce manuscrit, le détail des calculs se trouve en Annexe XA



**Figure 2** System diagram at the whole-farm level for dairy farms in (a) South Mali, (b) Reunion Island, and (c) Poitou-Charentes and Bretagne

The largest emergy inputs to farms in SM and RI were feed concentrates (40.0 and 50.5%, respectively). In contrast, in PC and BR, N fertiliser was the largest input (33.0 and 18.8%, respectively), followed by feed concentrates (15.8 and 18.1%).

Main differences between the system diagrams include the absence of non-forage crops in RI and no use of crop inputs or labour on forage crops in SM.

Total emergy flow came mainly (66-85%) from purchased materials (M) in all four territories, while the percentage from renewable natural resources (R) ranged from 6% in RI to 24% in SM (Table 5).

**Table 5**

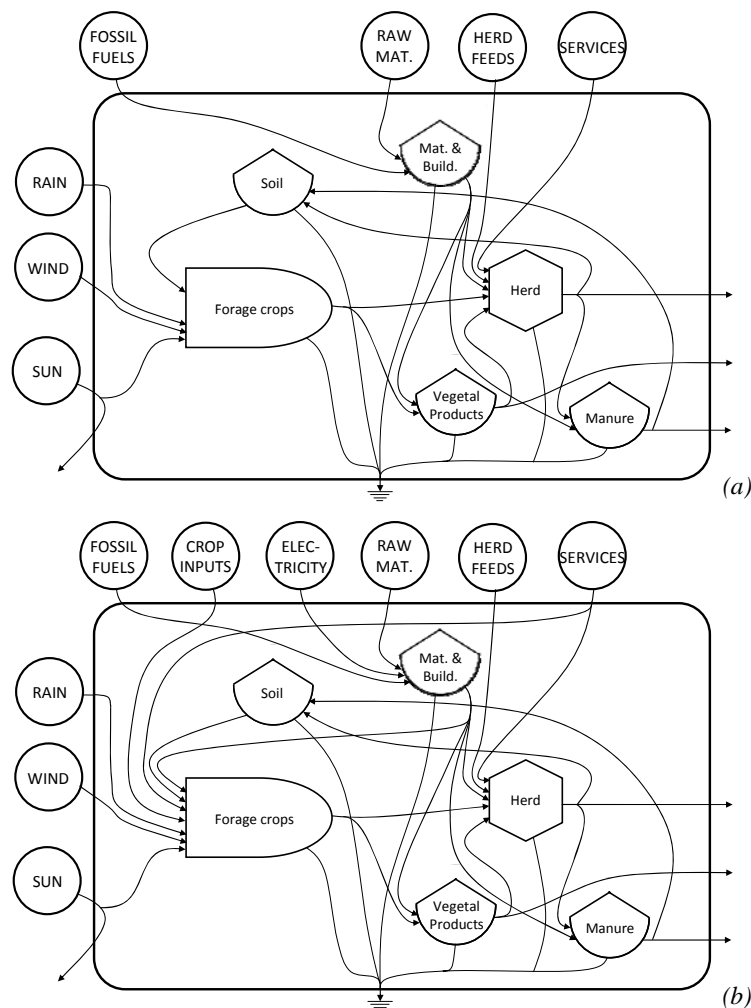
Emergy indicators of dairy farms from four territories (SM: South Mali, RI: Reunion Island; PC: Poitou-Charentes, BR: Bretagne) calculated at all levels

| Level        | Emergy indicators   | SM   | RI   | PC   | BR   |
|--------------|---|------|------|------|------|
| Whole-farm   | Renewable natural resources (R) (%)                           | 24   | 6    | 10   | 13   |
|              | Non-renewable natural resources (N) (%)                       | 3    | 5    | 1    | 1    |
|              | Purchased materials (M) (%)                                   | 66   | 85   | 85   | 80   |
|              | Services (S) (%)  | 7    | 4    | 3    | 6    |
|              | Transformity of milk ( $\times 10^{12}$ seJ.L <sup>-1</sup> ) | 1.51 | 4.06 | 0.62 | 0.81 |
|              | Renewability (%Renew) (%)                                     | 45   | 21   | 19   | 23   |
|              | Emergy Yield Ratio (EYR)                                      | 1.92 | 1.34 | 1.26 | 1.31 |
|              | Emergy Investment Ratio (EIR)                                 | 1.09 | 2.95 | 3.88 | 3.19 |
|              | Emergy Loading Ratio (ELR)                                    | 1.23 | 3.86 | 4.23 | 3.33 |
|              | Emergy Sustainability Index (ESI)                             | 1.56 | 0.35 | 0.30 | 0.39 |
| Dairy-system | Renewable natural resources (R) (%)                           | 22   | 6    | 9    | 13   |
|              | Non-renewable natural resources (N) (%)                       | 3    | 5    | 2    | 2    |
|              | Purchased materials (M) (%)                                   | 69   | 85   | 84   | 77   |
|              | Services (S) (%)  | 7    | 4    | 5    | 8    |
|              | Transformity of milk ( $\times 10^{12}$ seJ.L <sup>-1</sup> ) | 3.64 | 4.06 | 2.21 | 1.52 |
|              | Renewability (%Renew) (%)                                     | 44   | 21   | 21   | 24   |
|              | Emergy Yield Ratio (EYR)                                      | 1.89 | 1.34 | 1.13 | 1.35 |
|              | Emergy Investment Ratio (EIR)                                 | 1.12 | 2.95 | 3.95 | 2.86 |
|              | Emergy Loading Ratio (ELR)                                    | 1.25 | 3.86 | 4.39 | 3.25 |
|              | Emergy Sustainability Index (ESI)                             | 1.51 | 0.35 | 0.26 | 0.42 |
| Herd         | Renewable natural resources (R) (%)                           | 25   | 0    | 0    | 0    |
|              | Non-renewable natural resources (N) (%)                       | 0    | 0    | 1    | 2    |
|              | Purchased materials (M) (%)                                   | 69   | 97   | 93   | 90   |
|              | Services (S) (%)  | 6    | 3    | 6    | 8    |
|              | Transformity of milk ( $\times 10^{12}$ seJ.L <sup>-1</sup> ) | 2.11 | 3.70 | 2.08 | 1.39 |
|              | Renewability (%Renew) (%)                                     | 44   | 21   | 21   | 24   |
|              | Emergy Yield Ratio (EYR)                                      | 2.09 | 1.26 | 1.32 | 1.34 |
|              | Emergy Investment Ratio (EIR)                                 | 1.12 | 3.83 | 4.04 | 2.94 |
|              | Emergy Loading Ratio (ELR)                                    | 1.23 | 3.84 | 4.39 | 3.25 |
|              | Emergy Sustainability Index (ESI)                             | 1.71 | 0.33 | 0.26 | 0.41 |

Transformity of milk was by far highest in RI ( $4.06E+12 \text{ seJ.l}^{-1}$ ), followed by SM, BR, and PC (1.51, 0.81, and  $0.62E+12 \text{ seJ.l}^{-1}$ , respectively). %Renew of the systems was highest in SM (45%) while in the other territories it ranged from 19% (PC) to 23% (BR). EYR was highest in SM (1.92) than that for other territories which present close values (1.26 in PC, 1.31 in BR and 1.34 in RI). Conversely, EIR (1.09) in SM was the lowest. Its highest value was obtained in PC (3.88), with RI and BR in-between (2.95 and 3.19, respectively). Lowest and highest values of ELR were also obtained respectively in SM (1.23) and PC (4.23) with RI and BR in-between (3.86 and 3.33, respectively). ESI was close in RI, PC and BR (0.35, 0.30 and 0.39, respectively), but about five times higher for SM (1.56).

### 3.2. Energy evaluation at the dairy-system level

To focus on dairy production, Cash&Food crops were omitted at the dairy-system level, resulting in two different diagrams (Figure 3): one for SM and one for the French dairy systems (RI, PC and BR).



**Figure 3** System diagrams at dairy-system level for dairy farms in (a) South Mali and (b) Reunion Island, Poitou-Charentes and Bretagne (b)

The main difference between the two diagrams is the absence of electricity and no use of crop inputs or labour on forage crops in SM.

Total emergy input in RI (595.45E+14 seJ.ha<sup>-1</sup>) was five times higher than in PC (122.31 E+14 seJ.ha<sup>-1</sup>) and BR (108.25 E+14 seJ.ha<sup>-1</sup>) and just less than ten times higher than SM (71.72 E+14 seJ.ha<sup>-1</sup>) (Table 6).

**Table 6**

Emergy flow in the four territories (SM: South Mali, RI: Reunion Island, PC: Poitou-Charentes, BR: Bretagne) at the dairy system level (x10<sup>14</sup> seJ.ha<sup>-1</sup>)

| Note                                       | Item                   | SM     |      | RI     |      | PC     |      | BR     |      |
|--|------------------------|--------|------|--------|------|--------|------|--------|------|
|  |                        | Emergy | %    | Emergy | %    | Emergy | %    | Emergy | %    |
| <b>Natural renewable resources (R)</b>     |                        |        |      |        |      |        |      |        |      |
| 1  | Sunlight               | 0.57   | -    | 0.48   | -    | 0.31   | -    | 0.32   | -    |
| 2  | Rain                   | 15.36  | 22.0 | 37.71  | 6.3  | 11.43  | 9.4  | 13.81  | 12.8 |
| 3  | Wind                   | 1.35   | -    | 0.57   | -    | 0.33   | -    | 0.23   | -    |
| <b>Non-renewable natural resources (N)</b> |                        |        |      |        |      |        |      |        |      |
| 4  | Erosion                | 1.91   | 2.7  | 27.84  | 4.7  | 0.47   | 0.4  | 0.56   | 0.5  |
| 5  | Water                  | <0.01  | <0.1 | 0.30   | <0.1 | 1.74   | 1.4  | 2.03   | 1.9  |
| <b>Materials (M)</b>                       |                        |        |      |        |      |        |      |        |      |
| 6  | Fuel                   | 0.01   | <0.1 | 15.06  | 2.5  | 5.24   | 4.3  | 4.41   | 4.1  |
| 7  | Electricity            | 0.00   | 0.0  | 3.69   | 0.6  | 10.78  | 8.9  | 8.10   | 7.5  |
| 8  | N Fertiliser           | 0.00   | 0.0  | 34.61  | 5.8  | 29.32  | 24.1 | 12.75  | 11.9 |
| 9  | P Fertiliser           | 0.00   | 0.0  | 10.73  | 1.8  | 4.30   | 3.5  | 1.84   | 1.7  |
| 10   | K Fertiliser           | 0.00   | 0.0  | 0.93   | 0.2  | 0.31   | 0.3  | 0.11   | 0.1  |
| 11   | Manure                 | 0.00   | 0.0  | 4.17   | 0.7  | 0.26   | 0.2  | 0.74   | 0.7  |
| 12   | Chemicals              | 0.00   | 0.0  | 0.10   | <0.1 | 0.05   | <0.1 | 0.06   | 0.1  |
| 13   | Plastics               | 0.00   | 0.0  | 0.62   | 0.1  | 2.20   | 1.8  | 1.35   | 1.3  |
| 14   | Feed concentrates      | 36.28  | 52.0 | 300.92 | 50.5 | 21.88  | 18.0 | 26.63  | 24.8 |
| 15   | Milk powder            | 0.00   | 0.0  | 9.56   | 1.6  | 2.35   | 1.9  | 0.50   | 0.5  |
| 16   | Crop residues pasture  | 9.57   | 13.7 | 0.00   | 0.0  | 0.00   | 0.0  | 0.00   | 0.0  |
| 17   | Forages                | 0.06   | 0.1  | 57.67  | 9.7  | 12.89  | 10.6 | 15.89  | 14.7 |
| 18   | Animals                | 1.78   | 2.5  | 41.05  | 6.9  | 0.00   | 0.0  | 0.00   | 0.0  |
| 19   | Minerals               | 0.29   | 0.4  | 0.02   | <0.1 | 0.03   | <0.1 | 0.05   | <0.1 |
| 20   | Seeds                  | 0.00   | 0.0  | 2.12   | 0.4  | 0.57   | 0.5  | 1.45   | 1.3  |
| 21   | Machinery depreciation | 0.01   | <0.1 | 8.16   | 1.4  | 2.10   | 1.7  | 2.12   | 2.0  |
| 22   | Buildings - Wood       | <0.01  | <0.1 | 0.00   | 0.0  | 0.00   | 0.0  | 0.00   | 0.0  |
| 23   | Buildings - Mud        | <0.01  | <0.1 | 0.00   | 0.0  | 0.00   | 0.0  | 0.00   | 0.0  |
| 24   | Buildings - Concrete   | <0.01  | <0.1 | 9.98   | 1.7  | 4.27   | 3.5  | 3.18   | 2.9  |
| 25   | Buildings - Steel      | <0.01  | <0.1 | 8.36   | 1.4  | 4.93   | 4.0  | 3.47   | 3.2  |
| <b>Services (S)</b>                        |                        |        |      |        |      |        |      |        |      |
| 26   | Veterinary costs       | 3.31   | 4.7  | 17.51  | 2.9  | 5.27   | 4.3  | 7.01   | 6.5  |
| 27   | Human labour           | 1.10   | 1.6  | 4.29   | 0.7  | 1.28   | 1.1  | 1.64   | 1.5  |
| 28   | Animal labour          | 0.12   | 0.2  | 0.00   | 0.0  | 0.00   | 0.0  | 0.00   | 0.0  |
| <b>Total emergy (Y)</b>                    |                        | 71.72  |      | 596.45 |      | 122.31 |      | 108.25 |      |
| <b>Outputs (O)</b>                         |                        |        |      |        |      |        |      |        |      |
| 29   | Milk                   | 339    | 2.9  | 44,026 | 95.8 | 20,488 | 88.3 | 21,359 | 87.6 |
| 30   | Meat                   | 449    | 3.9  | 1,526  | 3.3  | 1,606  | 6.9  | 1,642  | 6.7  |
| 31   | Manure                 | 10,748 | 93.2 | 416    | 0.9  | 1,120  | 4.8  | 1,393  | 5.7  |

Footnotes given in appendix A2<sup>11</sup>

<sup>11</sup> Dans ce manuscrit, le détail des calculs se trouve en Annexe XB

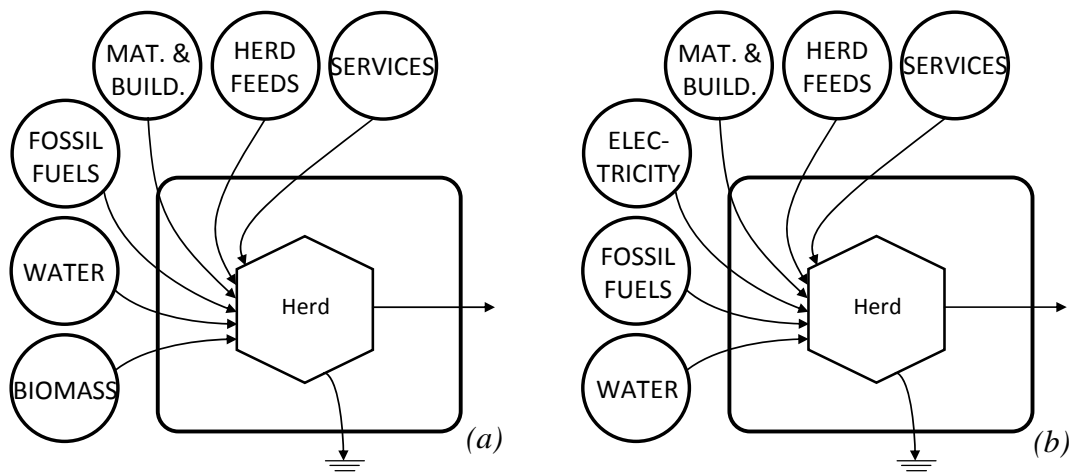


Concentrate feeds represented more than 50% of total energy inputs in SM and RI. In SM, remaining energy input was mainly represented by rain (22.0%) and crop residues (13.7%), whereas in RI it was shared among several sources. In PC and BR, total energy input was distributed between four main sources (rain, N fertiliser, feed concentrates and forages), with N fertiliser largest in PC (24.1%) and feed concentrates largest in BR (24.8%).

This total energy flow was predominantly represented by purchased materials (M) in the four territories (69-85%) while the percentage from renewable natural resources (R) ranged from 6% (RI) to 22% (SM) (Table 5). Transformity of milk was highest for RI ( $4.06E+12$  seJ.l<sup>-1</sup>) and SM ( $3.64E+12$  seJ.l<sup>-1</sup>) while it was lower in PC ( $2.21E+12$  seJ.l<sup>-1</sup>) and BR ( $1.52E+12$  seJ.l<sup>-1</sup>). %Renew was highest in SM (44%) followed by BR (24%) and RI and PC (21%). EYR was also highest in SM (1.89) while it was close in RI and BR (1.34 and 1.35, respectively) and lowest in PC (1.13). Conversely, SM presented the lowest value of EIR (1.12). Highest value of EIR was obtained in PC (3.95) while values in RI (2.95) and BR (2.86) are in-between. Similarly, highest and lowest values for ELR were found respectively in PC (4.89) and SM (1.25) while they were 3.86 in RI and 3.25 in BR. ESI was highest for SM (1.51). Values for other territories were lower than 0.50 times (0.42 for BR, 0.35 for RI and 0.26 for PC).

### 3.3. Energy evaluation at the herd level

Construction of herd-level system diagrams resulted in two diagrams differentiated in SM by the absence of electricity and presence of biomass from natural pasture (Figure 4).



**Figure 4** System diagrams at the dairy-herd level for dairy farms from South Mali (a) and Reunion Island, Poitou-Charentes and Bretagne (b)

Total emergy per livestock unit was highest for RI (236.24E+14 seJ.LU<sup>-1</sup>) (Table 7). PC and BR had intermediate values (104.65E+14 seJ.LU<sup>-1</sup> and 85.12E+14 seJ.LU<sup>-1</sup>, respectively) whereas SM had the lowest value (54.51E+14 seJ.LU<sup>-1</sup>).

**Table 7**

Emergy flow in the four territories (SM: South Mali, RI: Reunion Island, PC: Poitou-Charentes, BR: Bretagne) at the herd level (10<sup>14</sup> seJ.LU<sup>-1</sup>)

| Note                                       | Item                      | SM     |      | RI     |      | PC     |      | BR     |      |
|--|---------------------------|--------|------|--------|------|--------|------|--------|------|
|  |                           | Emergy | %    | Emergy | %    | Emergy | %    | Emergy | %    |
| <b>Renewable natural resources (R)</b>     |                           |        |      |        |      |        |      |        |      |
| 1  | Biomass (natural pasture) | 13.48  | 24.7 | 0.00   | 0.0  | 0.00   | 0.0  | 0.00   | 0.0  |
| <b>Non-renewable natural resources (N)</b> |                           |        |      |        |      |        |      |        |      |
| 2  | Water                     | 0.01   | <0.1 | 0.12   | 0.1  | 1.49   | 1.4  | 1.59   | 1.9  |
| <b>Materials (M)</b>                       |                           |        |      |        |      |        |      |        |      |
| 3  | Fuel                      | 0.01   | <0.1 | 1.21   | 0.5  | 0.78   | 0.7  | 1.35   | 1.6  |
| 4  | Electricity               | 0.00   | 0.0  | 1.46   | 0.6  | 9.27   | 8.9  | 6.40   | 7.5  |
| 5  | Feed concentrates         | 28.33  | 52.0 | 119.28 | 50.5 | 18.83  | 18.0 | 21.06  | 24.7 |
| 6  | Milk powder               | 0.00   | 0.0  | 3.79   | 1.6  | 2.02   | 1.9  | 0.39   | 0.5  |
| 7  | Forage pasture            | 0.00   | 0.0  | 12.91  | 5.5  | 7.92   | 7.6  | 13.68  | 16.1 |
| 8  | Crop residues pasture     | 7.46   | 13.7 | 0.00   | 0.0  | 0.00   | 0.0  | 0.00   | 0.0  |
| 9  | Given forages             | 0.05   | 0.1  | 67.52  | 28.6 | 50.68  | 48.5 | 28.12  | 33.0 |
| 10   | Animals                   | 1.39   | 2.5  | 16.27  | 6.9  | 0.00   | 0.0  | 0.00   | 0.0  |
| 11   | Minerals                  | 0.22   | 0.4  | 0.01   | <0.1 | 0.02   | <0.1 | 0.04   | <0.1 |
| 12   | Machinery depreciation    | 0.02   | <0.1 | 0.22   | 0.1  | 0.35   | 0.3  | 0.49   | 0.6  |
| 13   | Buildings - Wood          | 0.00   | 0.0  | 0.00   | 0.0  | 0.00   | 0.0  | 0.00   | 0.0  |
| 14   | Buildings - Mud           | 0.00   | 0.0  | 0.00   | 0.0  | 0.00   | 0.0  | 0.00   | 0.0  |
| 15   | Buildings - Concrete      | 0.00   | 0.0  | 2.44   | 1.0  | 3.56   | 3.4  | 2.51   | 3.0  |
| 16   | Buildings - Steel         | 0.00   | 0.0  | 2.84   | 1.2  | 4.10   | 3.9  | 2.74   | 3.2  |
| <b>Services (S)</b>                        |                           |        |      |        |      |        |      |        |      |
| 17   | Veterinary costs          | 2.58   | 4.7  | 6.94   | 2.9  | 4.53   | 4.3  | 5.54   | 6.5  |
| 18   | Human labour              | 0.86   | 1.6  | 1.33   | 0.5  | 1.10   | 1.1  | 1.21   | 1.4  |
| 19   | Animal labour             | 0.10   | 0.2  | 0.00   | 0.0  | 0.00   | 0.0  | 0.00   | 0.0  |
| <b>Total emergy (Y)</b>                    |                           | 54.51  |      | 236.54 |      | 104.65 |      | 85.12  |      |
| <b>Outputs (O)</b>                         |                           |        |      |        |      |        |      |        |      |
| 20   | Milk                      | 265    | 2.4  | 17,452 | 89.2 | 17,623 | 84.3 | 16,883 | 82.8 |
| 21   | Meat                      | 351    | 3.2  | 605    | 3.1  | 1,381  | 6.6  | 1,298  | 6.4  |
| 22   | Manure                    | 10,495 | 94.5 | 1,513  | 7.7  | 1,911  | 9.1  | 2,203  | 10.8 |

Footnotes given in appendix A3<sup>12</sup>

In SM and RI, total emergy input came mainly from feed concentrates (52.0 and 52.5%, respectively), followed by biomass from natural pasture in SM (24.7%) and purchased forages in RI (28.6%). In PC and BR, the main emergy sources were purchased forages (48.5 and 33.0%, respectively) and feed concentrates (18.0 and 24.7%, respectively).

The total emergy flow was almost totally represented by purchased materials in RI (97%), PC (93%) and BR (90%) (Table 5). If purchased materials (M) also represented the most important source in SM (69%); renewable natural resources (R) had a high percentage (25%) whereas they represent 0% in other territories. Transformity for milk was lowest in BR

<sup>12</sup> Dans ce manuscrit, le détail des calculs se trouve en Annexe XC

( $1.39\text{E}+12 \text{ seJ.l}^{-1}$ ) and highest in RI ( $3.70\text{E}+12 \text{ seJ.l}^{-1}$ ) while SM and PC presented close values ( $2.11$  and  $2.08\text{E}+12 \text{ seJ.l}^{-1}$ , respectively). %Renew were 44% of renewable energy flows in SM, 21% in RI and PC and 24% in BR. EYR was highest in SM (2.09) while it ranged from 1.26 (SM) to 1.34 (BR) for other territories. EIR was far lowest in SM (1.12) followed by BR, RI and PC (2.94, 3.83 and 4.04, respectively). Lowest and highest values for ELR were found respectively in SM (1.23) and PC (4.39) with RI and BR in-between (3.84 and 3.25, respectively). ESI was highest in SM (1.71) and considerably lower in other territories (0.33 for RI, 0.26 for PC and 0.41 for BR).

## IV. DISCUSSION

### 4.1. System comparison

Application of EmA on dairy systems from the four territories showed major differences in energy use and energy indicators among the territories. With little economic access to industrial inputs, especially fertiliser and feed concentrates (Table 3), SM systems were more based on direct use of local resources, which led to low total energy input and lower EIR. At the SM whole-farm level, natural resource use was especially high (24%), which appears a useful strategy to substitute industrial inputs. Strong interaction between crops and livestock is central for optimising the use of both. One approach is the use of dual-purpose crops (Herrero et al., 2010) whose grain and residues provide food for humans and livestock, respectively. At the SM dairy-system level, crop residues were an important energy input (13.7%). Another adaptation to low availability of agricultural inputs is the use of direct resources which need less energy, such as natural pasture, which represented 70% of usable agricultural area in SM. The ability of traditional low-input ruminant livestock systems to convert low-quality plant biomass into human food is known (Coughenour et al., 1985; de Ridder and Wagenaar, 1986). For SM farms, at the dairy and herd levels, high EYR (1.89 and 2.09, respectively) and a transformity of milk ( $3.64$  and  $2.11\text{E}+12 \text{ seJ.l}^{-1}$ , respectively) close to that of other systems indicates their efficiency in using these resources. Moreover, high use of natural pasture and crop residues, which do not constitute human food, places the SM farms closer to sustainability. Finally, low access to mechanisation in SM farms was compensated by relatively high energy flows from human and animal labour (2.6% at the whole-farm level, compared to 0.7-1.3% in the other territories). Use of few industrial inputs and efficient use of renewable resources and labour conferred a relatively low environmental impact of SM farms at all levels, illustrated by high renewability (44-45%) and low ELR

(1.23-1.25). ELR values close to 1 suggest that SM systems may have been environmentally sustainable (Brown and Ulgiati, 2004) which could appear in contradiction with dominant image of cattle as a large contributor to overgrazing (Delgado et al., 1999), air and water pollution, water depletion and biodiversity loss (Steinfeld et al., 2006).

Specialisation of agricultural systems tends to simplify their surrounding ecosystems (Swift et al., 1996, Izac and Sanchez, 2001), mainly by replacing ecosystem functions by external and industrialised inputs. The substitution of renewable resources with purchased materials at all levels of RI, PC and BR supports this assertion. EYR did not exceed 1.50 and showed large dependence of industrial inputs, similar to intensified agricultural systems previously studied (Castellini et al., 2006; Martin et al., 2006; La Rosa et al., 2008; Cavalett and Ortega, 2009; de Barros et al., 2009). The resulting ESI never reached 0.50, a value indicative of highly developed consumer-oriented economies (La Rosa et al., 2008). Use of a greater amount of industrialised inputs seemed to place systems further from environmental sustainability. Unlike in SM, %Renew did not exceed 30% in the other three territories, which is similar to intensified livestock systems previously studied (Cavalett et al., 2006 ; Agostinho et al., 2008) but lower than that for a grazing beef-cattle system in the Argentinean Pampas (Rótolo et al., 2007). In addition, ELR ranged from 3 to 4 among systems, indicating that they had a moderate impact on the environment (Brown and Ulgiati, 2004). Finally, specialisation of systems is often perceived as a strategy to increase their technical and economic efficiency (Simpson and Conrad, 1993; Reinhard et al., 1999; Alvarez et al., 2008). However, this assertion is first called into question by close or higher transformities of milk than SM at the herd level in respectively PC and RI illustrating a close or lower efficiency in transformation of mobilized resources. Secondly, higher EIR for the three territories in comparison to SM illustrates higher part of non-renewable purchased inputs in total emergy input. Assuming their economic costs, it indicates lower efficiency in valorizing economic inputs into milk.

Comparing the three intensive systems, the RI dairy system had the highest total emergy input. Development of the dairy sector in RI is supported financially and technically by the European Union to maintain population in the highlands and improve the island's food self-sufficiency. But limited availability of arable land is a critical factor for animal feeding. Because land there is dedicated mainly to sugarcane and meat production, imports of concentrate feeds are high. Despite a large use of concentrate feeds, RI milk yield per cow was 19% lower than the mean yield in PC and BR. It resulted in transformity of milk close to that observed by Brandt-Williams (2002) in Florida (USA), but lower than that of PC and BR. It thus had a low efficiency in transforming its mobilized resources into milk. ELR for RI and

PC were higher than those in BR, indicating greater environmental impact following the EmA methodology (Brown and Ulgiati, 2004). EYR and ELR values led to lower ESI for RI and PC than for BR. Farms in both PC and RI depended on transformed resources. RI farms use large amount of concentrate feeds to compensate for a lack of arable land. PC farms, in a harsher climate, use maize silage to secure forage systems (Amigues et al., 2006). It leads especially to higher use of mineral fertilisation at dairy system level and higher use of concentrate feeds at herd level mainly in the form of imported soybean meal as a high-protein complement. Conversely, BR farms are based more on grazing land, a more direct use of natural resources; their lower ESI argues for livestock grazing, as demonstrated by Rótolo et al. (2007). In this sense, BR dairy farms could appear as a good compromise between system intensification and low stress on the environment.

#### 4.2. Analysing the system at different scales

EmA at multiple levels was performed to offer a more complete assessment of dairy farms. Definition of system boundaries is a central issue when assessing an agricultural system; different boundaries may lead to different results and conclusions (Dixon et al., 2001), as observed in this study. Considering the whole-farm level is useful for assessing the overall influence of the farm on its environment, as done in previous studies of livestock systems (Martin et al., 2006; Rótolo et al., 2007; Agostinho et al., 2008). However, a transformity value per litre of milk produced may not be suitable or relevant at this level and confirms purpose for other energy indicators (Brown and Ulgiati, 1997). Indeed, farms in this study had large differences in structure and especially production. The presence of non-forage crops in SM, PC and BR may result in additional energy flows and modify energy indicators. Thus, comparison energy indicators for the same product from such different production systems may have less utility at the whole-farm level.

Energy indicators obtained at the dairy-system level had few differences from those at the whole-farm level despite the exclusion of Cash&Food crops. This is because the total energy per hectare and the profile of energy used on crops was similar to those used on dairy systems (forage lands and herd). For example, total energy used at whole-farm level in SM, PC and BR was 65.56, 132.61, and 108.08 seJ.ha<sup>-1</sup>, respectively, versus 71.72, 122.31, and 108.25 seJ.ha<sup>-1</sup> for their dairy systems, respectively. Moreover, despite a slightly higher energy use, non-forage crops covered less area in the dairy systems than forage crops (22-40%). However, a study of grazing cattle in Argentina noted larger differences between crop

and livestock subsystems [Rotoló et al. \(2007\)](#). Analysing both levels thus remains useful for highlighting the contribution of the livestock subsystem to the farm system.

Except for RI, only transformity of milk differed between the dairy-system and whole-farm levels, due to the similarity of both systems and the difference between grain and animal production transformities ([Cavalett et al., 2006](#)). Transformity of milk was about 500,000 seJ.J<sup>-1</sup> in PC and BR, while grain transformity was about 80,000 seJ.J<sup>-1</sup>. In this sense, the dairy-system level focuses on resources directly managed to feed animals and produce milk and thus appears more suitable for comparing milk production from different systems. However, it requires knowing internal farm flows to isolate resources and land used for the herd, for the land uses to include within a dairy system is open to debate. In our study, due to the integration of crops and livestock in SM systems ([Herrero et al., 2010](#)), the exclusion of Cash&Food crops in the dairy system would call into question the definition of the system. One could consider whole-farms in SM and their dairy systems similar. Assessment at different levels prevents definitive choices on boundaries and current associated questioning on boundaries in environmental assessment ([Tillman et al., 1994](#)) and allows consideration of specific characteristics of farms in each territory.

Focusing on the herd level avoids such debate, because it excludes all land use for crops, focusing specifically on herd management, such as feeding, housing or labour. This downscaling changes certain emergy indicators. Since all energy flows on forage land and their renewability are indirectly accounted for in plant products consumed by the herd, %Renew and ELR were similar in all territories. Similar EYRs at the dairy-system and herd levels of RI, PC and BR resulted mainly from the large percentage of Materials and Services in inputs at both levels. A larger difference was observed for EYR in SM, explained by its higher amount of natural resources input. EIR at both levels was similar for SM, PC and BR but differed for RI. In RI, emergy flows from erosion were indirectly included in purchased materials at the herd level through forage produced on farms and consumed by animals. At the dairy-system level, emergy flows from erosion were included in the numerator in the EIR equation (Table 1) but in the denominator at the herd level. Due to the larger percentage of this emergy source in RI (5%) than in other territories (1%), the change in EIR is larger in this territory. Transformity at herd level differed in the four territories in comparison to whole-farm and dairy levels. Conversely to [Cavalett et al. \(2006\)](#) on integrated production systems of grains, pig and fish in small farms in the South Brazil, manure was considered an output at the herd level, which increased total energy produced and decreased transformity of milk (following [Bastianoni and Marchettini, 2000](#)). As manure represents a small percentage of

outputs in intensified systems from RI, BR and PC (10-12%), the difference in transformity is low (6-9%). Conversely, a higher percentage of manure in SM systems (95%) leads to larger difference for transformity of milk (42%). Analysis at sub-farm levels (e.g., herd and crops) appears interesting, But it seems more interesting when performed along with analysis at the dairy-system level (e.g., [Cavalett et al., 2006](#); [Rótolo et al., 2007](#)). Such multi-level analysis may identify inefficiencies and local stress on the environment by system components.

#### 4.3. An improved methodology for emergy calculation for multi-level assessment

In our study, assessment at multiple levels included two recent improvements in EmA methodology: energy allocation of total emergy for accurate transformity calculation and use of renewability factors for purchased materials and services.

Lack of allocation in EmA has been described as its most confusing aspect ([Hau and Bakshi, 2004](#)). [Bastianoni and Marchettini \(2000\)](#), studying co-production accounting scenarios, concluded that traditional emergy indicators were inadequate. They proposed weighting total emergy among co-products based on their energy contents. Calculating transformity for each product in an inseparable multi-product system with this method is a useful way to compare different ways to produce the same product. Due to the diversity of ways to produce milk in the world ([FAO, 2009](#)), it is an interesting example. Without allocation, transformity of milk in SM systems would have equalled  $83.69 \text{ seJ.l}^{-1}$  at the whole-farm level and  $64.65 \text{ seJ.l}^{-1}$  at the dairy-system and herd levels, 20-30 times higher than those in our study. While it could illustrate the inefficiency of SM farms in producing milk, these differences actually result from low milk production by herds. Their roles are production of manure and labour, in addition to storing capital ([Randolph et al., 2007](#)), as milk represents only 2.9% of the total gross energy produced by SM dairy farms (Table 6). Avoiding energy allocation penalises co-products that represent a small percentage of total gross energy production by assigning them additional emergy. This highlights the utility of the proposal by [Bastianoni and Marchettini \(2000\)](#) to compare different ways to produce the same product, including multi-product systems.

Inclusion of renewability factors improves assessment of system sustainability ([Cavalett et al., 2006](#)). Since their introduction by [Ulgiati et al. \(1994\)](#), they have been used in several studies ([Castellini et al., 2006](#); [Agostinho et al., 2008](#); [Takahashi and Ortega, 2010](#)). It provides a method to assess processes that do not use natural resources directly, such as those found in industry or confinement animal production. Renewability factors were especially useful at the herd level in our study. For example, the original ELR equation proposed by

Odum (1996) excluded the emergy of renewable inputs from purchased materials and services in the denominator ( $ELR = (M+S+N)/R$ ). Consequently, since renewable resources (R) were not used at the herd level in RI, PC and BR, their ELR and ESI values could not have been calculated (Table 8).

The methodology proposed by Bastianoni and Marchettini (2000) leads to different emergy indicators than those calculated with the Odum (1996) methodology (Table 10). The largest difference is notable for EIR at the herd level, where use of renewability factors increased EIR by around 140 times, resulting mainly from the increase of EIR of more than 520 times in RI due to the low percentage of non-renewable resources compared to purchased materials. Differences in emergy indicators due to inclusion of renewability factors were observed by Cavalett et al. (2006). They have shown that use of renewability factors are especially valid considering use of renewable inputs purchased at the local or regional economy, such as maize, soybean, manure and services. Importance of organic purchased inputs in agricultural systems studied in this study such as forage and concentrates confirms such interest.

**Table 8**

Emergy indicators calculated at dairy-system and herd levels with the original Odum (1996) methodology for the four territories (SM: South Mali, RI: Reunion Island; PC: Poitou-Charentes, BR: Bretagne)

| Level of analysis | Territory              | EYR<br>(Y/(M+S)) | EIR<br>((M+S)/(R+N)) | ELR<br>((M+S+N)/R) | ESI<br>((EYR/ELR)) |
|-------------------|------------------------|------------------|----------------------|--------------------|--------------------|
| Dairy-system      | SM                     | 1.28 (- 32%)     | 3.56 (+ 218%)        | 4.00 (+ 220%)      | 0.32 (- 78%)       |
|                   | RI                     | 1.13 (- 16%)     | 7.98 (+ 171%)        | 14.58 (+ 277%)     | 0.08 (- 77%)       |
|                   | PC                     | 1.15 (- 2%)      | 6.57 (+ 66%)         | 7.66 (+ 75%)       | 0.15 (- 42%)       |
|                   | BR                     | 1.22 (- 10%)     | 4.65 (+ 31%)         | 5.45 (+ 67%)       | 0.22 (- 48%)       |
|                   | <i>Mean difference</i> | - 15%            | + 122%               | + 160%             | - 61%              |
| Herd              | SM                     | 1.28 (- 39%)     | 3.52 (+ 214%)        | 3.53 (+ 187%)      | 0.36 (- 79%)       |
|                   | RI                     | 1.00 (- 21%)     | 2001.70 (+ 52,163%)  | -                  | -                  |
|                   | PC                     | 1.01 (- 10%)     | 74.29 (+ 1739%)      | -                  | -                  |
|                   | BR                     | 1.02 (- 24%)     | 57.36 (+ 1851)       | -                  | -                  |
|                   | <i>Mean difference</i> | - 24%            | + 13,992%            | -                  | -                  |

*Values between brackets are differences with indicators calculated in this study)*

Large differences between the two methodologies were also observed for ELR. In particular, the method of Odum (1996) places the ELR of RI close to that of the two intensive systems (BR and PC). Such a high ELR appears to contradict previous environmental assessment of RI dairy systems (Vigne et al., 2009; Vayssieres et al., 2011) and previous comparison of these 4 systems (Vigne et al., unpublished). The ELR proposed by Odum (1996) was based on the strong hypothesis that “most purchased resources cause environmental degradation during their production, use and environmental assimilation”



(Martin et al., 2006). But when considering renewability factors, ELR is based more on a correlation between use of non-renewable resources and negative impact. ELR calculated with renewability factors is thus similar to %Renew, which can be written as:

$$\begin{aligned}\%Renew &= 100 \times ((R+M_R+N_R)/Y) \\ &= 100 \times ((R+M_R+N_R)/(R+M_R+N_R+N+M_N+S_N)) \\ &= 100 \times (1+(R+M_R+N_R)/(N+M_N+S_N)) \\ &= 100 \times (1+1/ELR)\end{aligned}\tag{1}$$

In this sense, ELR is another way to translate the percentage of renewable and non-renewable resources used. As demonstrated in other study with strong link between EYR and EIR (Brown and Ulgiati, 1997), it is probably not always required to calculate all indicators. Link between ELR and %Renew explains also the low ELR for RI farms despite their high amount of imported feed concentrates, which are based mainly on plant matter requiring natural resources. As highlighted by Lu et al. (2009), highly industrialised systems do not have to be considered highly “non-renewable” if they can increase the percentage of renewable resources in their purchased inputs. More work should be performed to better assess the real environmental impact of inputs.

The original definition of ELR by Odum (1996) may be better adapted to its original aim of translating pressure of processes on the local ecosystem. However, if renewability factors are to be used, calculation of ELR at the herd level with Odum’s methodology needs to include some renewable resources to allow it to be calculated. Among previous studies, only Castellini et al. (2006) studied a confinement livestock system (conventional poultry production); they quantified renewable resources as the area occupied by animal buildings. In SM dairy farms, herds are usually not reared in buildings, which limits using this method of accounting. In other studies analysing livestock subsystems within a whole-farm systems (pigs by Cavalett and Ortega (2006), cows by Rotolo et al. (2007) or ducks by Zhang et al. (2012)), animals were always associated with an area, even if it was non-productive (e.g. waiting area). This is not suitable at the animal or herd level, for which no area should be included; thus, an accurate way to account for natural resources at this level is needed, for example, by estimating genetic information. Jørgensen et al. (2004) suggest that emergy required to generate the genetic information might be on the order of  $2.00E+10 \text{ sej.J}^{-1}$  of genetic information. Oxygen consumption by animals could be also interesting to investigate. Gas measurement is currently used in emergy analyses of industrial systems, such as production of electricity (Brown and Ulgiati, 2002), aluminium bars (Siracusa et al., 2007) or sulphuric acid (Zhang et al., 2010). In fish farming systems (Vassalo et al., 2007, Zhang et al.,

2011), natural resource use can indirectly estimated through water use. In industrial process, water is often considered a renewable natural resource (Peng et al., 2008; Ciotola et al., 2011; Mu et al., 2012), an approach that could be applied to livestock systems, even if its renewability is debatable in some contexts such as SM where water is lacking for some periods.

## **V. CONCLUSION**

Application of EmA at different levels on four contrasting dairy systems highlighted the potential environmental sustainability of low-input systems from SM, with low use of total energy and higher use of renewable resources. Despite of their low quality, efficiency in using these resources was similar to that of intensive systems at the three levels, contradicting the perceived lack of productivity of agricultural systems from developing regions. The current image of high environmental impact of cattle production in these regions was also called into question by the potential environmental sustainability highlighted by the indicator results. Emergy accounting also revealed interesting characteristics of the three intensive systems. Those in RI and PC appeared less efficient in resource transformation and further from environmental sustainability. These characteristics resulted mainly from feeding strategies that differed due to socio-climatic conditions. RI and PC farms used more transformed resources than biomass from grazed pasture, the opposite of those from BR, where the climate is more favourable for pasture growth. Transformed feeds were concentrate feeds in RI, to maintain high milk production despite the lack of arable land, and maize silage in PC, to secure forage systems with a higher risk of experiencing droughts. Emergy assessment of systems within each territory would probably be useful in the future to identify local ways to increase emergy performance.

Results suggest that EmA should be performed at multiple levels within farms. The whole-farm level appears useful for assessing the overall influence of the farm on its environment, whereas the dairy-system level seems more suitable for comparing multi-product systems. Both highlight the contribution of livestock production to impacts of global agriculture. The herd level focuses on management practices such as feeding, housing or labour, avoiding debate about boundary definition by excluding land management. It becomes most interesting when done along with a farm-level analysis, which may identify inefficiencies and local stress on the environment caused by system components.

Studying multiple levels also highlighted discussion on recent improvements in emergy methodology. Emergy allocation appears useful for studying multiple levels and comparing similar products from different production systems. Inclusion of renewability factors has redefined the original emergy indicators proposed by Odum, but definitions and goals have changed little. It appears useful to calculate accurate renewability or EYR but is less for EIR and for ELR, since results are similar to those with renewability. In this sense, Odum's original ELR seems more interesting. Calculation of ELR at the herd level needs additional study to increase the accuracy of accounting for renewable natural resources. The differences in indicator results between the two methodologies argues for a global discussion of both, with the aim of standardising EmA methodology.

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## **Chapitre VI**

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# **ANALYSE INTRA-TERRITOIRE**



**L'application de la méthode d'Analyse pluri-énergétique et de la méthode Emergy dans le cadre des systèmes de production laitiers des quatre territoires a confirmé leurs potentialités pour analyser les différents flux d'énergie dans des systèmes très diversifiés et faire apparaître des modes de gestion des ressources différents selon les territoires.**

**Ce chapitre a pour but d'analyser l'intérêt de ces méthodes pour caractériser une diversité de gestion des ressources selon les différents systèmes présents dans un territoire et mettre en lumière des voies d'intensification écologique basées sur la gestion efficiente de ces ressources.**

**Compte tenu du temps imparti pour la thèse, nous ne pouvions appliquer les deux méthodes sur l'ensemble des territoires. Aussi, considérant le plus faible pouvoir discriminant de la méthode Emergy entre des territoires mobilisant des ressources pourtant différentes (Ile de la Réunion et Poitou-Charentes), nous nous sommes concentrés sur l'Analyse pluri-énergétique.**

**Dans la première partie de ce chapitre, la méthode a été appliquée dans le cadre des systèmes du Mali Sud qui offraient l'intérêt de mobiliser une grande diversité de types d'énergie contrairement aux territoires français où le recours à l'énergie fossile est très majoritaire. Cette application s'est révélée utile pour mettre en lumière différentes voies d'amélioration de l'efficience des ces systèmes représentatifs des régions chaudes.**

**Dans la seconde partie de ce chapitre, nous avons recherché, à travers l'application de la méthode Data Envelopment Analysis (DEA) dans deux territoires (Poitou-Charentes et Bretagne), à mettre en avant les pistes pour accroître l'efficience d'utilisation de l'énergie fossile dans un souci conjoint de performances économiques et environnementales.**

## **1. Analyse de la variabilité intra-territoire au Mali selon les différents types de système<sup>13</sup>**

**Pluri-energy assessment to provide ways of ecological intensification in dairy farming systems from the periurban area of Sikasso, Mali**

***Evaluation pluri-énergétique afin de produire des voies d'intensification écologique dans des systèmes de production laitiers de la zone périurbaine de Sikasso, Mali***

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*Original Research Article* – **Submitted in Animal**

### **Résumé**

Le changement climatique a fait de l'impact environnemental des activités d'élevage un débat sociétal majeur. Compte tenu de la future demande en produits animaux en réponse à la population mondiale croissante, la conception de systèmes de production laitiers plus productifs mais également plus durables est un challenge majeur notamment dans les pays en développement. Parmi les nombreux impacts environnementaux, la consommation d'énergie fossile a couramment été étudiée dans les systèmes d'élevage. La consommation d'énergie fossile est fortement liée aux autres types d'énergie. Ses apports ont pour but principal d'améliorer la transformation via la photosynthèse de l'énergie solaire en énergie métabolisable pour l'homme et les animaux. Elle permet également de remplacer l'énergie physique dépensée lors des travaux agricoles par les hommes et les animaux qui constitue encore la majeure source d'énergie mécanique dans les systèmes manuels des pays en développement. Cette étude présente une analyse pluri-énergétique de 14 systèmes de production laitiers de la zone périurbaine de Sikasso (Mali) depuis des systèmes traditionnels jusqu'à des systèmes plus intensifs avec animaux en bâtiment.

Les résultats obtenus sur ces différents systèmes ont montré différents modes de gestion de l'énergie dépendants à l'échelle globale du système de la place respective des activités agricoles et d'élevage et du degré d'intensification de chacune d'elles. Les systèmes pour lesquels l'activité agricole tient une place prépondérante ont des consommations d'énergie

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<sup>13</sup> Cette partie est présentée sous forme d'un article scientifique tel qu'il a été soumis dans Animal auquel a été ajouté un résumé en français

fossile élevées sous forme d'engrais minéraux ainsi qu'une utilisation du travail humain et animal élevée. Dans ces systèmes, les troupeaux sont principalement alimentés à partir de la biomasse pâturée sur les parcours naturels et dans un moindre degré à partir des résidus de cultures de l'exploitation ou extérieurs. Les systèmes pour lesquels l'activité d'élevage est plus importante sont caractérisés par des consommations d'énergie fossile plus faibles. Cependant, la part des aliments concentrés dans l'énergie fossile et brute consommées par le troupeau est plus élevée.

Les résultats obtenus ont également montré des voies possibles d'intensification écologique. A l'échelle des cultures, une augmentation des intrants industriels principalement sous forme de fertilisants minéraux améliore l'efficacité énergétique solaire et par conséquent la productivité solaire. La traction animale joue également un rôle positif dans la durabilité environnementale du système en améliorant la valorisation des intrants fossiles. A l'échelle du troupeau, les aliments concentrés améliorent de manière conjointe la productivité du troupeau et l'efficacité énergétique fossile dans les systèmes traditionnels. Leur effet positif est plus limité dans les systèmes plus intensifs.

Cependant, malgré leur efficacité énergétique fossile plus élevée, la faible productivité des systèmes en intégration agriculture - élevage traditionnels limite leur intérêt pour couvrir la demande locale en produits laitiers. Les systèmes plus intensifs gardent donc un intérêt mais posent un dilemme entre une augmentation de la production animale et un risque d'augmentation de l'impact environnemental de l'élevage. Afin d'éviter ou de limiter une telle augmentation, les coûts en énergie fossile de différentes voies d'intensification des systèmes de production laitiers de la zone doivent être étudiés.

### **Abstract**

Climate change has led to global concern about the environmental impacts of the livestock sector. Because of the increasing demand in response to increasing world population, designing both productive and environmentally sustainable dairy systems are major challenges, especially in developing countries. Among numerous environmental impacts, fossil energy use is of importance. The use of fossil energy is tightly linked to other types of energy. It is mainly used to improve the conversion of solar energy into metabolisable energy, via photosynthesis, used to feed people and domestic animals. In addition, fossil energy is used to substitute for energy from human and animal labour, which still represent the main mechanical energy sources in most smallholder farming systems. This study is a pluri-energy

analysis of 14 dairy farms from the periurban region of Sikasso (Mali), from smallholder to indoor-reared systems, to highlight methods for improving fossil energy efficiency.

The results reveal different modes of energy management depending on the whole-farm level, on the respective place of cropping and livestock activities in the systems and the degree of intensification of each one. Systems that consist primarily of cropping activity have high fossil energy use from fertiliser and high labour energy use. In these systems, herds are mainly fed with biomass grazed on natural pasture and to a small degree, from on-farm and external crop residues. Systems with a higher level of livestock activity are characterised by low fossil energy use, but the proportion of feed concentrates in the fossil and gross energy consumed by the herd is increasing.

In addition, some ways of ecological intensification have been highlighted. At the crop level, an increase in the use of industrialised inputs improves solar energy efficiency and, thus, crop productivity. The use of animal traction also plays a positive role in the environmental sustainability of systems for better valorisation of fossil inputs. At the herd level, feed concentrate supplementation seems to improve both milk productivity and fossil energy efficiency in smallholder systems but is limited in intensified models based on indoor-reared animals. However, despite their higher fossil energy efficiency, the low productivity of traditional integrated crop – livestock systems limits their ability to reach the increasing demand for milk products in the area. Intensified systems are interesting in this way, but a dilemma between an increase in animal production and an increase in the environmental impact of livestock activity is present. In this sense, different methods for the intensification of dairy systems in these areas and their fossil energy cost require investigation.

## **1. INTRODUCTION**

Climate change resulting from greenhouse gas (GHG) emissions has led to global concern about the environmental impacts of human activities. Agriculture, particularly livestock farming, is primary among these societal challenges (Steinfeld et al., 1996). Because it contributes to GHG by producing CO<sub>2</sub>, fossil energy use in agricultural systems has been investigated by others (Vigne et al., 2012). Fossil energy is used at every step of the agricultural supply chain: upstream of the farm to produce inputs, on the farm to operate machines and downstream of the farm to transport and transform agricultural products. The use of fossil energy is strongly linked to other types of energy use. Fossil energy is mainly used to improve the unique ability of agriculture to convert solar energy into metabolisable

energy via photosynthesis to feed people and domestic animals (Ferrière et al., 1997). It tends to substitute energy from human and animal labour, which still represent the main mechanical energy sources in most smallholder agricultural systems.

To compare the management of all types of energy in dairy systems from different territories, Vigne et al. (2012) have designed a pluri-energy analysis method. Among the systems studied, smallholder crop-livestock systems from the periurban area of Sikasso (Mali) appeared as low fossil energy users because they are mainly based on labour energy and natural resources from natural pastures. Studying such dairy systems is of interest in the current dynamics in the world livestock sector. The demand for milk is expected to double in the coming decades in response to the increasing world population (FAO, 2009). Whereas in the OECD and North American countries, agricultural yields are already high and the land available for agriculture is limited (Paillard et al., 2010), future challenges are of particular concern in developing countries, where increasing life expectancies will accentuate the demand for livestock products. Designing more productive dairy systems with limited environmental impacts in these areas are thus major challenges for a ecological intensification way.

The development of dairy production in the Sikasso area is a good example of adaptation to increasing demand in the periurban area of West Africa (Coulibaly, 2008). In addition to traditional grazing and systems and integrated crop – livestock systems, several studies have noted the development of more productive systems (Duteurtre, 2007). Moreover, the migration of Sahelian livestock holders to Soudanian zones more favourable for livestock activity (Pradère, 2007) due to the increasing recurrences of dry periods during the recent past has resulted in a wide diversity of livestock systems in the area. The assessment of the different types of energy management in the diversity of systems observed is most likely a relevant way to design productive and environmentally sustainable systems. This study aims to provide a pluri-energy analysis of the different dairy farming systems found in the periurban area of Sikasso and to propose first ways to improve dairy development of the area through ecological intensification.

## **2. MATERIALS AND METHODS**

### **2.1. Pluri-energy analysis method**

#### *Principles of the method*

The pluri-energy analysis is a method designed by [Vigne et al. \(soumis\)](#). Its application is based on three basic principles, resulting in a generic conceptual framework of energy flow and use in an agricultural system (Figure 1).

The first principle accounts for the four types of energy used in agricultural systems: fossil energy, gross energy, energy from labour and solar energy. Fossil energy corresponds to fossil energy consumed directly on the farm (fuel, electricity and gas) or indirectly to produce crop inputs (fertiliser, seeds, chemicals and water), herd inputs (forage, concentrate feeds, veterinary costs and animal replacement) and agricultural equipment (materials and buildings). Gross energy is the calorific energy contained in animal and crop products and the renewable energy sources produced on farms as photovoltaic electricity. Labour energy corresponds to the physical energy expended on the farm by animal and human labour. Solar energy corresponds to the solar radiation received by lands.. The second principle divides the agricultural system into subsystems. Six subsystems were identified: i) the material and building capital represented by materials and buildings on the farm, ii) the livestock, including the productive herd and draft animals, iii) the crops, iv) plant production storage, v) manure storage and vi) the family. The third principle accounts for all energy flows entering the system, circulating in the system among different components and then leaving the system.

#### *Calculation of energy coefficients<sup>14</sup>*

The quantification of energy flow requires the calculation of locally adapted energy coefficients corresponding to the amount of energy per unit of measured flow. Table 1 reports some examples of fossil energy coefficients used in this study.

**Table 1**

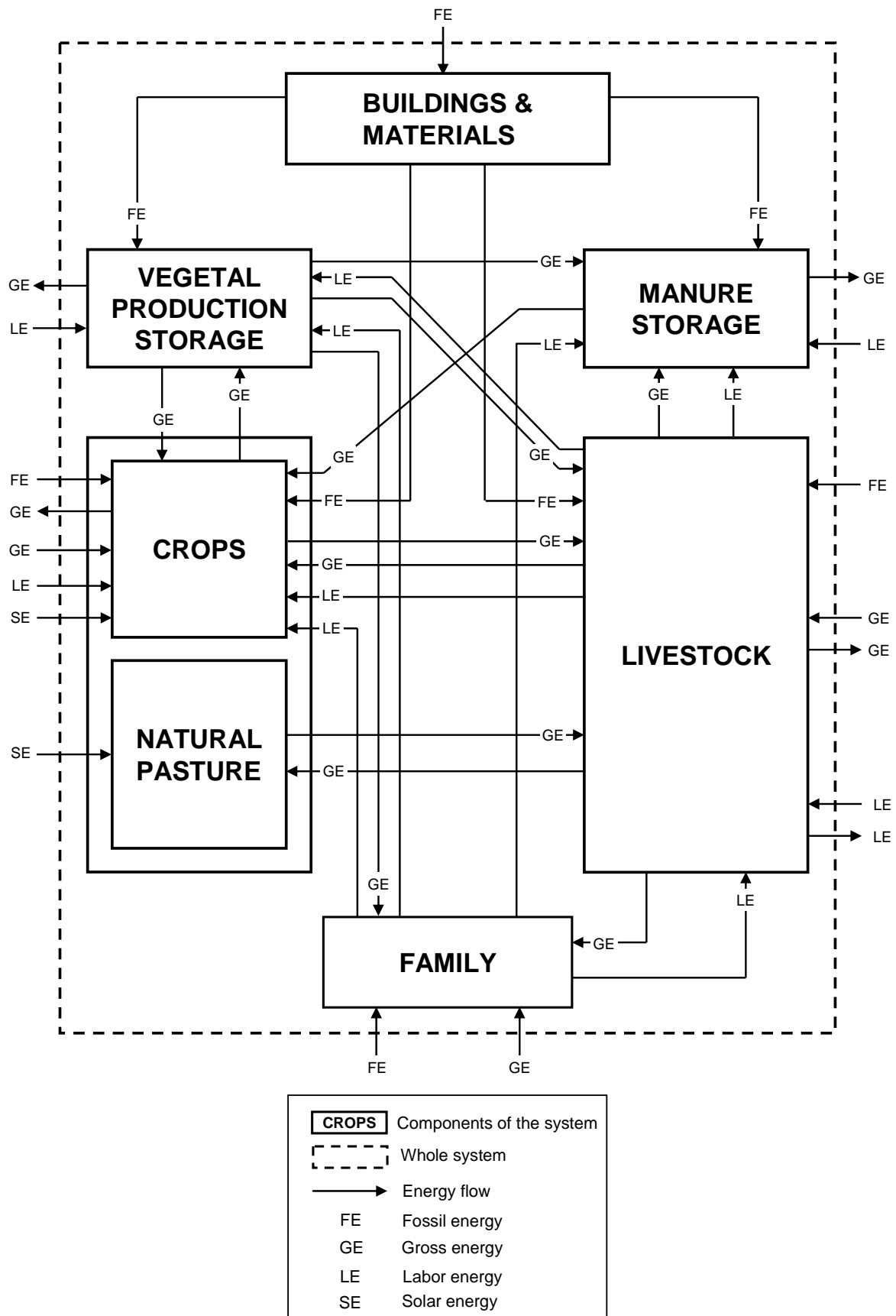
Values of fossil energy coefficients for seven of forty-nine fossil inputs

| Flow type         | Value (MJ.unit <sup>-1</sup> ) | Unit | References |
|-------------------|--------------------------------|------|------------|
| Fuel              | 42,36                          | l    | [1]        |
| Electricity       | 5,04                           | kWh  | [1]        |
| Cereal fertiliser | 149                            | kg   | [1]        |
| Cotton seeds      | 5,7                            | kg   | [2]        |
| Crop residues     | 0,088                          | kg   | [1]        |
| Cotton meal       | 0,966                          | kg   | [2]        |
| Veterinary costs  | 0,0076                         | FCFA | [2]        |

[1] Calculation from this study, [2] [Risoud and Théobald \(2002\)](#)

Fossil energy coefficients are from the original calculations or from the literature when the lifecycle of inputs was difficult to define.

<sup>14</sup> Des explications plus précises sur les calculs des coefficients sont donnés dans le Chapitre IV et l'Annexe VI



**Figure 1** Generic conceptual model of energy flow in the dairy system from a periurban area of Sikasso

Gross energy coefficients are mainly from values of feeds from the literature (INRA, 2007; Tran et al., 2010) or from measurements taken in the laboratory. Table 2 reports some values used in our study.

**Table 2**

Values of gross energy coefficients for eleven animal and vegetal products

| Flow type                    | Value (MJ.unit <sup>-1</sup> ) | Unit              | References |
|------------------------------|--------------------------------|-------------------|------------|
| Biomass from natural pasture | 17,46                          | kgDM              | [1]        |
| Cereal crop residues         | 13,80                          | kgDM              | [2]        |
| Shallow crop residues        | 14,35                          | kgDM              | [2]        |
| Maize                        | 16,14                          | kg                | [3]        |
| Sweet potato                 | 4,52                           | kg                | [4]        |
| Maize straw                  | 13,93                          | kg                | [3]        |
| Sorghum straw                | 18,36                          | kg                | [5]        |
| Cowpea residues              | 18,02                          | kg                | [5]        |
| Cotton hulls                 | 14,66                          | kg                | [6]        |
| Cow                          | 9,19                           | kg of live weight | [7]        |
| Heifer                       | 6,11                           | kg of live weight | [7]        |

[1] Calculated from Richard et al. (1990), [2] Calculated from INRA (2007) and from laboratory measurements by CIRAD, [3] INRA (2007), [4] FAO (1991), [5] Data from laboratory measurements by CIRAD, [6] Data from INERA, [7] Risoud and Théobald (2007)

Due to the variability of activities on the farm (33 activities), people performing these activities (men, women, children, and draft animals) and the values found in the literature for similar contexts, the labour energy coefficients were recalculated following several steps. A stress score similar to the Physical Activity Ratio (Loake, 2001), which is correlated with the level of physical energy expended while working, was first established for each work activity. The scores were obtained through interviews with the heads of household. These interviews aimed to classify work activities on a scale from 1 (easy) to 5 (difficult). When the same score was given by at least 75% of the heads of household, the announced value was confirmed. In other cases, the final scores were taken as the means of the announced values. Then, the energy coefficient for each work activity was weighted, with weights ranging between the minimum stress score value of 1 (0.703 MJ.h<sup>-1</sup> for driving an engine) and the maximum stress score value of 5 (1.481 MJ.h<sup>-1</sup> for manual ploughing) found in the literature (Passmore and Durnin, 1955).

Table 3 shows the stress score established for certain activities and the associated labour energy coefficients. The labour energy coefficients for women and children reach 85% and 75% of the values for men, respectively, based on the daily energetic needs for a woman and a 14-year-old child provided by the FAO and OMS (FAO and OMS, 1973).



**Table 3**

Stress score for twelve of thirty-three activities and the associated labour energy coefficients

| Activities                     | Stress score | Labour energy coefficients |  | Unit |
|--------------------------------|--------------|----------------------------|--|------|
|                                |              | (MJ.unit <sup>-1</sup> )   |  |      |
| Manual chemical spreading      | 1.75         | 0.806                      |  | h    |
| Manual crop residue harvesting | 1.75         | 0.806                      |  | h    |
| Manual feed distribution       | 1.5          | 0.754                      |  | h    |
| Manual fertiliser spreading    | 2            | 0.858                      |  | h    |
| Manual grain harvesting        | 2.5          | 0.962                      |  | h    |
| Manual manure spreading        | 3            | 1.066                      |  | h    |
| Manual milking                 | 2.5          | 0.962                      |  | h    |
| Manual tillage                 | 5            | 1.481                      |  | h    |
| Rice transplanting             | 4.5          | 1.377                      |  | h    |
| Walking with animals           | 1            | 0.650                      |  | h    |
| Walking with load              | 4            | 0.858 <sup>a</sup>         |  | km   |

The labour energy coefficients for animal labour were taken from the literature (Lawrence and Stibbards, 1990; Fall et al., 1997) or, given the sparse data, were calculated using the same ratio as the human coefficients. For example, for human labour, the energy coefficient for mounding is 83% higher than that of ploughing (Table 4).

**Table 4**

Labour energy coefficients for animal activities

| Activities | Unit | Value (MJ.unit <sup>-1</sup> ) |                    | References |
|------------|------|--------------------------------|--------------------|------------|
|            |      | Bovine                         | Donkey             |            |
| Transport  | km   | 0.416 <sup>a</sup>             | 0.208 <sup>a</sup> | [1]        |
| Tillage    | h    | 3.000                          | -                  | [2]        |
| Ridging    | h    | 2.490                          | -                  | [3]        |
| Weeding    | h    | 3.180                          | -                  | [3]        |
| Sowing     | h    | 2.820                          | -                  | [3]        |

<sup>a</sup> Considering an average loading of 160 kg for bovine and 80 kg for donkey

[1] Lawrence and Stibbards (1990), [2] Fall et al. (1997), [3] Calculation from this study

The solar energy coefficients are based on the photosynthetically active radiation (PAR) in the solar spectrum. PAR is the proportion of total solar energy incident on the Earth's surface and available for photosynthesis. PAR is commonly considered to consist of wavelengths ranging from 400 to 700 nm. Varlet-Grancher et al. (1989) reported several values of PAR for different plant species. Due to a lack of data for several plant species present on the studied farms, a simplified value of 50% was used, as proposed by Bonnet and Combarnous (1996).

### Energy indicators

Pluri-energy analysis enables the calculation of the total amount of energy used and produced and the establishment of indicators of energy conversion efficiencies. These

indicators can be calculated at the farm level and the crop (forage land and cash and food crops) and herd level. At each level, the total energy use was calculated by summing all flows of energy for the different types of energy. At the crop level, energy from animal manure was calculated by allocating energy among the different animal products. A similar energy allocation process was used at the livestock level to calculate the energy from the forage and feeds consumed by the herd. The energy produced at each level is the amount of gross energy produced by the system. In this method, internal flows (e.g., gross energy from crops produced on-farm and consumed by the herd at the farm level or milk directly fed at the livestock level) are not accounted for in energy production. Efficiency indicators are calculated at each level from the ratio of gross energy produced and the amount of energy used. Energy used and produced is expressed in megajoules per hectare ( $\text{MJ}\cdot\text{ha}^{-1}$ ) of the total area (cropping area and natural pasture used) at the whole-farm level, in megajoules per hectare ( $\text{MJ}\cdot\text{ha}^{-1}$ ) of the cropping area at the crop level, and in megajoules per livestock unit ( $\text{MJ}\cdot\text{LU}^{-1}$ ) at the herd level. The efficiency indicators are dimensionless.

## 2.2. Description of studied farms and data

The study concerns farms situated in the periurban region of Sikasso and with dairy activity. Sikasso is situated in southern Mali ( $11^{\circ} 19'$  North,  $5^{\circ} 40'$  West) and is representative of the savannah area of Western Africa. The climate is characterised by high annual average temperatures ( $26^{\circ}\text{C}$ ) and two seasons: a dry period from December to May and a rainy season from June to November, with rainfall totalling approximately  $1.1 \text{ m}\cdot\text{yr}^{-1}$ .

The 14 farms were previously studied by Coulibaly (2008) with the aim of assessing the role of milk marketing in management changes of livestock systems in the area. The farms were chosen to cover a wide gradient of herd intensification illustrated by (i) feed concentrate supplementation (cotton by-products and cereal bran) and (ii) milk yield per productive cow. These gradients can be classified into 5 types of dairy production strategies (DPSs) (Table 5). The six farms of DPS1 are characterised by low milk yield ( $69 \text{ l}\cdot\text{cow}^{-1}\cdot\text{yr}^{-1}$ ) despite large herd numbers (43.5 LU). Large cropping areas (16.1 ha) illustrate the importance of cropping activity in these systems. On these farms, livestock activity plays a larger role in economic capital than productive function. The feed mainly consists of grazing on natural pasture and crop residues, while feed concentrate supplementation is low ( $76 \text{ kg}\cdot\text{cow}^{-1}\cdot\text{yr}^{-1}$ ). Although cropping activity remains the major activity (7.3 ha), farms of DSP2 are developing dairy activity with a slightly higher milk yield ( $98 \text{ l}\cdot\text{cow}^{-1}\cdot\text{yr}^{-1}$ ). A higher milk yield is enabled by

better management of the natural pastures because feed concentrate supplementation is low (35 kg.cow<sup>-1</sup>.yr<sup>-1</sup>) and herd size remains high (43.0 LU).

**Table 5**

Characteristics of the 14 studied farms among the different dairy production strategies (DPSs)

|  | DPS1        | DPS2        | DPS3        | DPS4 | DPS5 |
|--|-------------|-------------|-------------|------|------|
| Number of farms                                    | 6           | 3           | 3           | 1    | 1    |
| Cropping area (ha)                                 | 16.1 (8.1)  | 7.3 (4.0)   | 2.7 (4.2)   | 11.0 | 5.5  |
| Natural pasture used (ha) <sup>a</sup>             | 31.6 (13.7) | 27.6 (8.1)  | 26.7 (10.9) | 14.6 | 0.6  |
| Herd size (LU)                                     | 43.5 (18.0) | 43.0 (13.9) | 45.1 (20.1) | 19.0 | 7.9  |
| Proportion of productive cows (%)                  | 43 (5)      | 50 (6)      | 63 (19)     | 74   | 63   |
| Feed concentrates given (kg.cow.yr <sup>-1</sup> ) | 76 (68)     | 35 (41)     | 402 (159)   | 1906 | 3082 |
| Milk yield (l.cow.yr <sup>-1</sup> )               | 69 (10)     | 98 (12)     | 117 (32)    | 601  | 828  |
| Workforce (number of persons)                      | 12 (4)      | 5 (2)       | 1 (1)       | 5    | 1    |

Values given are the **mean** (*min-max*)

LU: Livestock Unit (1 LU corresponds to an animal of 250 kg)

<sup>a</sup> Natural pasture has been estimated from the production of natural pasture by Penning de Vries and Djitéye (1982)

Despite a close milk yield (117 l.cow<sup>-1</sup>.yr<sup>-1</sup>), DSP3 farmers are breeders. Because crop residues are less available due to the smaller cropping area (2.7 ha), large herds (45.1 LU) are fed with higher levels of concentrate supplementation (402 kg.cow<sup>-1</sup>.yr<sup>-1</sup>). The farm classified as DSP4 is an innovative farm. While cropping activity remains important (11.0 ha), the herd size is smaller (19.0 LU) and the milk yield is higher (601 l.cow<sup>-1</sup>.yr<sup>-1</sup>), in particular due to the high level of concentrate supplementation (1,902 kg.cow<sup>-1</sup>.yr<sup>-1</sup>). Finally, the DSP5 farm is a specialised system, with animals reared in buildings and fed with feed concentrates (3,082 kg.cow<sup>-1</sup>.yr<sup>-1</sup>). The resulting milk yield reaches 828 l.cow<sup>-1</sup>.yr<sup>-1</sup>.

The application of the pluri-energy analysis method requires data on structural factors (e.g., total area, material equipment and buildings), crop management (e.g., area occupation, fertilisation and crop yield), livestock management (e.g., herd size, feed and milk yield) and human and animal labour (e.g., type of activity and duration). Much of the data are from the previous study led by Coulibaly (2008). These data have been collected by survey follow-up during agricultural periods from 2005 to 2006 and specifically concern structural factors, herd management and production and milk strategy. Supplementary data on crop management and animal and human activities were needed for our study. These data were collected by one survey per farm during 2011.

### **3. RESULTS AND DISCUSSION**

#### **3.1. Energy management at the whole-farm level is representative of each type of system**

Energy indicators obtained at the whole-farm level are representative of the structural characteristics and production aim of the system (Table 6).

For the DPS1 and DPS2 types, the greater importance of cropping activity is illustrated by a high proportion of fertiliser in the total fossil energy use (75% and 58%, respectively). This fossil energy input is attained in DPS2 by a higher input of external resources through external crop residues (14%) to relieve the lack of on-farm crop residues due to a higher livestock stocking rate (4.9 vs. 2.5 LU.ha<sup>-1</sup>). The use of external crop residues leads to a higher output of manure deposits (32% of gross energy production). Conversely, the higher cropping area for DPS1 produces more crop residues than needed to feed the herd. Crop residues are then grazed by other herds, explaining their high proportion of total gross energy production (60%) and the high proportion of manure deposits in the total gross energy use (35%). The proportion of milk in the total gross energy production is low for the DPS1 and DPS2 types (respectively, 1 and 3%), illustrating the low productive role of herds. The two DPS types are differentiated by the higher availability of the family workforce for DPS1, which explains the lower labour energy use (79 MJ.ha<sup>-1</sup>), whereas DPS2 is more dependent on an external workforce (122 MJ.ha<sup>-1</sup>).

The increasing importance of livestock activities in type DPS3 is illustrated by the higher proportion of feed concentrates in the total fossil energy use (47%). Similar to DPS2, the use of external crop residues is high (19% of total fossil energy use) to relieve the lack of cropping area. The higher use of external feeding resources is also illustrated by the higher proportion of feed concentrates and external crop residues in the total gross energy use (respectively, 48% and 51%). Gross energy produced also confirms the greater importance of livestock activity in this system. While gross energy production is low ( $3.5 \times 10^3$  MJ.ha<sup>-1</sup>) in comparison to previous systems, it is mainly represented by animal products and especially manure (72%). Milk is at a higher proportion (5%) than DPS1 and DPS2. Low availability of the family workforce leads to higher labour energy use (197 MJ.ha<sup>-1</sup>).

Livestock intensification in the DPS4 and DPS5 types is illustrated by the higher proportion of feed concentrates (respectively, 41% and 23%) and veterinary costs (respectively, 8% and 9%) in the total fossil energy use. Compared to DPS3, cropping activity remains important in the two systems, which maintains a high proportion of fertiliser in the total fossil energy use (respectively, 27% and 30%).

**Table 6**

Energy indicators obtained at the whole-farm level among the different dairy production strategies (DPSs)

| Indicators | Type of energy                                      | DPS type          |                  |                  |             |             |
|------------|---|-------------------|------------------|------------------|-------------|-------------|
|            |   | DPS1              | DPS2             | DPS3             | DPS4        | DPS5        |
| Use        | Fossil energy ( $\times 10^3$ MJ.ha <sup>-1</sup> ) | <b>1.1 (0.3)</b>  | <b>0.7 (0.3)</b> | <b>0.3 (0.3)</b> | <b>0.7</b>  | <b>2.9</b>  |
|            | <i>Fuel</i>   | 1%                | 2%               | 2%               | 0%          | 5%          |
|            | <i>Fertiliser</i>                                   | 75%               | 58%              | 10%              | 27%         | 30%         |
|            | <i>Chemicals</i>                                    | 9%                | 6%               | 2%               | 4%          | 14%         |
|            | <i>Feed concentrates</i>                            | 2%                | 2%               | 47%              | 41%         | 23%         |
|            | <i>External crop residues</i>                       | 2%                | 14%              | 19%              | 0%          | 0%          |
|            | <i>Buildings</i>                                    | 0%                | 0%               | 1%               | 6%          | 11%         |
|            | <i>Labour</i>                                       | 5%                | 9%               | 9%               | 9%          | 7%          |
|            | <i>Veterinary costs</i>                             | 3%                | 4%               | 6%               | 8%          | 9%          |
|            | <i>Other<sup>a</sup></i>                            | 4%                | 5%               | 4%               | 5%          | 1%          |
|            | Gross energy ( $\times 10^3$ MJ.ha <sup>-1</sup> )  | <b>3.1 (1.5)</b>  | <b>5.2 (3.6)</b> | <b>8.0 (7.5)</b> | <b>19.8</b> | <b>49.3</b> |
|            | <i>Manure</i>                                       | 35%               | 5%               | 0%               | 1%          | 4%          |
|            | <i>Animal replacement</i>                           | 3%                | 2%               | 0%               | 0%          | 0%          |
|            | <i>Family food</i>                                  | 13%               | 4%               | 1%               | 1%          | 0%          |
|            | <i>External crop residues</i>                       | 23%               | 78%              | 51%              | 0%          | 0%          |
|            | <i>Feed concentrates</i>                            | 26%               | 14%              | 48%              | 98%         | 96%         |
|            | Labour energy (MJ.ha <sup>-1</sup> )                | <b>79 (45)</b>    | <b>122 (13)</b>  | <b>197 (85)</b>  | <b>199</b>  | <b>974</b>  |
|            | <i>Human</i>  | 99%               | 100%             | 99%              | 82%         | 94%         |
|            | <i>Animal</i>                                       | 1%                | 0%               | 1%               | 18%         | 6%          |
| Production | Gross energy ( $\times 10^3$ MJ.ha <sup>-1</sup> )  | <b>15.9 (7.4)</b> | <b>6.8 (4.0)</b> | <b>3.5 (4.1)</b> | <b>24.9</b> | <b>20.0</b> |
|            | <i>Milk</i>   | 1%                | 3%               | 5%               | 3%          | 7%          |
|            | <i>Given manure</i>                                 | 0%                | 0%               | 47%              | 0%          | 74%         |
|            | <i>Manure deposits during external grazing</i>      | 4%                | 32%              | 25%              | 0%          | 0%          |
|            | <i>Animal</i>                                       | 1%                | 9%               | 8%               | 1%          | 0%          |
|            | <i>Crop residues grazed by external herd</i>        | 60%               | 22%              | 0%               | 54%         | 19%         |
|            | <i>Vegetal products</i>                             | 34%               | 34%              | 15%              | 42%         | 0%          |
| Efficiency | Fossil energy (dmml)                                | <b>14.1 (2.6)</b> | <b>7.2 (3.9)</b> | <b>2.3 (0.6)</b> | <b>37.5</b> | <b>1.8</b>  |
|            | Labour energy (dmml)                                | <b>268 (223)</b>  | <b>56 (34)</b>   | <b>25 (31)</b>   | <b>125</b>  | <b>21</b>   |
|            | Solar energy ( $\times 10^{-3}$ ) (dmml)            | <b>1.2 (0.3)</b>  | <b>0.9 (0.6)</b> | <b>0.6 (0.8)</b> | <b>1.5</b>  | <b>0.6</b>  |

Values given are the **mean** (min-max); MJ : megajoule; ha : hectare; dmml : dimensionless<sup>a</sup> Inputs representing individually less than 5% in all types of DPS : Animal replacement, fuel, minerals, forage, materials, veterinary costs, manure

In the two systems, cropping area is sufficient to provide forage for herds. In this sense, the total gross energy input is primarily represented by feed concentrates (respectively, 98% and 96%). The cropping area in DPS4 represents the main proportion of gross energy produced through crop residues grazed by an external herd (54%) and vegetal products (42%). Conversely, total gross energy production for DPS5 is mainly represented by animal products through given or sold manure (74%). The proportion of milk in total gross energy produced remains low in the two systems, especially for DPS4 (3%), while it represents the highest proportion of all the DPS types for DPS5 (7%), which illustrates the main role of livestock activity in this system. The need for an external workforce differentiates the two systems. Labour energy use is higher for DPS5 (974 MJ.ha<sup>-1</sup> vs. 199 MJ.ha<sup>-1</sup>) and illustrates the commercial character of this farm, which is in this sense far removed from smallholder systems.

The analysis of energy efficiencies reveals a higher global efficiency for DPS4 in comparison to the other DPS types. Fossil energy and solar energy efficiency are thus the highest (respectively, 37.5 and 1.5). Labour energy efficiency is lower than DPS1 (125 vs. 268) but is higher than the other types. While lower than DPS4, DPS1 presents high fossil energy and solar efficiency (respectively, 14.1 and 1.2), which illustrates a high global efficiency. DPS2 presents intermediate efficiencies on whole indicators: 7.2 for fossil energy efficiency, 56 for labour energy efficiency and 0.9 for solar energy efficiency. Finally, DPS3 and DPS5 appear as the least efficient systems. Fossil energy efficiencies are 2.3 and 1.8, respectively, labour energy efficiencies are 25 and 21 and solar energy efficiencies are similar for the two systems (0.6).

However, analysis of the efficiencies at the whole-farm level seems irrelevant to assess the global performance of the systems. The total gross energy produced, for example, depends on the proportion of production that is autoconsumed. Smallholder systems in which this proportion is high could be in this sense penalised compared to commercial systems, where the entire production leaves the system. Moreover, the importance of cropping activity in the system can impact the different efficiencies. Indeed, previous fossil energy analyses have shown a fossil energy efficiency for intensive (Kuesters and Lammel, 1999; Rathke et al., 2007) or manual (Singh et al., 2002; Canakci et al., 2005) cropping systems greater than 5, while livestock systems barely reach 1 (Benoit and Laignel, 2010; Veysset et al., 2010). The analysis of the different efficiencies appears to be more relevant at the level of productive components, in addition to the analysis of other indicators that could appear representative of modes of management and the performance of each activity.

### 3.2. Crop intensification plays a major role in the efficiency of smallholder systems

At the crop level (Table 7), intensification in DPS1 and DPS2 is illustrated by the three times higher fossil energy use (respectively,  $3.4 \times 10^3 \text{ MJ}\cdot\text{ha}^{-1}$  and  $3.5 \times 10^3 \text{ MJ}\cdot\text{ha}^{-1}$ ) than in DSP3 ( $1.1 \times 10^3 \text{ MJ}\cdot\text{ha}^{-1}$ ) and DSP4 ( $0.9 \times 10^3 \text{ MJ}\cdot\text{ha}^{-1}$ ). The higher use in DPS1 and DPS2 results mainly from changes in crop management with the use of fertiliser, which represents a large portion of fossil energy use (respectively, 74% and 61%) in the substitution of manure in DPS3 and DPS4 (respectively, 61 and 59% of fossil energy use). Intensification through mineral fertilisation use appears to yield positive consequences on gross energy production, which is higher for DPS1 ( $98 \times 10^3 \text{ MJ}\cdot\text{ha}^{-1}$ ) and DPS2 ( $155 \times 10^3 \text{ MJ}\cdot\text{ha}^{-1}$ ) than for DPS3 ( $36 \times 10^3 \text{ MJ}\cdot\text{ha}^{-1}$ ) and DPS4 ( $59 \times 10^3 \text{ MJ}\cdot\text{ha}^{-1}$ ). This intensification results in higher solar energy efficiencies for DPS1 ( $2.5 \text{ MJ}\cdot\text{ha}^{-1}$ ) and DPS2 ( $3.2 \text{ MJ}\cdot\text{ha}^{-1}$ ) than DPS3 ( $1.1 \text{ MJ}\cdot\text{ha}^{-1}$ ) and confirms the positive effect of mineral fertilisation on the yield of manual cropping systems in West Africa (Bationo and Ntare, 2000; Wopereis et al., 2006). However, high fossil energy efficiency is not necessarily related to high mineral fertilisation use. For example, despite the low fossil energy use, DSP3 achieves closer fossil energy efficiency (37.8) than DSP1 and DSP2. In the same way, DSP4 even achieves higher fossil energy efficiency (66.7). DSP5 confirms the lack of a relationship. While fossil energy use is intermediate ( $2.1 \times 10^3 \text{ MJ}\cdot\text{ha}^{-1}$ ) and mainly represented by mineral fertiliser (44%) and manure stored (31%), gross energy produced remains low ( $51.4 \text{ MJ}\cdot\text{ha}^{-1}$ ), which leads to low fossil energy efficiency (24.5).

The use of draft animals appears to be a key factor in the fossil energy efficiency of the crops. We can thus observe a positive correlation ( $R^2=0.72$ ) between the proportion of animal labour in the labour energy expended on crops and fossil energy efficiency of crops at all the farms that were studied (Figure 2). The positive role of animal traction on crop yields and labour has already been demonstrated (Starkey, 1988; Williams, 1997; Savadogo et al., 1998; Guthiga et al., 2007). However, this result also confirms the positive effect of animal traction on the environmental sustainability of cropping systems through the better valorisation of fossil inputs (Schiere et al., 2002).

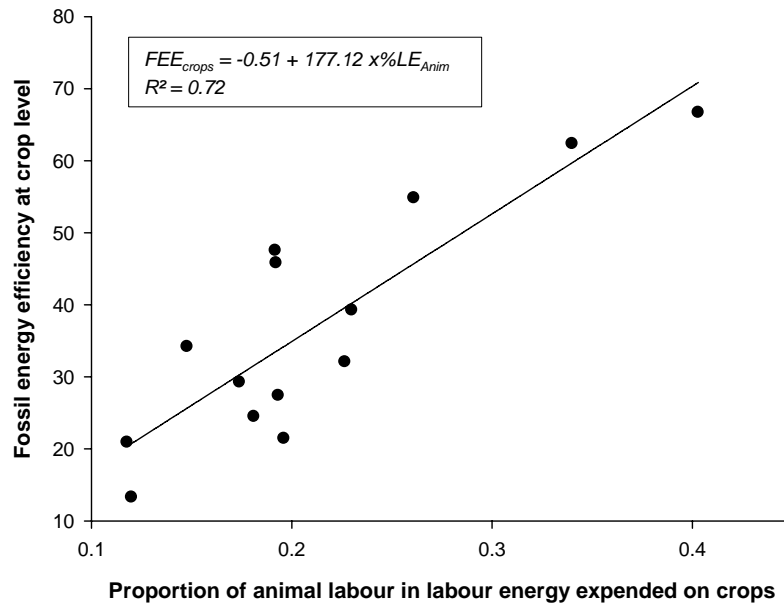
**Table 7**  
Energy indicators at the crop level among the different dairy production strategies (DPSs)

| Indicators                            | Type of energy                                      | DPS                |                    |                    |             |             |
|---------------------------------------|---|--------------------|--------------------|--------------------|-------------|-------------|
|                                       |   | DPS1               | DPS2               | DPS3               | DPS4        | DPS5        |
| Use                                   | Fossil energy ( $\times 10^3$ MJ.ha <sup>-1</sup> ) | <b>3.4</b> (1.2)   | <b>3.5</b> (2.2)   | <b>1.1</b> (1.3)   | <b>0.9</b>  | <b>2.1</b>  |
|                                       | Fertiliser  | 74%                | 61%                | 29%                | 31%         | 44%         |
|                                       | Chemicals   | 9%                 | 7%                 | 3%                 | 5%          | 20%         |
|                                       | Labour  | 3%                 | 3%                 | 3%                 | 4%          | 3%          |
|                                       | Manure deposits by herd during grazing              | 3%                 | 10%                | 3%                 | 12%         | 0%          |
|                                       | Manure deposits by humans                           | 7%                 | 16%                | 58%                | 47%         | 31%         |
|                                       | Other <sup>a</sup>                                  | 4%                 | 3%                 | 4%                 | 1%          | 2%          |
|                                       | Labour energy (MJ.ha <sup>-1</sup> )                | <b>488</b> (61)    | <b>538</b> (77)    | <b>422</b> (291)   | <b>357</b>  | <b>374</b>  |
|                                       | Human   | 80%                | 78%                | 72%                | 60%         | 82%         |
|                                       | Animal  | 20%                | 22%                | 28%                | 40%         | 18%         |
| Production                            | Gross energy ( $\times 10^3$ MJ.ha <sup>-1</sup> )  | <b>98</b> (21)     | <b>155</b> (65)    | <b>36</b> (2)      | <b>59</b>   | <b>51</b>   |
|                                       | Vegetal products given or sold                      | 17%                | 9%                 | 14%                | 27%         | 0%          |
|                                       | Vegetal products consumed by family                 | 30%                | 26%                | 35%                | 14%         | 47%         |
|                                       | Crop residues stored and given to animals           | 7%                 | 27%                | 19%                | 13%         | 45%         |
|                                       | Crop residues grazed by on-farm herd                | 19%                | 29%                | 32%                | 11%         | 2%          |
| Crop residues grazed by external herd | 27%   | 9%                 | 0%                 | 35%                | 6%          |             |
| Efficiency                            | Fossil energy (dmnl)                                | <b>31.8</b> (12.5) | <b>40.9</b> (10.1) | <b>37.8</b> (14.9) | <b>66.7</b> | <b>24.5</b> |
|                                       | Labour energy (dmnl)                                | <b>206</b> (55)    | <b>274</b> (184)   | <b>100</b> (57)    | <b>245</b>  | <b>137</b>  |
|                                       | Solar energy ( $\times 10^3$ ) (dmnl)               | <b>2.5</b> (0.5)   | <b>3.2</b> (1.6)   | <b>1.1</b> (0.3)   | <b>2.3</b>  | <b>1.3</b>  |

Values given are the **mean** (min-max); MJ : megajoule; ha : hectare; dmnl : dimensionless

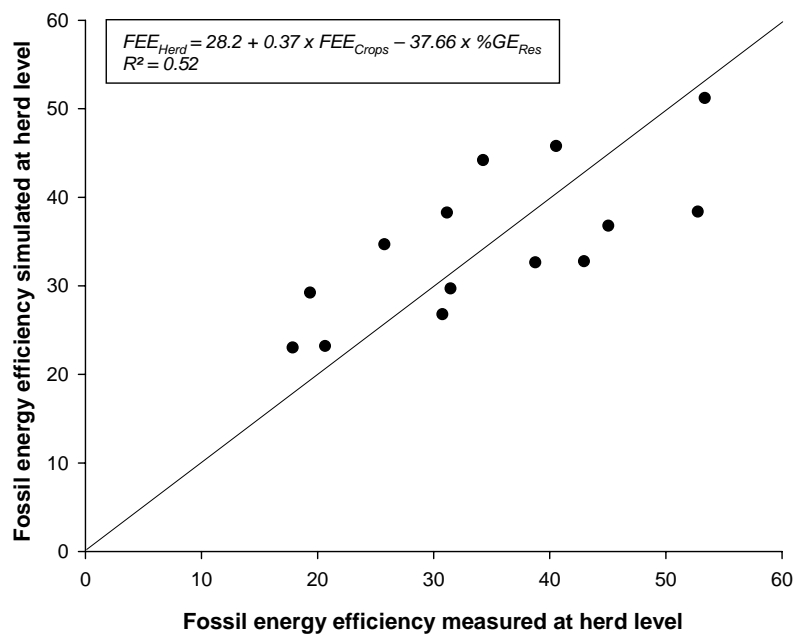
<sup>a</sup> Inputs representing individually less than 5% in all types of DPS : Fuel, manure from external herd





**Figure 2** Relation between the proportion of animal labour in labour energy expended on crops ( $\%LE_{Anim}$ ) and fossil energy efficiency of crops ( $FEE_{Crops}$ )

Improvement of cropping system efficiency through intensification and a higher use of animal traction is not of interest only to decrease the fossil energy cost of vegetal products for human food. Considering the close integration between agriculture and livestock in these systems, this improvement is also interesting to improve fossil energy efficiency at the herd level by decreasing the fossil energy cost of crop residues. This interest increases with the proportion of crop residues in total gross energy consumed by the herd ( $R^2=0.52$ ) (Figure 3).



**Figure 3** Effect of fossil energy efficiency of crops ( $FEE_{Crops}$ ) and proportion of crop residues in gross energy consumed by herd ( $\%GE_{Res}$ ) on the fossil energy efficiency of the herd

This is of particular interest for smallholder systems with low feed concentrate supplementation. Table 8 shows that if total crop residues (both external and on-farm) represent only close to a quarter of gross energy consumed by the herd for DPS1 (25%) and DPS2 (29%), they represent close to three quarters of total fossil energy use (respectively, 73% and 77%).

### 3.3. Traditional systems efficiently convert fossil energy use despite different feeding strategies

However, if rational intensification combined with the use of draft animals improved the efficiency of traditional systems in our study, livestock activity in these systems shows high fossil energy efficiency (from 34.2 to 40.6). These values are higher than previously studied livestock systems, although comparisons are difficult because no studies in similar systems have been published (Vigne et al., 2012). It is interesting to note that these high levels of fossil energy efficiency are obtained through different profiles of gross energy consumed, illustrating different feeding strategies.

In DPS1, DPS2 and DPS3, gross energy is mainly consumed through grazing on natural pasture (from 61 to 69%), while it is shared between pastures (40%) and feed concentrates for DPS4 (40%). These different feeding strategies result in close values for gross energy consumed (from  $36.6 \times 10^3$  to  $41.2 \times 10^3$  MJ.LU<sup>-1</sup>) and gross energy production (from  $15.4 \times 10^3$  to  $16.4 \times 10^3$  MJ.LU<sup>-1</sup>). Close values for gross energy efficiency are thus a result (from  $36.6 \times 10^{-2}$  to  $40.3 \times 10^{-2}$ ). Similarly, the different feeding strategies result in close values for fossil energy use (from 379 to 501 MJ.LU<sup>-1</sup>) and consequently in fossil energy efficiency (from 34.2 to 40.6). This finding is mainly due to the fossil energy cost of crop residues close to feed concentrates. Despite an industrial transformation step, the close fossil energy cost for the co-products of cotton is due to higher fossil energy efficiency of cotton crops in comparison to other crops, as observed by Singh et al. (2003). For cereal bran, because transformation is mainly manual, fossil energy cost appears similar to crop residues. Moreover, crop residues are strongly penalised by gross energy values close to grain. Because allocation is based on gross energy allocation, the mass ratio between grain and crop residues is 1:3 (N'Faly, 1995); a large part of fossil energy use invested is allocated to crop residues.

However, we can observe profiles of gross energy production that are different among feeding strategies, which highlights their different goals for the production of animal products compared with human food. If milk represents only 1 to 2% for DPS1, DPS2 and DPS3, this proportion increases in DPS4 (6%) with an increase in feed concentrate use.

**Table 8**

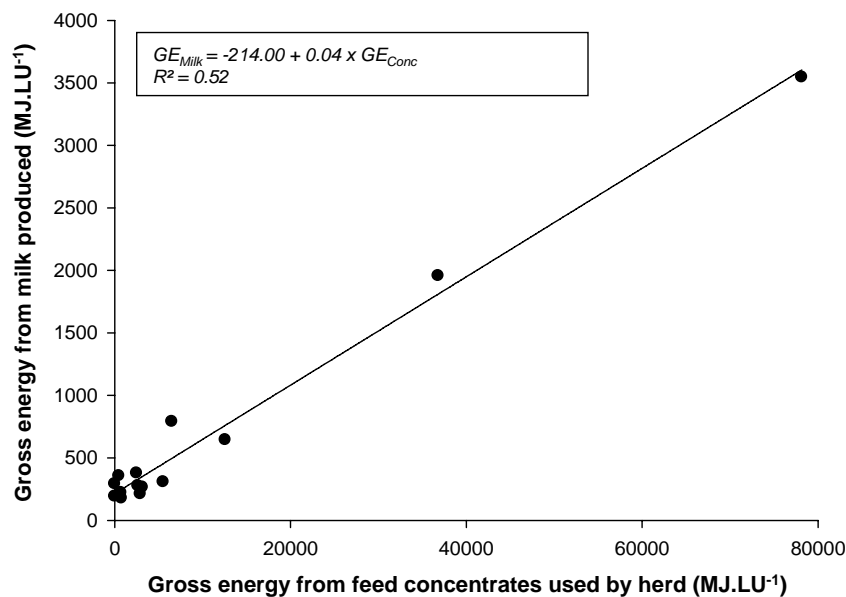
Energy indicators at the herd level among the different dairy production strategies (DPSs)

| Indicators | DPS  |                    |                    |                    |             |             |
|------------|--|--------------------|--------------------|--------------------|-------------|-------------|
|            | Type of energy                                 | DPS1               | DPS 2              | DPS3               | DPS4        | DPS5        |
| Use        | Fossil energy ( $MJ.UBT^{-1}$ )                | <b>501 (109)</b>   | <b>481 (115)</b>   | <b>431 (105)</b>   | <b>379</b>  | <b>1217</b> |
|            | <i>Fuel</i>                                    | 2%                 | 1%                 | 1%                 | 0%          | 7%          |
|            | <i>Labour</i>                                  | 5%                 | 8%                 | 8%                 | 7%          | 4%          |
|            | <i>Feed concentrates</i>                       | 8%                 | 4%                 | 50%                | 63%         | 33%         |
|            | <i>On-farm crop residues grazed</i>            | 49%                | 29%                | 4%                 | 6%          | 0%          |
|            | <i>On-farm crop residues stored and given</i>  | 17%                | 29%                | 5%                 | 8%          | 43%         |
|            | <i>External crop residues grazed</i>           | 7%                 | 19%                | 21%                | 0%          | 0%          |
|            | <i>Veterinary costs</i>                        | 8%                 | 6%                 | 7%                 | 12%         | 13%         |
|            | <i>Other<sup>d</sup></i>                       | 4%                 | 4%                 | 4%                 | 4%          | 0%          |
|            | Gross energy ( $\times 10^3 MJ.UBT^{-1}$ )     | <b>37.8 (5.0)</b>  | <b>41.2 (6.9)</b>  | <b>36.6 (1.7)</b>  | <b>40.5</b> | <b>49.9</b> |
|            | <i>Feed concentrates</i>                       | 2%                 | 1%                 | 17%                | 41%         | 58%         |
|            | <i>On-farm crop residues grazed</i>            | 18%                | 13%                | 2%                 | 8%          | 2%          |
|            | <i>On-farm crop residues stored and given</i>  | 7%                 | 16%                | 4%                 | 11%         | 36%         |
|            | <i>External crop residues grazed</i>           | 4%                 | 9%                 | 15%                | 0%          | 0%          |
|            | <i>Biomass from natural pasture</i>            | 69%                | 61%                | 61%                | 40%         | 4%          |
|            | <i>Other<sup>e</sup></i>                       | 0%                 | 0%                 | 1%                 | 0%          | 0%          |
|            | Labour energy ( $MJ.UBT^{-1}$ )                | <b>105 (25)</b>    | <b>127 (18)</b>    | <b>160 (44)</b>    | <b>188</b>  | <b>216</b>  |
|            | <i>Human</i>                                   | 100%               | 100%               | 100%               | 100%        | 100%        |
| Production | Gross energy ( $\times 10^3 MJ.UBT^{-1}$ )     | <b>16.0 (4.1)</b>  | <b>16.4 (0.7)</b>  | <b>16.2 (0.4)</b>  | <b>15.4</b> | <b>21.8</b> |
|            | <i>Milk</i>                                    | 1%                 | 1%                 | 2%                 | 6%          | 6%          |
|            | <i>Manure deposits on on-farm crops</i>        | 18%                | 22%                | 1%                 | 17%         | 0%          |
|            | <i>Manure deposits on natural pasture</i>      | 25%                | 25%                | 24%                | 12%         | 0%          |
|            | <i>Manure stored</i>                           | 49%                | 44%                | 63%                | 64%         | 94%         |
|            | <i>Manure deposits on external crops</i>       | 6%                 | 5%                 | 7%                 | 0%          | 0%          |
|            | <i>Animal consumed by family or sold</i>       | 1%                 | 3%                 | 4%                 | 1%          | 0%          |
| Efficiency | Fossil energy ( $MJ.l$ of milk <sup>-1</sup> ) | <b>0.09 (0.03)</b> | <b>0.09 (0.03)</b> | <b>0.08 (0.02)</b> | <b>0.08</b> | <b>0.18</b> |
|            | Fossil energy ( $dmml$ )                       | <b>34.2 (13.1)</b> | <b>37.5 (15.5)</b> | <b>39.6 (12.0)</b> | <b>40.6</b> | <b>17.9</b> |
|            | Gross energy ( $\times 10^{-2}$ ) ( $dmml$ )   | <b>37.5 (7.4)</b>  | <b>36.6 (7.8)</b>  | <b>40.3 (1.8)</b>  | <b>38.0</b> | <b>43.6</b> |
|            | Labour energy ( $dmml$ )                       | <b>154 (39)</b>    | <b>113 (15)</b>    | <b>108 (32)</b>    | <b>82</b>   | <b>101</b>  |

Values given are the **mean** (*min-max*); *MJ* : megajoule; *ha* : hectare; *dmml* : dimensionless<sup>a</sup> Inputs representing individually less than 5% in all types of DPS: Animals, Buildings, Forage, Materials, Minerals<sup>b</sup> Inputs representing individually less than 5% in all types of DPS: Animals, Forage

Despite the greater labour energy needed to feed and milk animals, traditional integrated crop-livestock systems have the potential to intensify their milk production without increasing their fossil energy use and their environmental impact. Figure 4 confirms that feed concentrate supplementation promotes milk production due to its high energy and digestibility values (Feedipedia, 2012).

The positive effect of feed concentrates supplementation on milk production for dairy herds of smallholder systems close to those of Sikasso has been shown (Muinga et al., 1993; Romney et al., 2003; Muraguri et al., 2004). These results explain why policies facilitating access to feed concentrates is a method cited to improve the productivity of these systems (Brumby and Gryseels, 1984; Leng, 1991; Dugmore et al., 1996). However, we can observe in Figure 4 that this improvement mainly concerns systems that yield at least 5,000 MJ.cow<sup>-1</sup> of feed concentrates, corresponding to approximately 300 kg.cow<sup>-1</sup>. In other systems, the ratio between gross energy produced as milk and gross energy consumed as feed concentrates ranges from 0.08 to 0.75, showing some inefficiencies in using these resources. These inefficiencies show that beyond the need to increase supplementation, there is first an interest in finding ways to improve the valorisation of feed concentrates already given.



**Figure 4** Relation between gross energy from milk produced ( $GE_{Milk}$ ) and gross energy from feed concentrates used by the herd ( $GE_{Conc}$ )

### 3.4. Productivity of traditional livestock systems remains low

Intensive systems as illustrated by DPS5 show some environmental limits for intensification based on an intensification model from developed countries. The gross energy consumed by the herd of DPS5 is highest (49.9 MJ.LU<sup>-1</sup>) and is represented to a large part by

feed concentrates (25%) and crop residues (36%) (Table 8). If the resulting gross energy is slightly higher ( $21.8 \text{ MJ.LU}^{-1}$ ), an increase in milk yield (Table 5) and the milk proportion in the total gross energy produced (6%) tend to justify this feeding strategy. However, despite an efficient use of gross energy (43.6), this feeding strategy and the resulting milk production requires a higher use of labour energy ( $216 \text{ MJ.LU}^{-1}$ ) and fossil energy ( $1,217 \text{ MJ.LU}^{-1}$ ) and leads to lower fossil energy (17.9) and labour energy (101) efficiency. Higher fossil energy use is first due to the substitution of biomass from natural pasture with zero fossil energy cost by feeds (feed concentrates and crop residues) getting higher fossil energy cost. In addition, it is due to the specific management of reared-indoor livestock, which leads to higher cost in buildings, fuel and labour to feed the animals.

However, traditional systems are far to respond to global aims to cover the local urban demand. If we consider a demand in milk product close to  $60 \text{ kg.hab}^{-1}.\text{yr}^{-1}$  (Poccard et al. 2005) and a population of 200,000 people in the periurban area of Sikasso (Commissariat à la sécurité alimentaire, 2007), local demand can be estimated at 12 million litres of milk per year. Considering an individual production of  $600 \text{ l.cow}^{-1}.\text{yr}^{-1}$  as observed for DPS4, which represents 15,000 cows. Because approximately 150 livestock holders are present in the area, 130 cows per farm would be required; the mean herd size is presently 19 cows. Technical improvements would be required for the farmers to rear such large herds. Moreover, this number of cows and accompanying animals would increase the competition for land between agriculture and livestock activities and increase conflicts already existing in the area (Hussein et al., 1999). In this sense, periurban intensified systems similarly to DPS5 have not to be excluded. First, because they are represented in our study only by one farm and more farms need to be studied to draw definite conclusions. Furthermore, fossil energy use per litre of milk produced ( $0.2 \text{ MJ.l}^{-1}$ ) is far from previous values obtained in intensified dairy systems from developed countries, which range from  $1.3 \text{ MJ.l}^{-1}$  in Germany (Haas et al., 2001) to  $6.6 \text{ MJ.l}^{-1}$  on Reunion Island (Vigne et al., soumis). However, milk production for DPS5 is still low ( $828 \text{ l.cow}^{-1}.\text{yr}^{-1}$ ), and considering this level, the number of animals to reach local demand remains high (approximately 100 cows per farm). In this sense, it could be interesting to assess the environmental cost of different ways of improving milk yield levels sufficient to reach the local demand for dairy products.

As noted previously, a path to improvement could be to increase the proportion of milk in the total gross energy produced by the use of feed concentrates. However, because the fossil energy cost of feed concentrates is hardly reducible, this could lead to a decrease of fossil energy efficiency as observed in DPS5. Thus, there is a conflict between the increase of

animal production and the increase in the environmental impact of livestock activity, represented in our study by fossil energy use. Moreover, this increase must not penalise the production of manure, which remains a central component of agriculture – livestock integration in these systems, even in DPS5. Beyond these questions, designing intensified systems presents some logistical problems related to the organisation of a network upstream of the farm to provide inputs and downstream to manage the milk products. In Soudano-Guinean of Africa, [Corniaux et al. \(2007\)](#) consider the weakness of the network to collect and distribute milk as one of the major limiting points for the development of dairy activity at the periurban areas of a large city. However, the establishment of a well-organised collection network leads to higher economic costs. In addition to the higher cost of industrialised inputs, it could question the final cost of one litre of milk and its competitiveness with imported milk from an already well-organised supply chain.

#### **4. CONCLUSION**

The application of a pluri-energy analysis to different agricultural systems from the periurban area of Sikasso with dairy activity has highlighted different modes of energy management. At the whole-farm level, these different modes of energy management largely depend on the respective place of cropping and livestock activities in the system and the degree of intensification of each component. In this sense, systems presenting mainly cropping activity have high fossil energy use, primarily from fertiliser and labour energy use. Gross energy for herd feeding mainly comes from biomass grazed on natural pasture and, to a small degree, from on-farm and external crop residues. Systems with a higher importance of livestock activity are illustrated by increasing milk yield and low fossil energy use. Gross energy from biomass from natural pasture decreases, while the proportion of feed concentrates increases with milk yield.

Pluri-energy analysis has also highlighted the impact of modes of management on the efficiencies of each component and, thus, some ways of ecological intensification. At the crop level, the increase of industrialised inputs, mainly fertiliser, improves solar energy efficiency and crop productivity. The use of animal traction plays a positive role in the environmental sustainability of the system in better valorisation of fossil inputs. At the herd level, feed concentrate supplementation of herds seems to improve milk productivity and fossil energy efficiency in smallholder systems but is limited in an intensified model based on indoor-reared animals.

However, despite their higher fossil energy efficiency, the low productivity of traditional integrated crop – livestock systems limits their ability to reach the increasing demand in the area for milk products. Intensified systems appear more interesting in this way, but there is a dilemma between increased animal production and the increased environmental impact of livestock activity, represented in our study by fossil energy use. Different ways to intensify dairy systems in these areas and their environmental cost must be investigated. Such investigations must include several farms; here, intensified systems were analysed only on one farm. Moreover, the environmental impact of such methods must be assessed with indicators other than fossil energy use, such as GHG emissions or land use.

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## 2. Analyse de la variabilité intra-territoire en Poitou-Charentes et Bretagne selon les différents types de systèmes<sup>3</sup>

Improving the fossil energy efficiency of dairy systems in western France – An application of a data envelopment analysis

*Améliorer l'efficacité énergétique fossile des systèmes de production laitiers de l'Ouest de la France - Une application de la méthode Data Envelopment Analysis*

M. Vigne, J.L. Peyraud, P. Faverdin

*Original Research Article – In preparation*

### Résumé

L'amélioration de l'efficacité d'utilisation de l'énergie fossile au sein des systèmes laitiers est un enjeu majeur du secteur pour faire face à l'accroissement probable du coût de l'énergie fossile mais aussi compte tenu de l'impact environnemental croissant des activités d'élevage. Cet article propose dans un premier temps une analyse énergétique fossile de systèmes de production laitiers de deux territoires français, la Bretagne (BR) et le Poitou-Charentes (PC), classé en 3 types de systèmes fourragers selon la place de l'ensilage maïs dans le système fourrager : herbager, herbe-maïs et maïs. Cette analyse est ensuite complétée par une application de la méthode Data Envelopment Analysis (DEA) afin d'identifier les exploitations les plus efficaces et des voies d'amélioration de l'efficacité d'utilisation de l'énergie fossile dans les exploitations inefficaces.

Les résultats de l'analyse énergétique fossile ont montré des consommations moyennes d'énergie fossile par litre de lait produit différentes entre les territoires (3,6 MJ.l<sup>-1</sup> en BR et 4,9 MJ.l<sup>-1</sup> en PC) et entre les types de système (3,3 MJ.l<sup>-1</sup> pour les systèmes herbagers, 4,4 MJ.l<sup>-1</sup> pour les systèmes herbe - maïs et 5,7 MJ.l<sup>-1</sup> pour les systèmes maïs). Les résultats de l'application du DEA ont quant à eux montré un score d'efficacité technique (Technical Efficiency, TE) global de 0,82 principalement dépendant du score d'efficacité technique pure (Pure Technical Efficiency, PTE). L'efficacité d'échelle (Scale Efficiency, SE) élevée (0,95)

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<sup>3</sup> Cette partie est présentée sous forme d'un article scientifique en préparation pour une soumission prochaine dans la revue Animal auquel a été ajouté un résumé en français

démontre ainsi que les exploitations opèrent globalement à une échelle appropriée. Le score de PTE pour les systèmes herbe - maïs (0,83) et maïs (0,84) sont plus faible que les systèmes herbagers (0,93) ce qui explique en partie l'efficacité plus faible des systèmes en PC due à la place plus importante de l'ensilage maïs dans ces systèmes. De plus, le score de SE plus faible en PC (0,93) qu'en BR (0,98) démontre les conditions climatiques plus limitantes en PC et qui tendent à diminuer l'efficacité de ces systèmes. L'application DEA a également permis de mettre en lumière des consommations d'énergie globales optimales et réalistes dans les deux territoires (3,3 MJ.l<sup>-1</sup> en BR et 4,0 MJ.l<sup>-1</sup> en PC) mais également des consommations spécifiques pour chaque intrant dans chaque type de système.

### **Abstract**

Considering the increasing environmental impacts and the economic efficiency of livestock activities, especially in the dairy sector, methods for improving the efficiency of fossil energy use are a priority. This study analyses fossil energy use on dairy farms from two regions of western France (Bretagne, BR, and Poitou-Charentes, PC) that were classified into three types of forage systems (grassland, grassland-maize and maize). A data envelopment analysis (DEA) is then used to identify efficient farms and to highlight methods to improve the efficiency of fossil energy use.

The results of the fossil energy analysis showed different mean values for fossil energy use per litre of raw milk produced in the region (3.6 MJ.l<sup>-1</sup> in BR and 4.9 MJ.l<sup>-1</sup> in PC) and the type of system (3.3 MJ.l<sup>-1</sup> for grassland systems, 4.4 MJ.l<sup>-1</sup> for grassland-maize systems and 5.7 MJ.l<sup>-1</sup> for maize systems). The results of the DEA gave a mean technical efficiency (TE) score of 0.82. This score was mainly dependent on the pure technical efficiency (PTE) score because the mean scale efficiency (SE) score was 0.95, illustrating that farms are operating globally at an appropriate scale. The PTE scores for grassland-maize (0.83) and maize systems (0.84) were lower than that for grassland systems (0.93), which, because of the larger role of maize silage in these systems, partially explains the lower efficiency of the PC systems. However, the mean values of SE were lower in PC (0.93) than in BR (0.98), illustrating the disadvantageous conditions under which PC farms operate, which could tend to decrease the efficiency of systems in this region. The DEA also enabled us to highlight a realistic energy use target for the two regions (3.3 MJ.l<sup>-1</sup> for BR and 4.0 MJ.l<sup>-1</sup>). Moreover, by comparing the profile of energy use of each farm with the others, the DEA provides a specific target energy usage and the optimal energy requirement for each input.

## I. INTRODUCTION

The livestock sector is currently blamed for causing environmental degradation, such as nitrogen pollution, land use and greenhouse gas (GHG) emissions (Steinfeld et al., 2006). The dairy sector is an important contributor to environmental degradations (Gerber et al., 2010). Among numerous environmental impacts, fossil energy use and the efficiency of its use by dairy systems has received special attention in fossil energy analyses (Cederberg and Mattsson, 2000 ; Basset-Mens et al., 2005 ; Dalgaard et al., 2006 ; Grönroos et al., 2006 ; Bos et al., 2007 ; Azeez and Hewlett, 2008 ; Vigne et al., 2009 ; Rabier et al., 2010 ). In most cases, milk production represents the central economic activity of farms with a dairy subsystem (FAO, 2009). Considering the continuous increase in the price of fossil energy, the improvement in the efficiency of its use in dairy systems poses thus an important challenge both for decrease environmental impact and milk cost production.

Milk production occurs throughout the world by a variety of systems, from extensive smallholder systems with low inputs to confinement systems with high inputs. Ways of improvement include both extensive systems from developing countries and intensive systems from OECD countries.

Although fossil energy analysis has been mainly used to assess average fossil energy use for milk production in a given territory, it can also enable highlighting lower energy-consuming farms per unit of production or structural unit, considering them as efficient. However, it is possible that in the same territory and with a similar production system, different methods of production leading to different levels of optimum use of fossil energy translate to the different constraints in which the systems operate.

DEA has been widely used to analyse the fossil energy use of agricultural systems to determine the level of efficiency for different farms and to calculate target uses to improve global efficiency (Chauhan et al., 2006; Heidari et al., 2011; Mousavi-Avval et al., 2011a, 2011b, 2011c; Pahlavan et al., 2011). When comparing a production system to other production systems of similar input and output profiles, this method can be used to identify efficient farms at different levels of fossil energy use.

Dairy systems in western France are representative of intensive dairy systems from OECD countries. The French National Livestock Institute commonly differentiates them by their forage systems. The typology is based on the proportion of maize silage area in the total forage land that characterises the feeding systems (Charroin et al., 2005). Dairy systems are considered as “grassland systems” when this proportion is lower than 10%. When this

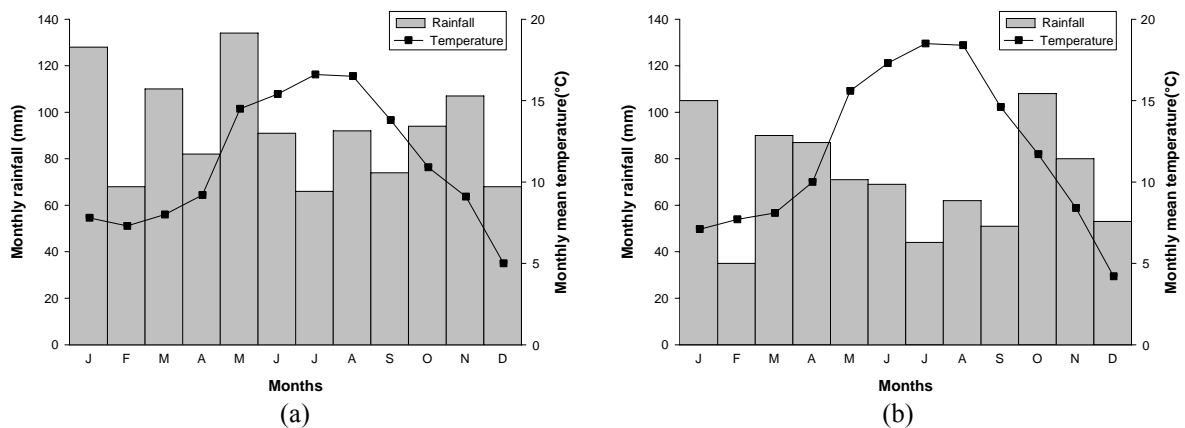
proportion is between 10 and 30%, dairy systems are considered to be “grassland-maize systems”. Finally, dairy systems with proportions greater than 30% are considered as “maize systems”.

The aim of this study is to apply the DEA method to dairy systems in western France in order to identify efficient farms and to highlight methods of improving the efficiency of fossil energy use among the different types of systems.

## II. MATERIALS AND METHODS

### 2.1. Studied territories and production systems

The two territories, Bretagne (BR) (48° 00' North, 03° 00' West) and Poitou-Charentes (PC) (46° 05' North, 00° 10' East), are French administrative regions situated in the western portion of the country. Both territories have an oceanic climate, which results in similar average annual rainfalls (respectively, 1.1 and 0.9 m) and temperatures (respectively 11, and 12°C). However, while rainfall is distributed throughout the year in BR, it is less abundant during the summer in PC (Figure 1).



**Figure 1** Mean rainfall and temperature for 2008 in (a) Bretagne and (b) Poitou-Charentes (data from the Climatik database (INRA, 2012))

Moreover, the range of temperature is high in PC, with higher temperatures in the summer. Frequent lack of rainfall during this season leads to current drought period.

The initial farm data were collected from the national DIAPASON database (Charroin et al., 2005) on 126 farms. The data collected cover dairy activities during 2008 or 2009 for each farm and focus on structural factors (forage land and herd size), direct energy use (fuel and electricity), livestock inputs (feed concentrates, forage, drinking water, veterinary costs), crop

inputs (mineral fertilisation, manure, chemicals, seeds, irrigation water, plastics), machinery and buildings.

The systems studied in the two regions have different characteristics (Table 1).

**Table 1**

Description of study farms from the two regions (BR: Bretagne; PC: Poitou-Charentes)

|  | <b>BR</b><br>(n=37)        | <b>PC</b><br>(n=89)        |
|--|----------------------------|----------------------------|
| Herd size (LU)   | <b>79.4</b> (38.0-125.5)   | <b>94.4</b> (27.9-220.0)   |
| Proportion of cows (%)   | <b>72</b> (62-87)          | <b>71</b> (59-98)          |
| Total area (ha)  | <b>80.3</b> (28.6-200.0)   | <b>135.3</b> (30.0-378.3)  |
| Forage land (%)  | <b>78</b> (56-100)         | <b>60</b> (15-100)         |
| Cash and food crops (%)  | <b>22</b> (0-44)           | <b>40</b> (0-85)           |
| Livestock stocking rate on forage land (LU.ha <sup>-1</sup> )            | <b>1.27</b> (0.60-2.20)    | <b>1.42</b> (0.36-3.12)    |
| Amount of mineral N on forage land (kgN.ha <sup>-1</sup> )               | <b>41</b> (0-93)           | <b>77</b> (0-220)          |
| Amount of organic N on forage land (kgN.ha <sup>-1</sup> )               | <b>86</b> (16-344)         | <b>52</b> (0-260)          |
| Biomass production of grasslandland <sup>a</sup> (tDM.ha <sup>-1</sup> ) | <b>6.4</b> (5.5-7.5)       | <b>5.8</b> (3.9-9.0)       |
| Biomass production of maize silage (tDM.ha <sup>-1</sup> )               | <b>13.4</b> (7.1-17.0)     | <b>12.8</b> (10.0-17.0)    |
| Proportion of biomass from forage land grazed (%)                        | <b>57</b> (31-92)          | <b>26</b> (00-83)          |
| Feed concentrates (t.cow <sup>-1</sup> )                                 | <b>1.3</b> (0.7-2.1)       | <b>2.0</b> (0.3-3.6)       |
| Milk yield (l.cow <sup>-1</sup> )  | <b>7,033</b> (4,757-8,950) | <b>7,419</b> (4,477-9,719) |

Values given are the **means** (min-max)

ha: hectare, LU: Livestock Unit, kgN: kilogram of N fertiliser, tDM: ton of Dry Matter, t: ton

Dairy farms in BR have smaller mean herd sizes (79.4 LU) and total area (80.3 ha) than those in PC (94.4 LU and 135.3 ha). The total area in BR is mainly represented by forage land (78%) than PC (60%) where commercial cropping is an important activity of the system. Mineral fertilisation on forage land in BR is lower than in PC (41 vs. 77 kgN.ha<sup>-1</sup>), where, due to the higher proportion of cash and food crops (40% of the total area), manure is shared between it and forage land and it is necessary to import mineral fertilisers. This explains why more fertilisation on forage land in BR is organic fertilisers (86 kgN.ha<sup>-1</sup>) and less so in PC (52 kgN.ha<sup>-1</sup>). Direct deposits by animals during grazing are not accounted for here. These two types of fertilisation result, however, in similar biomass production for grasslandland (6.4 vs. 5.8 tDM.ha<sup>-1</sup>) and maize silage (13.4 vs. 12.8 tDM.ha<sup>-1</sup>). More biomass produced on forage land is from grazing in BR (57%) than in PC (26%), illustrating a greater use of maize silage in PC. This higher use of maize silage is associated with a larger distribution of feed concentrates (1.3 vs. 2.0 t.cow<sup>-1</sup>) and higher milk production (7,033 vs. 7,419 l.cow<sup>-1</sup>).

In addition to the regions, the different types of forage systems also have different characteristics (Table 2).

**Table 2**

Description of study farms from the two regions (BR: Bretagne; PC: Poitou-Charentes)

|   | <b>Grassland</b><br>( <i>n</i> =20) | <b>Grassland-Maize</b><br>( <i>n</i> =34) | <b>Maize</b><br>( <i>n</i> =72) |
|---|-------------------------------------|---|---------------------------------|
| Number of farms in BR   | <b>5</b>                            | <b>13</b>                                 | <b>15</b>                       |
| Number of farms in PC   | <b>15</b>                           | <b>21</b>                                 | <b>53</b>                       |
| Herd size ( <i>LU</i> )   | <b>56.1</b> (27.9-88.0)             | <b>83.1</b> (33.4-132.1)                  | <b>102.8</b> (38.0-220.0)       |
| Proportion of cows (% <i>LU</i> )                                     | <b>73</b> (59-84)                   | <b>71</b> (62-98)                         | <b>72</b> (63-100)              |
| Forage land ( <i>ha</i> )   | <b>62.0</b> (30.0-115.6)            | <b>73.3</b> (36.2-156.0)                  | <b>65.9</b> (23.8-141.3)        |
| Livestock stocking rate for forage land ( <i>LU.ha<sup>-1</sup></i> ) | <b>0.99</b> (0.63-1.39)             | <b>1.20</b> (0.60-1.76)                   | <b>1.62</b> (0.67-3.12)         |
| Amount of mineral N on forage land ( <i>kgN.ha<sup>-1</sup></i> )     | <b>31</b> (0-217)                   | <b>51</b> (0-148)                         | <b>84</b> (0-220)               |
| Amount of organic N on forage land ( <i>kgN.ha<sup>-1</sup></i> )     | <b>90</b> (0-260)                   | <b>69</b> (0-171)                         | <b>34</b> (0-344)               |
| Proportion of biomass from forage land grazed (%)                     | <b>65</b> (39-85)                   | <b>45</b> (0-77)                          | <b>23</b> (0-92)                |
| Feed concentrates ( <i>t.cow<sup>-1</sup></i> )                       | <b>0.8</b> (0.0-2.3)                | <b>1.5</b> (0.1-3.1)                      | <b>2.2</b> (0.0-4.6)            |
| Annual Milk yield ( <i>l.cow<sup>-1</sup></i> )                       | <b>6,347</b> (4,862-7,873)          | <b>7,087</b> (4,477-9,291)                | <b>7,675</b> (5,379-9,719)      |

Values given are the **means** (*min-max*)

*ha*: hectare, *LU*: Livestock Unit, *kgN*: kilogram of N fertiliser, *tDM*: ton of Dry Matter, *t*: ton

Among the types of systems, herd size increases with the proportion of maize in the forage system, whereas the proportion of cows in the herd remains similar (Chatellier and Vérité, 2003). Grassland systems have mean herd sizes (56.1 LU) approximately two times smaller than do maize systems (102.8 LU), and the herd size of grassland-maize systems falls in between these values (83.1 LU). Grassland-maize systems have the highest mean forage land area (73.3 ha), followed by maize systems (65.9 ha) and grassland systems (62.0 ha). Values for the mean livestock-stocking rate are related to the use of maize silage. Grassland systems have livestock stocking rates close to one (0.99), while this value is 1.20 for grassland-maize systems and 1.62 for maize systems. Fertilisation on forage land is mainly based on organic fertilisation (90 kgN.ha<sup>-1</sup>) for grassland systems, while mineral fertilisation is low (31 kgN.ha<sup>-1</sup>). Organic fertilisation is high for grassland-maize systems (69 kgN.ha<sup>-1</sup>) and completed by mineral fertilisation (51 kgN.ha<sup>-1</sup>). Conversely, mineral fertilisation is high in maize systems (84 kgN.ha<sup>-1</sup>), whereas organic fertilisation is low (34 kgN.ha<sup>-1</sup>). The proportion of grazed

biomass from forage land corresponds directly to the type of system. It is high for grassland systems (65%), intermediate for grassland-maize systems (45%) and low for maize systems (23%). Conversely, the distribution of feed concentrates increases with the proportion of maize silage in the forage land. It is lowest in grassland systems ( $0.8 \text{ t.cow}^{-1}$ ) and highest in maize systems ( $2.2 \text{ t.cow}^{-1}$ ), with grassland-maize systems in between ( $1.5 \text{ t.cow}^{-1}$ ). The lowest mean milk yield is observed for grassland systems ( $6,347 \text{ l.cow}^{-1}$ ). The mean milk yield is higher for grassland-maize systems ( $7,087 \text{ l.cow}^{-1}$ ), but maize systems have the highest mean value ( $7,675 \text{ l.cow}^{-1}$ ).

## 2.2. Fossil energy analysis

A fossil energy analysis estimates the direct and indirect fossil energy use on farms (IFIAS, 1974). Direct fossil energy corresponds to energy contained in non-renewable energy directly used on farms, such as fuel, gas, or electricity. Indirect fossil energy corresponds to fossil energy used during the life cycle of an input from the extraction of raw material to transport on the farm. The amount of indirect fossil energy per unit of input is available through energy coefficients. In our study, energy coefficients are from the Dia'Terre method (ADEME, 2011) adapted to the context of mainland France.

In our study, the fossil energy analysis includes whole-dairy activity, including forage land and livestock activities. For each farm, fossil energy use, expressed in megajoules per hectare of forage land ( $\text{MJ.ha}^{-1}$ ) produced, is the sum of the quantity of each farm input multiplied by its energy coefficient divided by the area of forage land. Fossil energy use per litre of raw milk ( $\text{FE}_{\text{milk}}$ ) has also been calculated, corresponding to the total fossil energy use divided by milk production. This value is expressed in megajoules per litre of raw milk produced ( $\text{MJ.l}^{-1}$ ).  $\text{FE}_{\text{milk}}$  represents the inverse of fossil energy efficiency. The higher the value for  $\text{FE}_{\text{milk}}$ , the lower the efficiency of valorisation of the fossil energy directly and indirectly invested in the milk.

## 2.3. Data envelopment analysis (DEA)

DEA is a non-parametric approach introduced by Farrell (1957) and then developed by Charnes et al. (1978). It is based on the elaboration of a production frontier which envelops observation points as closely as possible through a piecewise linear envelopment of data by solving a sequence of linear problems for each farm. A farm, also called a decision-making



unit (DMU), is efficient when it uses the lowest number of inputs to produce one unit of output and is situated along this production frontier.

Two types of models for DEA application have been proposed. The CCR model, proposed by Charnes, Cooper and Rhodes (Charnes et al., 1978), assumes that farms are operating at their optimal scale (Fraser and Cordina, 1999) and is thus based on the assumption of constant returns to scale (CRS). This model calculates the overall technical efficiency (TE) by the ratio of the sum of weighted outputs to the sum of weighted inputs (Mousavi-Avval et al., 2011c):

$$TE_j = \frac{\sum_{r=1}^n u_r y_{rj}}{\sum_{s=1}^m v_s x_{sj}} \quad (1)$$

where  $x$  and  $y$  represent input and output and  $v$  and  $u$  denote input and output weights, respectively;  $s$  is the number of inputs ( $s=1, 2, \dots, m$ );  $r$  is number of outputs ( $r=1, 2, \dots, n$ ); and  $j$  represents  $j$ th DMU ( $j=1, 2, \dots, k$ ).

Eq. (1) can be translated into this linear programming problem:

$$\begin{aligned} \text{Maximise } TE_j &= \sum_{r=1}^n u_r y_{rj} \\ \text{Subject to } & \quad (i) \sum_{s=1}^m v_s x_{sj} = 1, \quad i = 1, 2, \dots, k \\ & \quad (ii) \sum_{r=1}^n u_r y_{rj} - \sum_{s=1}^m v_s x_{sj} \leq 0 \\ & \quad (iii) u_r \geq 0, \quad r = 1, 2, \dots, n \\ & \quad (iv) v_s \geq 0, \quad s = 1, 2, \dots, m \end{aligned} \quad (2)$$

TE can have a value between 0 and 1, where a value of 1 implies that the DMU is located on the efficiency frontier and has no reduction potential. A value lower than 1 indicates the DMU uses inputs inefficiently.

However, the overall inefficiency of a farm can arise from two causes: it can be caused by the inefficient operation of the farmer itself, or by the disadvantageous conditions under which the farmer is operating. To distinguish between these, Banker, Cooper and Charnes (Banker et al., 1984) calculated the pure technical efficiency (PTE) using the BCC model, considering a convexity constraint and assuming a variable return to scale (VRS). In the input-orientation chosen for our study, convexity constraint is added in the previous equation (Eq. 3) with the following dual linear problem (Mousavi-Avval et al., 2011c):

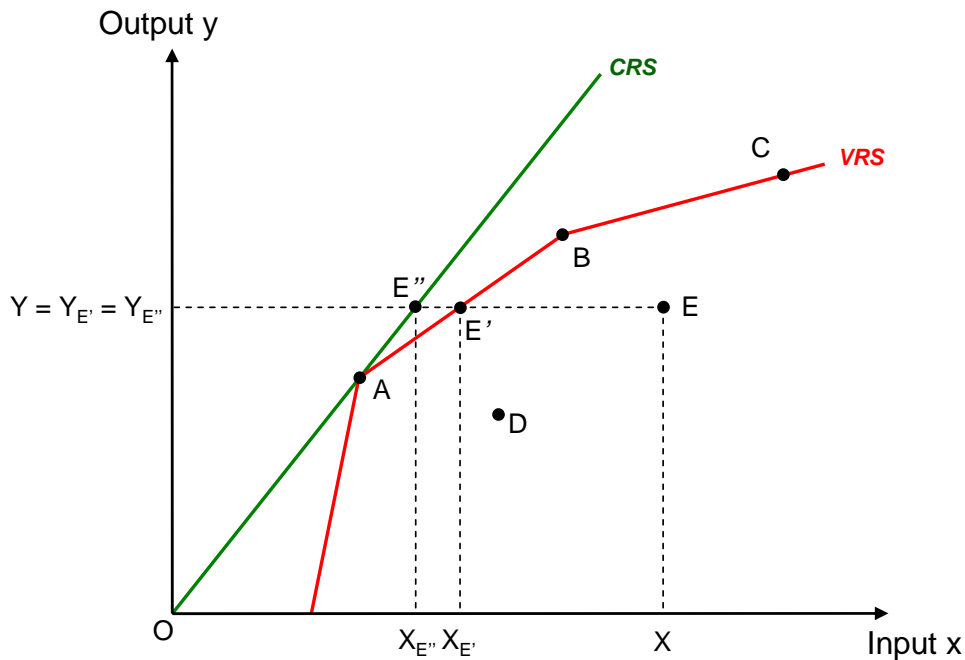
$$\begin{aligned} \text{Maximise } PTE_j &= u y_j - u_j \\ \text{Subject to } & \quad (i) v x_j = 1 \\ & \quad (ii) -vX + uY - u_0 e \leq 0 \\ & \quad (iii) v \geq 0, u \geq 0 \end{aligned} \quad (3)$$

where  $u_0$  is scalar and free in sign;  $u$  and  $v$  are output and input weight matrices; and  $Y$  and  $X$  are the corresponding output and input matrices, respectively.

When TE and PTE have been calculated, the scale efficiency (SE) can be calculated from their ratio:

$$SE = \frac{TE}{PTE} \tag{4}$$

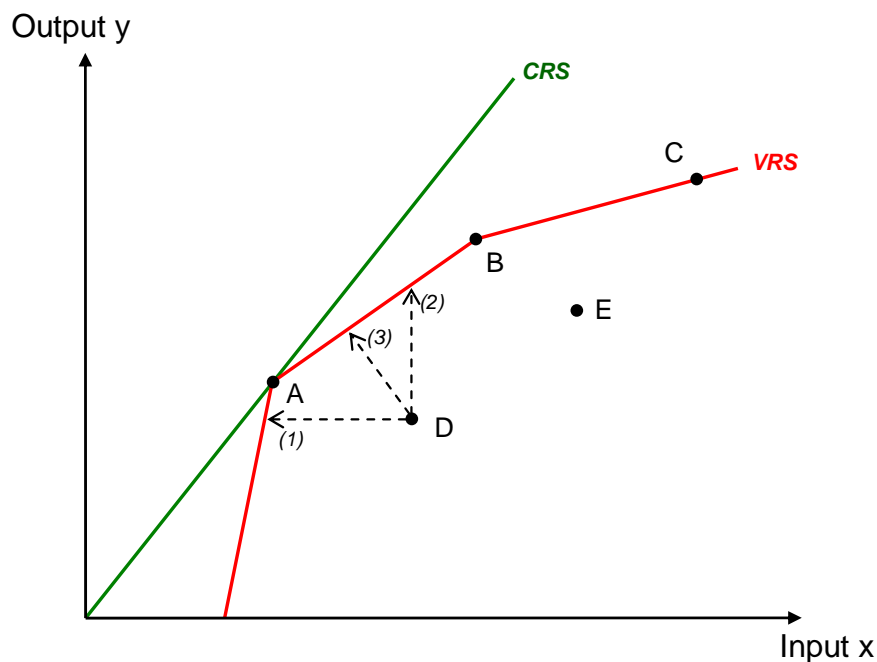
Figure 2 presents an illustration of the two models and the three types of efficiency.



**Figure 2** Graphical illustration for five decision making units (A, B, C, D, E) of the two models proposed for DEA application: the CCR model using constant return to scale (CRS) and the BCC model using variable return to scale (VRS)

In this figure, the envelopment of farm observations with CRS is represented by the straight line of OA that passes through the origin and the extreme data point corresponding here to the DMU A. All of the DMUs situated on this frontier line have a TE score of 1. The piecewise line joining observations for DMUs A, B and C represents the envelopment with VRS. All of the DMUs situated on this frontier line have a PTE score of 1. SE is represented by the distance between the two frontiers. With the example of the DMU E, the PTE score can be measured by the ratio  $OX_{E'}/OX_E$ . However, considering the estimated point E', the ratio  $OY_{E'}/OX_{E'}$  is lower than the maximum productivity represented by the ratio  $OY_A/OX_A$ . The SE score is represented by  $OX_{E''}/OX_{E'}$ . TE scores combine these two ratios and can be measured by the ratio  $OX_{E''}/OX_E$ .

However, in this example, efficiency scores of inefficient farms correspond to the distance between observations and frontier efficiency by a horizontal projection corresponding to the input-orientation. It assumes that to be efficient, a DMU must reduce its input level while the output is fixed. Other ways to be efficient also exist. A DMU can increase the output level while input is fixed (output orientation). Moreover, combining the two orientations is possible. This combination consists in a simultaneous reduction of inputs simultaneously with increasing outputs (mixed orientation). Figure 3 graphically illustrates the three orientations with the example of the DMU D.



**Figure 3** Graphical illustration for decision making unit D of the three orientations proposed for DEA application: input orientation (1), output orientation (2) and mixed orientation (3)

The choice between input and output orientation depends on the unique characteristics of the set of DMUs under study (Mousavi-Avval et al., 2011c).

In our study, DEA was performed using the R software v 2.15.0 (R Development Core Team, 2008) with the benchmarking package (Bogetoft and Otto, 2012). The orientation in our study is input-orientation. This choice is based on increasing oil prices and the environmental impact associated with fossil energy use.

In this DEA analysis, 5 inputs and 2 outputs were considered using the same energy unit, MJ.ha<sup>-1</sup>. To decrease the number of inputs in order to prevent the results of the analysis from being less discerning (Jenkins and Anderson, 2003), only the inputs accounting for more than 5% of the total energy use of dairy farms from the two regions were studied using the DEA application: fuel, electricity, fertiliser, concentrated feeds and buildings. The outputs

considered were the gross energy contained in the milk and meat sold, which were also expressed in MJ.ha<sup>-1</sup>. The gross energy contained in milk is based on fat and protein content and is calculated using equation 7 (Risoud and Theobald, 1999):

$$\text{Gross energy for milk (MJ.l}^{-1}\text{)} = \frac{(\text{Fat content} \times 38.6 + \text{Protein content} \times 25.4 + 782.2)}{1000} \times d \quad (7)$$

where *Fat* and *Protein contents* are expressed in g.kg<sup>-1</sup> and *d* corresponds to milk density, which estimated to be 1,030 kg.l<sup>-1</sup>. The gross energy for meat is based on the gross energy contained in animals as given by Risoud and Theobald (1999).

### III. RESULTS AND DISCUSSION

#### 3.1. Energy analysis

The mean fossil energy use, gross energy production and FE<sub>milk</sub> of the dairy systems are presented in Table 3.

**Table 3**  
Energy indicators for all farms and for each region (BR: Bretagne; PC: Poitou-Charentes)

|  | Global |    | BR     |    | PC     |    | p-value <sup>a</sup> |
|--|--------|----|--------|----|--------|----|----------------------|
|  | mean   | %  | mean   | %  | mean   | %  |                      |
| <b>Fossil energy use (MJ.ha<sup>-1</sup>)</b>                      |        |    |        |    |        |    |                      |
| Fuel   | 5,514  | 15 | 3,896  | 14 | 6,187  | 15 | ***                  |
| Electricity  | 5,596  | 15 | 4,085  | 15 | 6,224  | 15 | **                   |
| Human labour   | 40     | <1 | 41     | <1 | 39     | <1 | ns                   |
| Mineral fertilisation  | 7,968  | 22 | 6,928  | 25 | 9,063  | 22 | ***                  |
| External Manure  | 85     | <1 | 286    | 1  | 12     | <1 | ***                  |
| Chemicals  | 74     | <1 | 73     | <1 | 74     | <1 | ns                   |
| Water  | 681    | 2  | 387    | 1  | 769    | 2  | **                   |
| Seeds  | 159    | <1 | 199    | 1  | 143    | <1 | ***                  |
| Feed concentrates  | 10,823 | 30 | 7,066  | 25 | 12,801 | 31 | ***                  |
| Forage   | 956    | 3  | 806    | 3  | 1,054  | 3  | ns                   |
| Minerals   | 9      | <1 | 13     | <1 | 8      | <1 | ***                  |
| Veterinary Costs   | 1,349  | 4  | 1,483  | 4  | 1,294  | 3  | •                    |
| Plastics   | 999    | 3  | 898    | 3  | 1,121  | 3  | •                    |
| Buildings  | 1,747  | 5  | 1,675  | 6  | 1,777  | 4  | •                    |
| Materials  | 102    | <1 | 94     | <1 | 105    | <1 | ns                   |
| Total  | 36,102 |    | 27,930 |    | 40,671 |    | ***                  |
| <b>Gross energy production (MJ.ha<sup>-1</sup>)</b>                |        |    |        |    |        |    |                      |
| Milk   | 24,240 | 93 | 22,252 | 93 | 25,067 | 93 | •                    |
| Meat   | 1,873  | 7  | 1,717  | 7  | 1,939  | 7  | ns                   |
| Total  | 26,113 |    | 23,969 |    | 27,006 |    | ns                   |
| <b>Fossil energy use per litre of raw milk (MJ.l<sup>-1</sup>)</b> |        |    |        |    |        |    |                      |
|  | 4.4    |    | 3.6    |    | 4.9    |    | ***                  |

<sup>a</sup> p-value>0.10: ns, 0.10≤p-value< 0.05: •, 0.05≤p-value< 0.01: \*, 0.01≤p-value< 0.001: \*\*, p-value ≤0.001: \*\*\*

The mean fossil energy use in PC (40,671 MJ.ha<sup>-1</sup>) was approximately 50% higher than in BR (27,930 MJ.ha<sup>-1</sup>). Differences in fossil energy use have been noted by [Vigne et al. \(submitted\)](#). In PC, the use of maize silage, which is partially associated with the presence of irrigation to secure forage systems ([Amigues et al., 2006](#)), increased at the expense of grazing. This forage system requires higher FE inputs compared to grazing based on harvest costs, leading to higher fuel use (3,896 vs. 6,187 MJ.ha<sup>-1</sup>) and protein supplementation, which increase the need for feed concentrates (7,066 vs. 12,801 MJ.ha<sup>-1</sup>). Moreover, this higher supplementation results from the higher livestock rate allowed by higher production of this forage system. The overconsumption of fossil energy in PC resulted in a slight increase in the production of raw milk per hectare (25,067 vs 22,252 MJ.ha<sup>-1</sup>). However, the increase in milk production in PC was not proportional to the increase in fossil energy use, which resulted in a lower FE<sub>milk</sub> (4.9 MJ.l<sup>-1</sup>) in comparison to BR (3.6 MJ.l<sup>-1</sup>). In the two regions, fuel (14% for Br and 15% for PC), electricity (15% for the two regions), mineral fertilisation (25% for BR and 22% for PC) and feed concentrates (25% for BR and 31% for PC) were the major energy use inputs. These inputs represented 82% of the average energy use, with means of 79 and 83% in BR and PC, respectively. With the exception of buildings (6% for BR and 4% for PC), other inputs accounted for less than 5% of the fossil energy use. We assume these other inputs represent weak methods of fossil energy reduction. In this sense, only these five inputs (fuel, electricity, mineral fertilisation, feed concentrates and buildings) have been considered in the DEA analysis.

Among the three types of systems, energy use and production were related to the proportion of maize silage in the system (Table 4). Total fossil energy use increased with the proportion of maize silage, with the lowest value for grassland systems (13,403 MJ.ha<sup>-1</sup>), the highest for maize systems (29,213 MJ.ha<sup>-1</sup>), and an intermediate value for grassland-maize systems (19,535 MJ.ha<sup>-1</sup>). The higher need for direct and indirect fossil energy use for maize silage cropping was illustrated by the higher use of mineral fertilisation and chemicals relative to the grassland systems. Mineral fertilisation was especially low (946 MJ.ha<sup>-1</sup>) in the grassland systems. In addition, maize silage cropping requires higher fuel use for harvesting and plastic for biomass stocking in comparison with grassland, which is mostly directly harvested by animals. Thus, the fuel use in the maize systems (6,187 MJ.ha<sup>-1</sup>) was 32% higher than in the grassland-maize systems (4,658 MJ.ha<sup>-1</sup>) and more than two times higher than in grassland systems (2,653 MJ.ha<sup>-1</sup>). The increase of maize silage in the ration of dairy cows requires the incorporation of imported soybean meal as a high-protein complement.

**Table 4**  
Energy indicators for each type of system

|  | Grassland |    | Grassland-Maize |    | Maize  |    | p-value <sup>a</sup> |
|--|-----------|----|-----------------|----|--------|----|----------------------|
|  | mean      | %  | mean            | %  | mean   | %  |                      |
| <b>Fossil energy use (MJ.ha<sup>-1</sup>)</b>                      |           |    |                 |    |        |    |                      |
| Fuel   | 2,653     | 20 | 4,658           | 16 | 6,187  | 13 | ***                  |
| Electricity  | 3,712     | 28 | 4,214           | 15 | 6,774  | 14 | ***                  |
| Human labour   | 25        | <1 | 33              | <1 | 47     | <1 | ***                  |
| Mineral fertilisation  | 946       | 7  | 5,970           | 21 | 9,163  | 20 | ***                  |
| External manure  | 49        | <1 | 59              | <1 | 105    | <1 | NS                   |
| Chemicals  | 24        | <1 | 45              | <1 | 101    | <1 | ***                  |
| Water  | 1,302     | 10 | 1,539           | 5  | 1,836  | 4  | NS                   |
| Seeds  | 85        | 1  | 149             | 1  | 185    | <1 | ***                  |
| Feed concentrates  | 2,284     | 17 | 6,813           | 24 | 15,146 | 32 | ***                  |
| Forage   | 435       | 3  | 1,063           | 4  | 1,389  | 3  | *                    |
| Minerals   | 4         | <1 | 7               | <1 | 11     | <1 | ***                  |
| Veterinary Costs   | 931       | 7  | 1,188           | 4  | 1,543  | 3  | ***                  |
| Plastics   | 337       | 3  | 897             | 3  | 1,327  | 3  | ***                  |
| Buildings  | 802       | 6  | 1,624           | 6  | 2,873  | 6  | ***                  |
| Materials  | 113       | 1  | 83              | <1 | 108    | <1 | *                    |
| Total  | 13,703    |    | 28,342          |    | 46,795 |    | ***                  |
| <b>Gross energy production (MJ.ha<sup>-1</sup>)</b>                |           |    |                 |    |        |    |                      |
| Milk   | 14,495    | 93 | 19,535          | 93 | 29,213 | 7  | ***                  |
| Meat   | 1,135     | 7  | 1,532           | 7  | 2,226  |    | ***                  |
| Total  | 15,630    |    | 21,067          |    | 31,439 |    | ***                  |
| <b>Fossil energy use per litre of raw milk (MJ.l<sup>-1</sup>)</b> |           |    |                 |    |        |    |                      |
|  | 3.3       |    | 4.4             |    | 5.7    |    | ***                  |

<sup>a</sup> p-value>0.10: ns, 0.10≤p-value<0.05: ·, 0.05≤p-value<0.01: \*, 0.01≤p-value<0.001: \*\*, p-value≤0.001: \*\*\*

Fossil energy use from feed concentrates was around six times higher in maize systems than grassland systems. As shown previously, maize silage systems had a higher livestock stocking rate, needing more buildings and resulting in a higher fossil energy use from buildings, which was nearly 5 times higher in maize systems than in grassland systems. Moreover, maize systems led to higher milk production per hectare and thus higher use of electricity for milking per hectare.

Gross energy production was thus the highest for maize systems (31,439 MJ.ha<sup>-1</sup>), followed by grassland-maize systems (21,067 MJ.ha<sup>-1</sup>) and grassland systems (15,630 MJ.ha<sup>-1</sup>). Gross energy production was represented mainly by milk (93%) in the three types of systems. However, gross energy production resulting from fossil energy invested in maize silage was not proportional, and the more silage maize was present, the less efficient was the farm at converting fossil energy use invested into raw milk. Regarding the fossil energy use per litre of raw milk produced (FE<sub>milk</sub>), the grassland system appears to be the most efficient system (3.3 MJ.l<sup>-1</sup>), followed by the grassland-maize systems (4.4 MJ.l<sup>-1</sup>) and the

maize systems ( $5.7 \text{ MJ.l}^{-1}$ ). These results confirm the larger fossil energy efficiency of grazing-based systems compared to more intensive systems, as shown previously on dairy farms by Haas et al. (2001) in Germany and O'Brien et al. (2012) in Ireland.

### 3.2. DEA

Analysis of the 126 DMUs by DEA gave a mean TE score of 0.82 (Table 5). TE was significantly higher for BR (0.88) than PC (0.76). The lower mean score for PC than BR was due to the significantly lower values for the grassland-maize (0.72) and maize systems (0.71), while the values for grassland systems were similar for the two regions (0.89). In the two regions and among systems, TE seemed to be dependent of PTE, whereas the mean values of SE were equal to or higher than 0.93, indicating that the farms were globally operating at the appropriate scale. Similarly to TE, the mean PTE score in PC (0.82) was lower than in BR (0.91), confirming the lower efficiency of the dairy systems in PC in terms of converting the fossil energy invested into milk (Table 4). The lower PTE score in PC was mainly due to a significantly lower PTE score for grassland-maize systems (0.75) and maize systems (0.77), while the values were similar for grassland systems between the regions (0.91 for BR and 0.92 for PC). This result illustrates the disadvantageous conditions under which PC farms are operating. Drier conditions in PC lead to the use of higher quantities of inputs to maintain similar crop yields and consequently, similar milk production. Grassland systems were also affected by these conditions. However, to respond to less favourable climatic conditions, grassland systems from PC do not increase forage inputs, but accept the risk of lower milk production leading to a lower SE value (0.93) than BR (0.98).

The analysis of efficient farms showed that 34 DMUs (26% of the total DMUs) were efficient overall. No study has been made of the efficiency of the energy use of dairy systems by the DEA method. However, our data fall within the range obtained in studies of other agricultural systems, from 15% (Chauhan et al., 2006) to 36% (Mousavi-Avval et al., 2011c). The 34 DMUs were situated in every region and every type of system (Table 5), which confirms different ways to achieve efficiency resulting in different values of fossil energy efficiency. Figure 4 confirms this result. If the TE score is partially related to  $FE_{\text{milk}}$  ( $R^2=0.58$ ;  $see=0.12$ ), overall efficient farms with a TE score equal to 1 are not necessarily the most energy efficient users for milk production. They are thus situated along a large range of fossil energy use, from approximately  $2.0$  to  $4.5 \text{ MJ.l}^{-1}$ , showing a different level of TE.

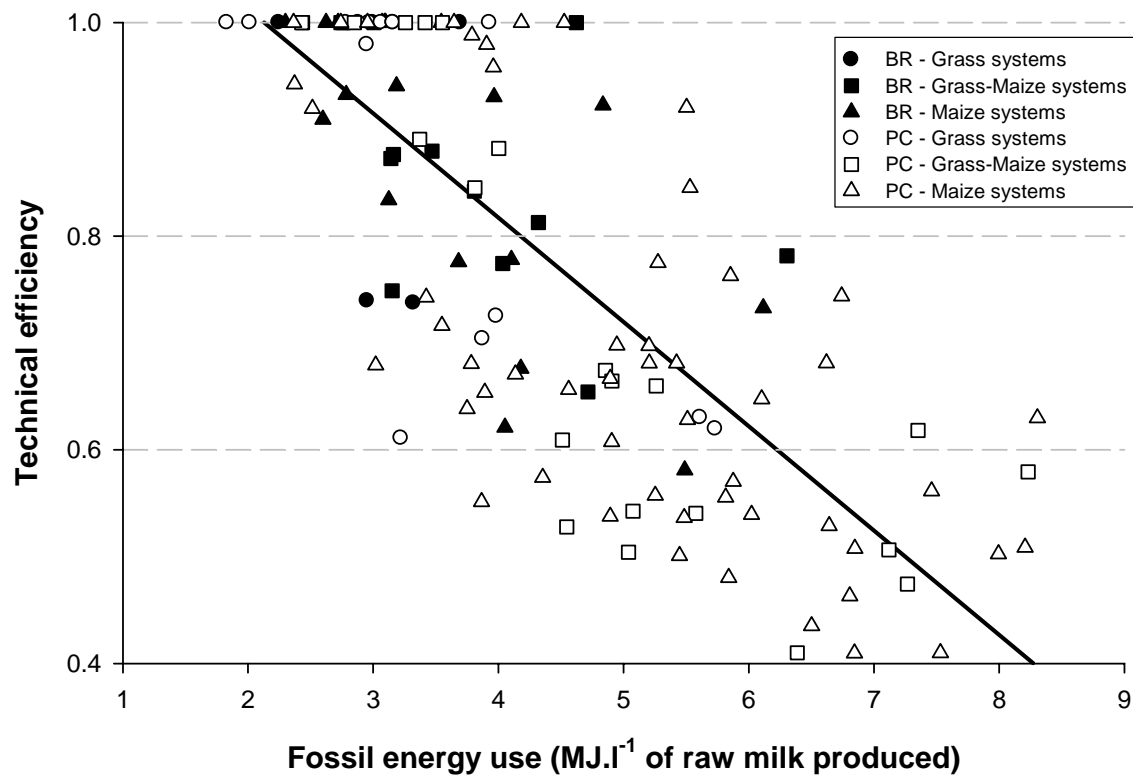
**Table 5**

Distribution of scores obtained for each efficiency indicator (TE: technical efficiency, PTE: Pure Technical Efficiency, SE: Scale efficiency)

| Mean score                   | TE    |      |      |         | PTE   |      |      |         | SE    |      |      |         |
|------------------------------|-------|------|------|---------|-------|------|------|---------|-------|------|------|---------|
|                              | Total | BR   | PC   | p-value | Total | BR   | PC   | p-value | Total | BR   | PC   | p-value |
| All types                    | 0.82  | 0.88 | 0.76 | **      | 0.86  | 0.91 | 0.82 | *       | 0.95  | 0.96 | 0.94 | ns      |
| Grassland                    | 0.89  | 0.89 | 0.89 | ns      | 0.92  | 0.91 | 0.92 | .       | 0.95  | 0.98 | 0.93 | ns      |
| Grassland-                   | 0.79  | 0.86 | 0.72 | *       | 0.83  | 0.90 | 0.75 | *       | 0.96  | 0.95 | 0.96 | ns      |
| Maize                        | 0.78  | 0.88 | 0.71 | ****    | 0.84  | 0.92 | 0.77 | **      | 0.93  | 0.95 | 0.92 | ns      |
| Maize                        |       |      |      |         |       |      |      |         |       |      |      |         |
| <b>p-value</b>               | .     | ns   | **   |         | .     | ns   | ***  |         | ns    | ns   | ns   |         |
| All types                    | *     | ns   | **   |         | *     | ns   | ***  |         | ns    | ns   | ns   |         |
| GxGM                         | *     | ns   | **   |         | *     | ns   | ***  |         | ns    | ns   | ns   |         |
| GxM                          | ns    | ns   | ns   |         | ns    | ns   | ns   |         | ns    | ns   | ns   |         |
| GMxM                         | ns    | ns   | ns   |         | ns    | ns   | ns   |         | ns    | ns   | ns   |         |
| <b>Nb of efficient farms</b> | 34    | 14   | 20   |         | 47    | 17   | 30   |         | 34    | 14   | 20   |         |
| All types                    | 12    | 3    | 9    |         | 15    | 3    | 12   |         | 12    | 3    | 9    |         |
| Grassland                    | 9     | 4    | 5    |         | 10    | 5    | 5    |         | 9     | 4    | 5    |         |
| Grassland-                   | 13    | 7    | 6    |         | 22    | 9    | 13   |         | 13    | 7    | 6    |         |
| Maize                        |       |      |      |         |       |      |      |         |       |      |      |         |
| Maize                        |       |      |      |         |       |      |      |         |       |      |      |         |

<sup>a</sup> p-value > 0.10: ns, 0.10 ≤ p-value < 0.05: ., 0.05 ≤ p-value < 0.01: \*, 0.01 ≤ p-value < 0.001: \*\*, p-value ≤ 0.001: \*\*\*





**Figure 4** Link between fossil energy efficiency calculated through the fossil energy use per litre of raw milk produced ( $\text{MJ.l}^{-1}$ ) and technical efficiency (TE) scores obtained for the 129 farms evaluated

### 3.3. Potential improvements for fossil energy use of dairy farms from western France

Decomposition of the efficiency into different levels of fossil energy use through the DEA method enables us to provide realistic potential improvements for fossil energy use. Indeed, establishing potential improvements could consist in assuming each inefficient farm had a potential to reach a  $\text{FE}_{\text{milk}}$  value that was similar to the most efficient farm of its type of system located in a similar territory. The target fossil energy use for these inefficient farms would correspond to the different values obtained from lower energy-using farms in each region and for each type of system. In our study, as shown in Table 6, this would mean that all grassland systems could reach 2.2 and 2.0  $\text{MJ.l}^{-1}$  for BR and PC, respectively, 2.4  $\text{MJ.l}^{-1}$  for grassland-maize systems in the two regions and 2.6 and 2.4  $\text{MJ.l}^{-1}$  for maize systems. This would result in mean energy savings of 40.8% among farms, and optimised fossil energy use would reach 2.4  $\text{MJ.l}^{-1}$  for BR and 2.3  $\text{MJ.l}^{-1}$  for PC. However, this assumption excludes the probability for different efficient farms existing in the same type of system for the same region.

**Table 6**

Optimum fossil energy use per litre of raw milk in each type of system in the two regions (BR: Bretagne; PC: Poitou-Charentes) calculated from lower fossil energy-using farms (energy analysis) or with the calculation of energy-saving target ratio (DEA)

|                        | Energy analysis |     | DEA |     |
|------------------------|-----------------|-----|-----|-----|
|                        | BR              | PC  | BR  | PC  |
| Grassland systems      | 2.2             | 2.0 | 3.0 | 3.3 |
| Grassland-maize system | 2.4             | 2.4 | 3.4 | 4.2 |
| Maize system           | 2.6             | 2.4 | 3.4 | 4.4 |

In the DEA method, a PTE score of less than one for a farm indicates that the farm is using more energy than required from the difference sources. The optimum use of fossil energy use can be estimated with the calculation of an energy-saving target (Hu and Kao, 2007). Energy-saving targets consist of the total decreasing amount of each input that could be reduced without decreasing output levels. The proportion of energy saved is illustrated by the energy saving target ratio (ESTR), corresponding to the ratio of optimum energy use to actual energy use. Calculating this ratio, the overall energy savings for inefficient farmers ranges from 0.3 to 42.4%, for a mean energy saving of 15.9%, which is far lower than previous estimations based on lower energy-use farms as the target use (40.8%). This results in a larger mean  $FE_{milk}$  for the different systems in each region (Table 6). When applying the optimum energy use calculated by the DEA analysis on each farm, the mean optimised  $FE_{milk}$  for BR and PC would be, respectively, 3.0 and 3.3  $MJ.l^{-1}$  for grassland systems, 3.4 and 4.2  $MJ.l^{-1}$  for grassland-maize systems and 3.4 and 4.4  $MJ.l^{-1}$  for maize systems. In each region, the mean optimised  $FE_{milk}$  would reach 3.3  $MJ.l^{-1}$  for BR and 4.0  $MJ.l^{-1}$  for PC. In DEA, the comparison of farms with similar profiles of fossil energy use would enable us to account for other factors also related to fossil energy-use efficiency (e.g., workforce, economic investment capacity, soil quality of arable land).

Moreover, in analysing an ESTR for each farm, it enables the determination of specific priorities for decreasing energy use. Table 7 presents actual energy use and optimum energy requirements for a panel of dairy farms from the different regions and types of systems. Among the regions and types of systems, different ways for fossil energy use reduction could appear. For example, in grassland systems from BR, sources of fossil energy reduction are fuel for DMU11 and fertiliser for DMU29. In grassland-maize systems, sources of fossil energy reduction decrease are feed concentrates for DMU47 and fuel and fertiliser for DMU118.

**Table 7**

Actual and optimum energy use for a panel of inefficient dairy farms from western France (BR: Bretagne, PC: Poitou-Charentes)

| Region | Type of system  | DMU | PTE  | Actual energy use (MJ.ha <sup>-1</sup> ) |       |        | Optimum energy requirement (MJ.ha <sup>-1</sup> ) |        |      | ESTR (%) |       |        |       |        |      |
|--------|-----------------|-----|------|--|-------|--------|---|--------|------|----------|-------|--------|-------|--------|------|
|        |                 |     |      | Fuel                                     | Elec. | Ferti. | Feeds   | Build. | Fuel |          | Elec. | Ferti. | Feeds | Build. |      |
| BR     | Grassland       | 11  | 0.84 | 5211                                     | 2810  | 1335   | 3221  | 668    | 547  | 0        | 0     | 0      | 0     | 4.1    |      |
|        |                 | 29  | 0.81 | 2584                                     | 3212  | 2317   | 2360  | 558    | 0    | 0        | 1217  | 0      | 0     | 0      | 11.0 |
|        | Grassland-Maize | 19  | 0.77 | 2964                                     | 5035  | 4172   | 5602  | 793    | 0    | 0        | 1784  | 0      | 0     | 0      | 9.6  |
|        |                 | 20  | 0.97 | 2770                                     | 3299  | 268    | 3985  | 851    | 0    | 0        | 0     | 1803   | 213   | 0      | 18.0 |
|        | Maize           | 9   | 0.80 | 4676                                     | 2956  | 2850   | 5305  | 753    | 0    | 0        | 0     | 0      | 46    | 0      | 0.3  |
| PC     | Grassland       | 1   | 0.97 | 4160                                     | 7299  | 808    | 15872   | 780    | 0    | 0        | 0     | 8278   | 0     | 0      | 28.6 |
|        |                 | 82  | 0.80 | 2736                                     | 3890  | 2537   | 1564  | 543    | 0    | 0        | 651   | 0      | 0     | 0      | 5.8  |
|        | Grassland-Maize | 81  | 0.85 | 3019                                     | 4404  | 2011   | 1047  | 566    | 0    | 928      | 1033  | 0      | 0     | 0      | 18.8 |
|        |                 | 47  | 0.64 | 5044                                     | 3764  | 4016   | 12195   | 776    | 0    | 0        | 0     | 3728   | 0     | 0      | 15.0 |
|        | Maize           | 118 | 0.92 | 7002                                     | 4426  | 5000   | 1390  | 443    | 2407 | 0        | 1180  | 0      | 0     | 0      | 36.3 |
|        |                 | 84  | 0.43 | 7584                                     | 6582  | 24791  | 7656  | 1335   | 0    | 8955     | 0     | 0      | 0     | 20.2   |      |
|        |                 | 58  | 0.55 | 8628                                     | 7744  | 26607  | 15748   | 779    | 0    | 11712    | 3484  | 0      | 0     | 25.5   |      |

Elec.: Electricity; Ferti.: Fertiliser; Feeds: Feed concentrates; Build.: Buildings

## IV. CONCLUSION

In our study, an application of fossil energy and DEA analysis on dairy farms representative of western France has shown higher efficiency of BR systems than PC systems of converting invested fossil energy into milk. Moreover, the study of the different forage systems showed grasslandland systems appeared more efficient in comparison to grasslandland-maize and maize systems illustrating higher need for fossil energy for producing high amount of milk with maize silage and increased amount of concentrates.

Nonetheless, the application of DEA analysis also showed efficient farms are present in the two regions studied and for each type of system which illustrates a potential gain in energy use without modifying the type of systems. DEA appeared useful for measuring potential gain because it provides realistic targets energy use efficiency, and because it enables specific reduction methods for each farm that could be useful for the individual environmental management of farms. Moreover, DEA results show that despite of unfavourable factors, some farms in PC are as efficient as farms from BR. Analysing those farms in detail could highlight original factors.

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## **Chapitre VII**

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# **DISCUSSION GENERALE**



**Après avoir présenté les méthodes utilisées, analysé les performances de systèmes dans leur grande diversité géographique en fonction des territoires, de leurs atouts et de leur contraintes très différents et analysé plus finement la diversité intra territoire en fonction des options techniques retenues, cette partie constitue la discussion générale du travail de thèse organisée autour de deux parties.**

**La première partie aborde la méthodologie mise en place pour répondre aux questions scientifiques posées. Les points forts et limites de chacune des deux méthodes choisies sont d'abord mis en lumière, une approche comparée des deux méthodes est ensuite fournie et dans un troisième temps nous justifions les modes de récolte des données utilisées dans notre étude ainsi que le choix des territoires.**

**La seconde partie de la discussion est une analyse comparée des résultats obtenus sur les différents territoires. Cette analyse est d'abord menée au regard des systèmes du Mali Sud considérés comme en partie représentatifs des systèmes familiaux en intégration agriculture - élevage des pays en développement. Les résultats obtenus à partir des deux méthodes sur les systèmes intensifs des pays développés représentés par les trois autres territoires sont ensuite comparés et analysés. Enfin une dernière partie est consacrée à l'analyse de la variabilité intra-territoire et de son intérêt sur l'ensemble des territoires pour rechercher des voies d'amélioration.**

## 1. Méthodologie mise en place

### 1.1. L'analyse pluri-énergétique

#### *Une méthode intéressante pour mettre en lumière les modes de gestion de l'énergie...*

La méthode originale d'analyse pluri-énergétique construite dans le cadre de ce travail de thèse a montré son adaptabilité à des systèmes très contrastés observables sur différents territoires. Elle apparaît générique tout en étant flexible en permettant des simplifications. Cette généricité/flexibilité s'exprime également à travers la capacité de prise en compte de l'ensemble des produits de l'exploitation et du troupeau. Dans le Chapitre V.1, la seule prise en compte des produits à destination de l'alimentation humaine (lait et viande) questionne les résultats provenant de l'allocation des impacts environnementaux par unité de produit. Ces interrogations sont d'autant plus importantes dans les systèmes non spécialisés des pays en développement tels que ceux rencontrés à Sikasso et où la part des effluents est largement majoritaire dans l'énergie brute produite par le troupeau (95%). Les estimations menées montrent que dans ces systèmes la consommation d'énergie fossile par litre de lait produit s'élèverait à 2.9 MJ.l<sup>-1</sup> sans comptabilisation des effluents alors qu'elle s'élève seulement à 0.1 MJ.l<sup>-1</sup> lorsque ces derniers sont considérés.

De plus, la méthode d'analyse pluri-énergétique a permis de lever un certain nombre de limites des méthodes classiques de bilan entrée/sortie à l'échelle de l'exploitation. En particulier, la décomposition du système en plusieurs composantes et l'analyse des flux internes permettent une analyse fine des efficacités d'utilisation de l'énergie à l'échelle de chacune des composantes du système. La méthode permet ainsi de mettre en lumière les étapes critiques de l'efficacité dans le fonctionnement du système.

Un intérêt majeur est également apporté par la prise en compte des différents types d'énergie qui permet d'analyser plus explicitement la capacité propre de chacune des composantes à transformer les ressources énergétiques. Par exemple, les cultures sont analysées selon leur capacité à valoriser l'énergie solaire en énergie brute alors que les animaux sont évalués à travers leur capacité à valoriser l'énergie brute issue de la ressource végétale en énergie brute contenue dans les produits animaux.

#### *... mais dont l'application peut s'avérer fastidieuse...*

La multiplication des flux consécutive à la décomposition du système et à la prise en compte des différentes énergies tend à complexifier son application en augmentant la quantité

de données nécessaires. Elle nécessite donc d'avoir recours à des bases de données importantes et/ou de mettre en place des suivis d'exploitations ou des protocoles d'enquête importants. Cette complexité est accrue par la nécessité d'adapter chaque coefficient énergétique fossile au territoire étudié pour ne pas biaiser les comparaisons entre territoires. Cependant, l'analyse du cycle de vie d'un intrant peut s'avérer fastidieuse. Toutefois, comme nous l'avons montré dans le Chapitre IV.1, et bien que celle-ci n'est pas été menée dans notre étude sur les quatre territoires, une analyse de sensibilité préalable peut permettre de gagner en identifiant les coefficients les plus sensibles sur lesquels devraient se porter les efforts d'adaptation.

La mise en place de bases de données détaillée pour l'agriculture et librement accessibles telle que FeedPrint (Vellinga et al., 2012) à l'inverse des bases générales et outils d'analyse de cycle de vie (ACV) couramment utilisés (Ecoinvent®, Simapro®, ...) pourrait constituer une aide supplémentaire. La mise en place de telles bases permettrait d'arrêter des coefficients pour un territoire et d'éviter la variabilité au sein d'un territoire telle que mise en lumière dans le chapitre IV.1. Par exemple, au Canada, le coefficient énergétique du diesel peut varier de 37,4 (McLaughlin et al., 2000) à 45,1 MJ.l<sup>-1</sup> (Clements et al., 1995) selon la référence choisie. Le choix de l'une ou l'autre référence n'est pas sans conséquence sur le résultat des consommations finales.

Ce risque est bien illustré par la comparaison des résultats obtenus dans notre étude sur les systèmes de Poitou-Charentes et de Bretagne avec ceux précédemment obtenus par l'Institut de l'élevage sur ces mêmes systèmes (Institut de l'élevage, 2010). Nos résultats apparaissent ainsi supérieurs pour les systèmes maïs-herbe (4.4 vs 3.1) et maïs (5.7 vs 3.5) alors que les systèmes herbagers sont proches (3.1 vs 3.3). Ces différences résultent en partie du fait que bien qu'étant issus de la même méthode (Dia'terre®), les coefficients énergétiques fossiles varient sensiblement entre les deux études (Tableau 1).

**Tableau 1**

Exemple de coefficients énergétiques fossiles utilisés par l'Institut de l'Élevage en 2010 et dans notre étude durant le travail de thèse

| Intrants    | Unité   | Etude Institut | Notre étude        |
|-------------|---------|----------------|--------------------|
| Electricité | kWh     | 9,6            | 10,4               |
| Fioul       | l       | 40,7           | 45,6               |
| Ammonitrate | unité N | 52,6           | 54,36 <sup>a</sup> |
| Céréales    | tonne   | 2410           | 2689 <sup>b</sup>  |

<sup>a</sup> N'ayant pas une description complète du type d'engrais dans les bases utilisées nous avons donc attribué pour l'ensemble des intrants le coût moyen des engrais N donné par Dia'terre

<sup>b</sup> N'ayant pas de description précise des céréales distribués mais les entrées de céréales dans les systèmes étudiés étant principalement sous forme de blé tendre (dire d'experts) nous avons donc affecté le coût énergétique du blé tendre donné par Dia'terre® à l'ensemble des céréales

En réalité, la méthode Dia'terre® est en constante évolution et ses coefficients sont régulièrement mis à jour. Les valeurs utilisées dans notre étude sont ainsi issues de la dernière mise à jour disponible au moment de l'étude (version 1.13 du 29/11/2011).

En utilisant les coefficients retenus en 2010 par l'Institut de l'Elevage sur les exploitations de notre échantillon, les valeurs obtenues tendent à se rapprocher pour la Bretagne des valeurs obtenues par l'Institut de l'Elevage (Tableau 2).

**Tableau 2**

Consommations d'énergie fossile calculées sur les exploitations de notre échantillon selon les coefficients énergétiques fossiles utilisés par l'IE en 2010 et ceux utilisés dans notre étude

| Territoire | Système    | Coefficients utilisés |                              |
|------------|------------|-----------------------|------------------------------|
|            |            | Dia'terre® 2010       | Dia'terre® 2012 <sup>a</sup> |
| BR         | Global     | 3.3                   | 3.6                          |
|            | Herbager   | 2.7                   | 2.8                          |
|            | Herbe-Maïs | 3.1                   | 3.6                          |
|            | Maïs       | 3.5                   | 4.6                          |
| PC         | Global     | 4.2                   | 4.9                          |
|            | Herbager   | 3.2                   | 3.6                          |
|            | Herbe-Maïs | 4.4                   | 4.9                          |
|            | Maïs       | 5.0                   | 6.1                          |

<sup>a</sup> Données issues du chapitre V.2 et d'une communication 3R (Annexe IV)

*... et qui nécessite encore des ajustements méthodologiques.*

Au-delà des limites liées à son application, un certain nombre d'améliorations méthodologiques sont sans doute à envisager. Une des limites de l'analyse pluri-énergétique réside dans une prise en compte partielle des différentes énergies. Comme indiqué dans le Chapitre V.1, les consommations d'énergies indirectes sont comptabilisées seulement pour l'énergie fossile. Si la comptabilisation de l'énergie brute indirecte apparaît moins intéressante, la prise en compte de l'énergie solaire indirecte et de l'énergie indirecte liée au travail pourrait s'insérer dans une démarche plus large d'évaluation multi-critères de la durabilité des systèmes. Ainsi, la comptabilisation de l'énergie liée au travail indirectement consommée pour produire les intrants à travers les ACV sociales par exemple (Wolf et al., 2002 ; Dreyer et al., 2006) pourrait permettre d'évaluer la participation du système à l'économie locale et l'insertion du système dans un réseau plus global. La prise en compte de l'énergie solaire indirecte pourrait être représentée par la radiation solaire captée par les surfaces extérieures pour produire les aliments du troupeau importés. Elle constituerait une représentation intéressante de la dépendance du système aux surfaces extérieures telle

qu'effectuée par la méthode d'Empreinte écologique (Wackernagel and Rees, 1996) ou le calcul de l'indicateur de « land use » dans les ACV (Mila i Canals et al., 2007).

Un autre aspect questionnant la méthodologie de l'analyse pluri-énergétique est celui de l'allocation des différentes énergies entrantes dans le système entre les différentes composantes et leurs produits. La question de l'allocation est un débat omniprésent dans l'évaluation environnementale des systèmes de production laitiers (Cederberg and Mattsson, 2000; Eide, 2002; Hospido et al., 2003). Dans l'analyse pluri-énergétique, elle s'est avérée particulièrement utile afin d'affecter un coût en énergie fossile pour les fourrages et les concentrés autoproduits propre à chaque exploitation. Dans notre étude, le mode d'allocation choisi parmi les nombreux modes déjà exposés (Dollé et al., 2011) est l'allocation énergétique basée sur le contenu en énergie brute de la biomasse produite. Comme démontré dans le Chapitre V.1, ce choix d'allocation impacte peu le coût en énergie fossile de ces ressources et par conséquent la valeur finale de consommation en énergie fossile à l'échelle du troupeau. L'impact semble beaucoup plus important en ce qui concerne l'allocation des entrées d'énergie fossile selon les différents produits du troupeau (Tableau 3).

**Tableau 3**

Consommation d'énergie fossile par litre de lait produit sur les systèmes des 4 territoires (SM: Mali sud, RI: Ile de la Réunion, PC: Poitou-Charentes, BR: Bretagne) selon différentes règles d'allocation entre les produits du troupeau

|                     |                         | SM    | RI  | PC  | BR  |
|---------------------|-------------------------|-------|-----|-----|-----|
| Règles d'allocation | Energétique             | 0.1   | 6.6 | 4.9 | 3.6 |
|                     | Protéique               | < 0.1 | 2.5 | 2.1 | 1.6 |
|                     | Massique                | 0.2   | 2.3 | 2.1 | 1.6 |
| Significativité     | Energétique x Protéique | ***   | *** | *** | *** |
|                     | Energétique x Massique  | *     | *** | *** | *** |
|                     | Protéique x Massique    | ***   | ns  | ns  | ns  |

<sup>a</sup>ns = p-value>0.05, \*\*\* = 0.05<p-value<0.01), \*\* = 0.01<p-value<0.001, \*\*\*\* = p-value<0.001

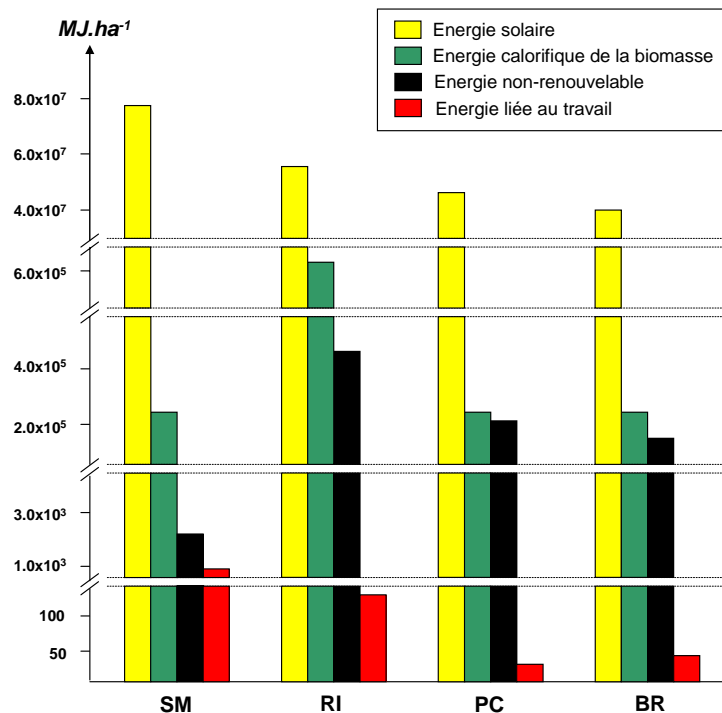
Dans cette estimation, l'allocation énergétique est comparée à l'allocation protéique basée sur le contenu des produits en azote et l'allocation massique basée sur le poids brut des produits. A l'exception de l'allocation protéique et massique sur les trois territoires intensifs (RI, PC et BR), il apparaît que le choix du mode d'allocation peut avoir un impact significatif sur les valeurs obtenues notamment du fait de la comptabilisation des effluents comme produit du troupeau. Pour remédier au choix parfois aléatoire et souvent discutable de ces unités fonctionnelles, l'allocation biologique apparaît de plus en plus pertinente (Cederberg and Stadig, 2003). Elle se base sur la répartition des besoins énergétiques et protéiques

couverts par l'alimentation entre les différentes fonctions biologiques de l'animal (production de lait, entretien, reproduction). Cependant, cette allocation nécessite de connaître précisément les pratiques d'élevage dans chaque territoire afin de produire des ratios précis entre les différents produits. Ces investigations sont d'autant plus importantes dans des systèmes tels que ceux de Sikasso où le ratio de 85% pour lait et 15% pour la viande tel que proposé par Cederberg and Stadig (2003) en système laitier n'est probablement pas adapté.

## 1.2. La méthode Emergy

### *Une méthode intéressante pour analyser l'utilisation des ressources par un système...*

L'application de la méthode Emergy a montré un intérêt particulier pour la prise en compte de l'ensemble des ressources consommées par le système sous une même unité (solar emjoule). Ceci permet d'aboutir à un profil de consommation des ressources différent selon les territoires. Cette prise en compte de l'ensemble des ressources sous une même unité constitue sans doute le principal atout de cette méthode. En effet, la prise en compte par exemple, de l'ensemble des ressources sur la seule base de l'énergie fossile nécessaire à leur production exclurait les ressources naturelles utilisées. Un autre moyen simple pourrait consister à cumuler les différentes énergies consommées sur l'exploitation et mesurées à partir de l'analyse pluri-énergétique (Figure 1).



**Figure 1** Différentes formes d'énergie entrante dans les systèmes des différents territoires (SM : Mali ; RI : la Réunion, PC : Poitou-Charentes, BR : Bretagne)

Comme explicité par Hülsbergen et al. (2001) et Rathke et Diepenbrock (2006), cette forme de comptabilisation entraîne un problème d'échelle principalement lié la prise en compte de l'énergie solaire. En effet, la radiation solaire excède les autres entrées d'énergie au minimum d'un facteur 100. Dans ce cas, les autres entrées d'énergie deviennent une composante insignifiante de l'énergie totale alors qu'elles représentent un intérêt tout aussi important dans le système.

La prise en compte de l'exergy des différentes ressources, définie comme la quantité d'énergie disponible correspondant au travail maximal que peut fournir un système à l'équilibre thermodynamique pourrait également apparaître comme une voie intéressante (Bösch et al., 2007). Or, selon Kabelac (2005), la part d'exergy dans la radiation solaire atteignant la surface terrestre s'élève de 50 à 80% selon les conditions atmosphériques. Compte tenu de sa part élevée dans l'énergie totale précédemment exposée, l'exergy ne résout toutefois pas les problèmes de dimension d'unité face aux autres énergies.

La méthode Emergy est également intéressante de par sa capacité à prendre en compte un large panel de ressources naturelles (soleil, pluie, eau, érosion). En ne se concentrant pas seulement sur l'énergie solaire, elle permet la prise en compte du potentiel bioclimatique de chaque territoire et des facteurs naturels limitant la production des surfaces. Bien que cela ne fasse qu'ajouter des données à la masse d'information nécessaire déjà élevée, ceci est d'autant plus intéressant qu'il peut exister à l'intérieur de chaque territoire différents potentiels bioclimatiques. A la Réunion par exemple, l'île présente des situations climatiques particulièrement contrastées liées à l'altitude et à l'exposition aux vents d'alizés. Sur la partie Est de l'île fortement exposée à ces vents humides, la pluviométrie annuelle est supérieure à 3,0 m alors que la partie Ouest de l'île, protégée des vents par les massifs du centre de l'île, reçoit moins de 1,0 m de pluie par an et est soumise à des sécheresses périodiques.

### ***... mais qui comporte encore des imprécisions méthodologiques***

La mise en place de la méthode Emergy reste limitée. Elle est notamment freinée par une méthodologie encore en cours de construction. Ainsi les récentes améliorations méthodologiques sont encore soumises à débat. En proposant d'allouer l'emergy entrante dans un système en fonction entre les différents co-produits du système selon leur contenu en énergie, Bastianoni and Marchettini (2000) ont selon Hau and Bakshi (2004) répondu à l'une des principales limites. Comme démontré dans le chapitre V.2, cette proposition est d'autant plus intéressante qu'elle permet une première approche de la multifonctionnalité des systèmes

d'élevage non spécialisés de la zone périurbaine de Sikasso. Cependant, cette allocation se confronte là aussi aux débats méthodologiques déjà exposés pour l'analyse pluri-énergétique.

L'inclusion des facteurs de renouvelabilité proposée par [Ulgiati et al. \(1994\)](#) est probablement l'autre avancée majeure de la méthodologie. Elle permet une analyse plus fine des ressources utilisées telles que les concentrés en considérant que celles-ci peuvent être issues à la fois de ressources renouvelables et non renouvelables. Comme démontré en chapitre V.2, ceci est d'autant plus intéressant dans les systèmes où la complémentarité est importante tels que ceux de l'Ile de la Réunion. Cela nécessite cependant des investigations plus fines sur le cycle de vie des différentes ressources utilisées, ces facteurs étant encore peu renseignés.

Ces investigations s'inscrivent dans les mêmes questionnements que l'adaptation des UEVs. Dans notre étude, nous avons fait l'hypothèse que la non adaptation des UEVs pourrait conduire à une incertitude importante sur les résultats de la méthode de façon similaire à ce qui est observé sur les coefficients énergétiques de l'analyse fossile. Cette hypothèse est en partie confortée par l'incertitude au sein des UEVs mise en lumière par [Ingwersen \(2010\)](#). Une prochaine étape consistant à mesurer à partir de ces incertitudes la variabilité obtenue sur les indicateurs est nécessaire pour confirmer définitivement notre hypothèse et appuyer la nécessité de développer la méthodologie de calcul des UEVs. En effet, de par sa récente application en particulier sur les systèmes agricoles, les UEVs disponibles sont encore peu nombreuses ce qui a mené à utiliser principalement les valeurs fournies par [Odum \(1996\)](#), [Odum et al. \(2000\)](#), [Brown and Bardi \(2001\)](#) et [Brandt-Williams \(2002\)](#) calculées sur un nombre de territoires et de technologies limitées.

### **1.3. Apport comparé des deux méthodes**

#### ***Une mise en lumière des modes de gestion de l'énergie intéressante par les deux méthodes***

Les deux méthodes ont permis de fournir un profil des consommations énergétiques sur les différents territoires à travers deux entrées : d'une part, une entrée « purement » énergétique pour l'Analyse pluri-énergétique et d'autre part, une entrée « ressources » pour la méthode Emergy. Dans les deux cas, les deux méthodes ont permis de fournir des indicateurs répondant au concept d'intensification écologique. Elles ont ainsi mis en lumière des systèmes ne répondant pas seulement à l'objectif de production mais utilisant de façon efficiente et écologiquement durable les différentes ressources mobilisées.



***Une prise en compte moins explicite de l'impact environnemental de l'utilisation des intrants pour la méthode Emergy***

Bien qu'étant monocritère à comparer du panel d'indicateurs utilisés dans l'ACV, la mesure de l'impact environnemental dans l'Analyse pluri-énergétique à travers la consommation d'énergie fossile est claire. La prise en compte environnementale dans la méthode Emergy selon la part de consommation de ressources non renouvelables dans les ressources totales semble moins aboutie. Comme indiqué par [Lu et al. \(2009\)](#), cela pourrait signifier que les systèmes hautement industrialisés qui parviendraient à augmenter la part de ressources renouvelables dans leurs intrants achetés auraient un impact environnemental plus faible. De plus, les valeurs seuils retenues par [Brown and Ulgiati \(2004\)](#) sont discutables car basées sur aucune réalité écologique (moins de 2 : faibles impacts environnementaux, entre 2 et 10 : impacts environnementaux moyens, plus de 10 : impacts environnementaux sévères). En ce sens, des investigations devraient être menées pour une prise en compte plus claire de l'impact environnemental des intrants dans cette méthode.

***Une discrimination fine des systèmes et une analyse en détail de leur fonctionnement par la méthode d'Analyse pluri énergétique***

De plus, l'Analyse pluri-énergétique révèle un intérêt à toutes les échelles d'analyse. A l'échelle globale, elle permet d'afficher les performances face à la diversité des systèmes de production laitiers étudiés. A l'échelle locale, elle permet de fournir des voies d'amélioration de l'efficacité propres à chaque territoire grâce à la prise en compte des différentes énergies et du calcul de l'efficacité d'utilisation et/ou de transformation de chacune d'entre elles. D'un point de vue environnemental, les calculs d'efficacité sont d'un intérêt notoire pour évaluer l'amélioration apportée par l'introduction d'énergie fossile directe et indirecte à la capacité naturelle de chacune des composantes de transformer l'énergie d'une forme sous une autre forme (e.g. conversion de l'énergie solaire en énergie brute par les végétaux).

Dans notre étude, l'analyse de la variabilité pluri-énergétique s'est toutefois limitée aux exploitations de Sikasso. En effet sur les autres territoires, la variabilité faible de l'énergie physique et de l'énergie solaire conditionnée en grande partie par l'utilisation de références, montre sans doute moins d'intérêt pour discriminer les systèmes. L'intérêt de l'analyse pluri-énergétique pour analyser la variabilité intra-territoire de systèmes moins intensifiés devra être approfondi sous condition de données plus précises sur ces dimensions énergétiques.

***Une discrimination des systèmes incomplète pour la méthode Emergy***

Dans la méthode Emergy, la discrimination des systèmes semble trouver des limites lorsqu'il s'agit de systèmes intensifs utilisant des ressources transformées telles que les concentrés à la Réunion ou l'ensilage maïs en Poitou-Charentes. Cela questionne donc l'utilisation de cette méthode pour mettre en lumière des voies d'amélioration sur un territoire où les systèmes sont peu diversifiés. Les précédentes applications sur des systèmes issus d'un même territoire concernaient principalement des systèmes très contrastés tels que les systèmes conventionnels et organiques (Castellini et al., 2006 ; La Rosa et al., 2008) et tendraient à confirmer cela. Ceci nous a donc conduit à ne pas mener de comparaison intra-territoire à partir de cette méthode. Cependant, une application de la méthode dans les territoires étudiés de manière similaire à la méthode d'analyse pluri-énergétique s'avère nécessaire afin d'offrir une réponse concrète à cette hypothèse.

#### **1.4. Récolte des données**

##### ***Trouver un bon compromis entre la qualité de l'information et son coût de collecte : intérêt et limites de l'utilisation de base de données existantes***

Dans ce travail de thèse nous avons fait le choix de nous appuyer principalement sur des bases de données déjà existantes. Ce choix a été motivé par la volonté de disposer très rapidement de données utilisables. L'utilisation de bases de données extérieures nécessite une bonne connaissance des terrains, des systèmes et des modes de récolte des données. Dans ce travail de thèse, les partenariats étroits préalablement tissés avec les acteurs (UMT RIEL, conventions, partenariats public et privé dans les programmes ANR, DP Cirad...) sur chacun des territoires ont permis d'obtenir l'expertise nécessaire à leur utilisation optimale. Cependant, le choix d'utilisation de bases de données déjà existantes se heurte au problème d'objectifs de recherche différents entre ceux à l'origine de la constitution des bases de données et ceux à l'origine de sa réutilisation. Dans notre cas, ceci a pour conséquence l'absence d'un certain nombre de données.

Dans le cas du Mali Sud les données manquantes concernaient principalement les cultures (intrants, productions et travaux réalisés). Les données initiales qui concernaient la campagne agricole 2005-2006 ont été complétées par enquête en 2011 soit près de cinq ans après la période étudiée. On peut légitimement se poser la question de la validité de ces données même si de l'avis des différents acteurs impliqués (membres de l'encadrement technique, scientifique et chefs d'exploitation), la qualité de l'information obtenue était pertinente.

Dans le cas de l’Ile de la Réunion, du Poitou-Charentes et de la Bretagne, les données manquantes concernaient principalement le travail réalisé sur l’exploitation. Ces travaux ont été reconstitués à partir de références issues de documents publiés ([Chambre d’Agriculture de Bretagne, 2006](#)) ou à dire d’experts. Ces valeurs se sont avérées utiles pour la comparaison inter-territoire permettant de mettre en valeur différents modes de gestion du travail. Mais ces références peuvent masquer la variabilité au sein des territoires qui pourraient s’avérer utile dans le cadre d’une étude des modes de gestion du travail. Dans ce cadre, la récolte des calendriers de travail pourrait être réalisée grâce à la méthode « Bilan Travail » mise en place par [Dedieu and Servière \(1997\)](#). Des études récentes ont notamment prouvé son adaptabilité à des contextes très différents ([Hostiou and Dedieu, 2009](#) ; [Hostiou et al., 2010](#)).

Quoiqu’il en soit, pour améliorer la qualité et la précision des données, un suivi d’exploitation sur la période étudiée constitue probablement l’option idéale. Cependant, ces suivis sont consommateurs en temps, en personne et par conséquent peuvent mener à un dispositif coûteux financièrement. A défaut, des enquêtes rétrospectives proches de la période étudiée et concernant l’ensemble des données sont également un moyen intéressant. Les observatoires permanents tels que le World Watch Agriculture Initiative ([CIRAD, 2011](#)) constituent également des éléments intéressants pour palier à ce genre de problèmes. Une autre piste pour pallier à la difficulté de générer de vastes ensembles de données réside dans l’utilisation de modèles d’exploitation tels que MELODIE sur les systèmes laitiers de l’Ouest de la France ([Chardon et al., 2009](#)) ou GAMEDE sur l’Ile de la Réunion ([Vayssières et al., 2009](#)).

### ***Une reproductibilité inter-annuelle des résultats à étudier***

En plus du mode de récolte choisi, le choix de la période étudiée peut s’avérer un point critique dans l’exploitation des résultats obtenus. En effet ces derniers sont fortement soumis à des variabilités structurelles (prix des intrants, demande du marché) et climatiques (sécheresses, inondations) pouvant fortement impacter le fonctionnement du système et donc ses indicateurs. La question de la reproductibilité des données devrait être ainsi centrale dans l’évaluation environnementale des systèmes agricoles. Dans notre étude, l’analyse des systèmes n’a concerné qu’une seule année à l’exception d’une majeure partie des exploitations de Poitou-Charentes qui ont fait l’objet d’une analyse sur deux années. La comparaison des résultats obtenus sur les indicateurs de consommation énergétique dans les systèmes de Poitou-Charentes tend à démontrer qu’il n’existe aucune différence significative entre les deux années (Tableau 2).

**Tableau 2** Indicateurs énergétiques fossiles obtenus sur 43 systèmes laitiers de Poitou-Charentes en 2008 et 2009 et corrélation entre ces deux années

|   | 2008 |      | 2009 |      | Différence | Correlation test |         |
|---|------|------|------|------|------------|------------------|---------|
|   | Mean | Sd   | Mean | Sd   | Mean       | R <sup>2</sup>   | p-value |
| Fossil energy use (MJ.l <sup>-1</sup> ) | 4.9  | 1.8  | 4.7  | 1.6  | -2%        | 0.89             | 0.0001  |
| Fossil energy efficiency                | 0.78 | 0.29 | 0.80 | 0.29 | +5%        | 0.81             | 0.0001  |

On observe ainsi que de 2008 à 2009, la consommation d'énergie fossile par litre de lait produit varie en moyenne de -2% sur les exploitations alors que l'efficacité énergétique fossile varie seulement de +5%. Les données des deux années sont ainsi également très corrélées.

Cependant, l'instabilité des différents facteurs peut varier selon les territoires et les résultats de bonne reproductibilité obtenus en Poitou-Charentes ne sont pas un gage de généralité pour cette conclusion. Il apparaît donc nécessaire dans les futures études de pouvoir analyser les systèmes sur plusieurs années ou à défaut de pouvoir tester sur un échantillon plus restreint d'exploitations la reproductibilité des résultats obtenus sur chacun des territoires.

### 1.5. Choix des territoires et des systèmes

#### *Une définition des territoires hétérogènes...*

Comme évoqué au chapitre II.2, le choix des territoires a obéi principalement à la recherche d'une diversité de systèmes de production laitiers représentative de la diversité des systèmes d'élevage présents à travers le monde (Seré and Steinfeld, 1996) plutôt qu'à une délimitation spatiale bien définie des territoires. En effet, si un territoire peut-être défini comme une entité avec des limites géographiques claires, la définition de ces limites obéit à des lois complexes et différentes selon les disciplines. Cette complexité est notamment mise en lumière par Di Méo (1996) qui décrit un territoire comme « *une appropriation à la fois économique, idéologique et politique de l'espace par des groupes qui se donnent une représentation particulière d'eux-mêmes, de leur histoire* ».

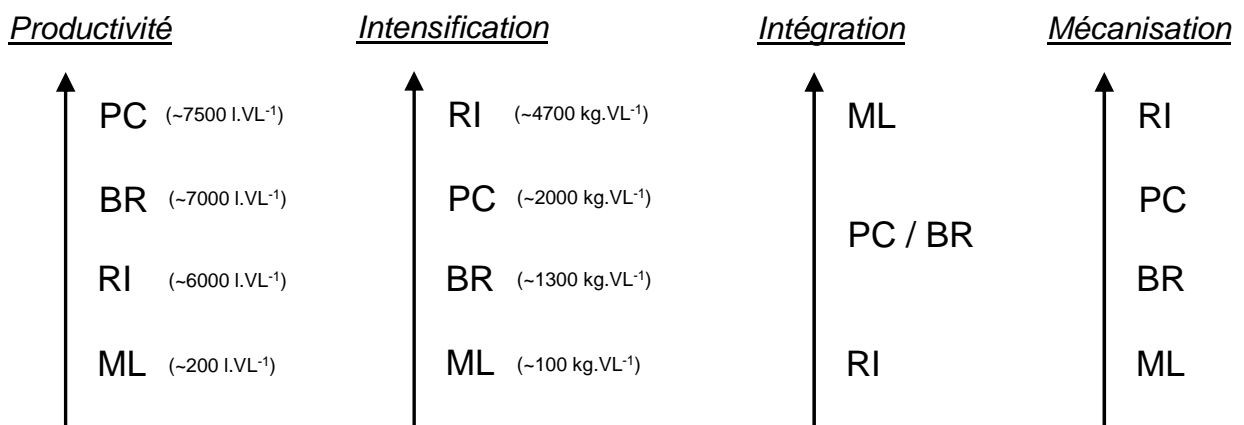
Les territoires choisis dans ce travail de thèse et leur définition obéissent de manière aussi complexe à cette définition. On retrouve ainsi 3 régions administratives (Ile de la Réunion, Poitou-Charentes et Bretagne) et un territoire plus restreint n'obéissant pas à des lois géopolitiques pures (Mali Sud). Dans ce dernier cas, la définition du territoire est plutôt fortement liée à la dimension économique avec la délimitation d'un bassin laitier fournissant en lait la ville de Sikasso. De plus, les deux régions métropolitaines se distinguent

principalement par des facteurs climatiques, ces deux régions et surtout les systèmes d'élevage obéissant à des contraintes économiques et politiques proches. Enfin, la dimension idéologique, qui peut être résumée comme la sensation « d'appartenir à un même territoire » (Guerin-Pace, 2006) est fortement ancrée dans les territoires bretons et réunionnais.

*... mais qui obéissent à une recherche de diversité des systèmes*

Nous avons recherché des territoires dont les atouts et contraintes différents ont conduit au développement de systèmes de production laitiers contrastés. Pour maximiser les différences entre les systèmes à analyser, nous avons retenus des territoires représentatifs des 3 grandes zones agroécologiques mises en lumière par Séré et Steinfeld (1996) : les régions tempérées (Poitou-Charentes et Bretagne), les régions arides et semi-arides (Mali Sud) et les régions tropicales humides (Ile de la Réunion). De plus, le choix a été établi à partir de 4 facteurs pouvant illustrer la diversité des systèmes d'élevage : deux facteurs quantitatifs qui sont la productivité laitière moyenne (exprimée en litre de lait produit par vache laitière par an) et l'intensification du troupeau (exprimée en kg de concentrés distribués par vache laitière par an) et deux facteurs qualitatifs qui sont le niveau d'intégration agriculture-élevage et le niveau de mécanisation.

La classification des systèmes laitiers des quatre territoires selon ces différents facteurs est représentée schématiquement en Figure 2.



**Figure 2** Représentation schématique de la classification des systèmes laitiers issus des quatre territoires étudiés (ML : Mali, RI : la Réunion, PC : Poitou-Charentes, BR : Bretagne) selon 4 facteurs : la productivité laitière, l'intensification du troupeau, l'intégration agriculture élevage et la mécanisation du système

Le choix des quatre territoires et des échantillons d'exploitations intra-territoire est validé par les fortes différences observées entre territoire selon les deux méthodes, notamment entre

Poitou-Charentes et Bretagne dont la séparation pouvait apparaître comme discutable. Il reste toutefois que notre échantillon final d'exploitation n'est pas représentatif de l'ensemble des systèmes de production laitiers dans le monde. Par exemple, dans une étude plus globale des émissions de GES liées au secteur laitier, la FAO (Gerber et al., 2010) ont défini neuf systèmes de production laitiers. Il serait ainsi intéressant de pouvoir appliquer les deux méthodes sur une telle diversité de système.

## 2. Evaluation des systèmes

### 2.1. Analyse des systèmes familiaux intégrés de Sikasso

#### *Des premières références sur les systèmes d'élevage familiaux des régions chaudes...*

Bien que les systèmes de production laitiers de la région périurbaine de Sikasso ne soient pas représentatifs de l'ensemble des systèmes d'élevage familiaux en régions chaudes, l'application de l'analyse pluri-énergétique apporte une référence originale sur les consommations énergétiques fossiles ( $0.1 \text{ MJ.l}^{-1}$ ) dans ces systèmes. Ainsi, bien que les émissions de  $\text{CO}_2$  représentent au plus 10% des émissions de GES (hors émissions liées au changement d'utilisation des terres) dans les systèmes laitiers à travers le monde (Gerber et al., 2010), ce type de référence constitue une première base de calcul pour des approches plus pertinentes des émissions de GES. Elles devraient confirmer que l'élevage extensif dans ces milieux est certes fort émetteur en  $\text{CH}_4$  par kg de produit mais peu émetteur de  $\text{N}_2\text{O}$  et de  $\text{CO}_2$  en raison du faible niveau des intrants (Gerber et al., 2011).

De plus, les chiffres obtenus posent des premières bases de références pour une comparaison et une évaluation des différentes voies d'intensification des systèmes familiaux des pays en développement. Il est couramment admis que l'intensification des systèmes d'élevage entraîne une augmentation de la consommation d'énergie fossile à travers l'import plus élevée d'intrants et donc des émissions de  $\text{CO}_2$  associées (Blanfort et al., 2011). Cependant, l'analyse de la diversité des systèmes dans la zone périurbaine de Sikasso a démontré que comme mis en avant par Dugué et al. (2012) d'autres voies d'intensification, plus écologiques que celles de la transposition des systèmes européens sur ces contextes sont envisageables. Des systèmes intégrés ont ainsi montré des productions lactières annuelles proches de  $600 \text{ l.VL}^{-1}$  soit près de 6 fois plus élevés que les systèmes traditionnels sans modification du coût énergétique par litre de lait ( $0.08 \text{ MJ.l}^{-1}$ ). Cependant ces niveaux de

production restent faibles et l'étude de systèmes plus industrialisés, même un peu plus impactant, dénote d'un intérêt particulier pour répondre aux scénarios envisageables pour concilier performances environnementales des systèmes et augmentation de la productivité.

***... qui tendent à montrer que ces systèmes sont peu impactant sur l'environnement...***

L'évaluation environnementale menée dans notre étude démontre également un faible impact des systèmes intégrés familiaux des régions chaudes sur l'environnement selon les critères retenus dans ce travail. La comparaison des consommations énergétiques fossiles obtenues avec celles de systèmes laitiers précédemment obtenues (Chapitre V.1 Figure 5) montre que celles-ci sont au minimum 10 fois inférieures aux valeurs obtenues sur des systèmes présents en pays de l'OCDE. De plus, les valeurs d'ELR obtenue sur l'ensemble des niveaux du système (de 1.23 à 1.25) sont parmi les plus faibles obtenues sur des systèmes d'élevage précédemment étudiés (Chapitre V.2). Les dégradations environnementales principalement mises en avant pour ces systèmes sont la participation au réchauffement climatique via les émissions de GES et la dégradation des écosystèmes (sols et habitats) (Steinfeld et al., 2006). Les résultats issus de l'analyse pluri-énergétique contrebalancent clairement l'idée globale de moindre efficacité de ces systèmes dans la gestion de leur ressource notamment face à leur faible productivité.

***... car ils doivent être analysés au regard de la multifonctionnalité de l'élevage dans ces régions***

Au-delà du rôle de producteur alimentaire que constituent les animaux, les fonctions de l'élevage dans ces zones sont multiples. Le troupeau est un facteur de production important à travers la fumure et la traction mécanique qu'il fournit (Randolph et al., 2007). De plus, l'élevage est un facteur essentiel de sécurisation des familles. Il peut ainsi représenter la source principale des revenus économiques (Alary et al., 2011). En l'absence d'assurance et de services institutionnels adaptés, il détient également un rôle de capital mobilisable qui est essentiel pour faire face aux risques divers et fréquents auxquels sont soumis ces familles (Dedieu et al., 2011). L'activité d'élevage offre également un ensemble de services écologiques (Millenium Ecosystem Assessment, 2005). La gestion raisonnée des parcours par exemple permet une régulation des écosystèmes en évitant la fermeture des milieux ou la restauration de zones dégradées (Blanfort et al., 2011). Par ailleurs, si sa quantification est toujours sujet à débat (Arrouays et al., 2002 ; Cerri et al., 2004 ; Lal, 2004 ; Soussana et al., 2010), le rôle des prairies dans la séquestration du carbone est aujourd'hui largement admis.

L'ensemble de ces facteurs rappelle la complexité des relations élevage – environnement, en particulier dans ces zones. Ils confirment la nécessité de tenir compte de la multifonctionnalité de l'activité d'élevage pour évaluer l'impact réel de ces systèmes sur les écosystèmes locaux et globaux afin de ne pas fournir des conclusions trop hâtives, dans un sens comme dans l'autre. Dans ce cadre, la comptabilisation originale des effluents comme produits à part entière des systèmes est une première tentative de prise en compte de cette multifonctionnalité. Les écarts obtenus sur les systèmes du Mali, de  $0,1 \text{ MJ.l}^{-1}$  avec prise en compte à  $2,9 \text{ MJ.l}^{-1}$  sans prise en compte (Chapitre V.1), confirme ce besoin d'approche intégrée.

## 2.2. Analyse des systèmes de la Réunion, de Poitou-Charentes et de Bretagne

### *Une grande diversité d'éco-efficience...*

Les deux méthodes ont permis de caractériser une diversité plus ou moins importante d'éco-efficience entre les systèmes de la Réunion, de Poitou-Charentes et de Bretagne. Cette diversité est assez semblable à celles observées dans la littérature sur les consommations d'énergie fossile dans les systèmes laitiers issus de pays développés (chapitre IV.1 Figure 2). Dans les deux méthodes, les systèmes bretons apparaissent comme à la fois plus efficaces pour valoriser leurs ressources (énergétiques ou globales) et plus respectueux de l'environnement. La discrimination entre les systèmes de Poitou-Charentes et ceux de la Réunion semble moins évidente. Selon l'Analyse pluri-énergétique, les systèmes de Poitou-Charentes sont plus efficaces alors que la méthode Emergy situe les systèmes des deux territoires sur un même niveau.

### *... dépendante d'une multitude de facteurs*

Comme détaillé dans le Chapitre V, ces différences trouvent une explication dans un ensemble de facteurs climatiques et socio-structurels propres à chaque territoire qui impactent les modes de gestion de ces intrants. En Poitou-Charentes, les sécheresses estivales plus ou moins récurrentes et dont la durée et l'intensité restent imprévisibles ont conduit une majeure partie des exploitants à se tourner vers des systèmes fourragers basés sur l'ensilage maïs afin de sécuriser le système (Delaby and Peyraud, 2009). Cette ressource plus consommatrice en intrants et donc en énergie fossile que le pâturage aboutit à des efficacités énergétiques fossiles plus faibles (Chapitre VI.2). De la même manière, elle constitue une entrée d'emergy



non renouvelable plus élevée que le pâturage, ressource prélevée directement et nécessitant moins d'intrants non renouvelables.

A la Réunion, malgré des conditions climatiques favorables à la production de ressources fourragères et des forts rendements à l'hectare, la volonté exprimée par la filière de maintenir une production locale élevée a conduit les éleveurs à augmenter leur chargement ( $4,4 \text{ UGB} \cdot \text{ha}^{-1}$ ) et par conséquent à utiliser une quantité élevée de concentrés ( $4672 \text{ kg} \cdot \text{VL}^{-1}$ ), concentrés qui sont importés sur l'île. De par les coûts en énergie fossile pour la production et le transport, ces niveaux d'utilisation de concentrés impactent très fortement la consommation énergétique fossile et d'énergie des systèmes. Ainsi si l'on considère un coût en énergie fossile des concentrés de  $4,0 \text{ MJ} \cdot \text{kg}^{-1}$  (coût moyen des concentrés commerciaux dans Dia'Terre) et que l'on applique ce coefficient sur les systèmes de la Réunion, la consommation moyenne en énergie fossile par litre de lait produit obtenu s'élève à  $5,7 \text{ MJ} \cdot \text{l}^{-1}$  soit une diminution de 14% par rapport à la valeur obtenue précédemment ( $6,6 \text{ MJ} \cdot \text{l}^{-1}$ ).

Compte tenu des efficiences mises en évidence, la question légitime du maintien des systèmes dans ces territoires pourrait se poser. En effet, dans un marché mondialisé, une des solutions afin de diminuer le coût environnemental de l'élevage laitier serait de concentrer la production laitière dans les zones les plus favorables d'un point de vue structurel et climatique. Il apparaît toutefois clairement que les surfaces disponibles ne sont pas illimitées et que la demande future en produit laitier devra nécessairement s'appuyer sur un ensemble hétérogène de territoires. De plus, il existe dans ces territoires une dimension sociale liée à l'activité laitière tout aussi importante que dans les régions du Sud et qui argumente pour leur maintien. A la Réunion par exemple, l'élevage laitier est une activité économique importante autour de laquelle se sont organisés des acteurs, des organisations et des dispositifs politiques d'incitation à l'installation afin de développer et maintenir une activité économique dans les hauteurs de l'île et freiner d'autant l'exode vers les zones côtières (Alary et al., 2002). Ainsi, malgré une baisse constante du nombre d'exploitations (de 250 éleveurs à près de 80 actuellement), il s'est organisé autour de cette production tout un ensemble d'activités (encadrement technique, transport, provendiers, collecte et transformation du lait, etc...). Il a été ainsi démontré que l'effet d'entraînement de la filière était de 3 et que l'emploi local liée à cette activité pouvait être estimé à 1100 lorsque l'on prend en compte les effets directs et indirects dans une matrice de comptabilité économique et sociale (D'Haese et al., 2008).

### **2.3. Concevoir des systèmes efficaces dans chacun des territoires**

Il apparaît difficile de transposer les solutions adoptées dans une région vers d'autres pour améliorer l'efficacité énergétique des systèmes. A la Réunion par exemple, des niveaux d'efficacité comparables à ceux de la Bretagne ne sont atteignables qu'en concevant les systèmes en fonction du potentiel de production des surfaces afin de valoriser le pâturage et diminuer des quantités de concentrés importés. Mais il en résulterait une baisse globale de la production et par conséquent un risque de disparition d'une filière peu productive déjà fortement soutenue économiquement par les politiques publiques. En Poitou-Charentes, les systèmes herbagers similaires à ceux de Bretagne montrent des efficacités énergétiques proches (Chapitre VI). Cependant, au regard du choix assumé de ces systèmes face aux conditions climatiques qui deviennent instables, d'autres choix pourraient mettre là aussi en danger la pérennité de la filière et appelleraient à une résilience accrue des systèmes (Nettier et al., 2012).

Pour diminuer le coût environnemental de l'activité laitière à l'échelle mondiale, l'amélioration des niveaux d'efficacité dans chacun des territoires est un objectif majeur. Les précédentes études menées sur les consommations énergétiques fossiles avaient démontré qu'au-delà du changement de systèmes il était difficile de trouver des facteurs structurels ou liés aux pratiques dans la variabilité des consommations d'énergie fossile (Vigne et al., 2007). La méthode DEA utilisée sur les systèmes de Poitou-Charentes et Bretagne (Chapitre V.2) s'est révélée particulièrement efficace pour mettre en lumière ces voies d'amélioration. Elle compare les exploitations selon leur profil d'intrants et rapproche des exploitations similaires considérant que les intrants sont représentatifs du fonctionnement du système. Au-delà du constat déjà affiché de la plus grande efficacité des systèmes herbagers, cette méthode s'est avérée particulièrement utile pour fournir des voies d'amélioration et des niveaux d'efficacité énergétique fossile optimaux spécifiques à chaque type de système au sein de ces territoires. Par exemple, si les systèmes herbagers de Bretagne semblent pouvoir atteindre une efficacité de  $3,0 \text{ MJ} \cdot \text{l}^{-1}$ , les systèmes maïs de Poitou-Charentes compte tenu des facteurs limitants et des performances observables semblent pouvoir difficilement atteindre une efficacité plus faible que  $4,4 \text{ MJ} \cdot \text{l}^{-1}$ .

Cependant, pour les mêmes raisons que la non application de la comparaison intra-territoire à travers les indicateurs de l'analyse pluri-énergétique, son application dans notre étude s'est limitée à la prise en compte de l'énergie fossile. Une telle application à partir de données plus précises permettrait de statuer définitivement sur le rôle de ces énergies dans l'efficacité des systèmes intensifs.

De plus, son application sur les résultats obtenus à partir de la méthode Emergy, non menée ici par manque de temps, pourrait s'avérer utile notamment pour comparer les résultats issus des deux méthodes. Cependant, son application nécessite un nombre élevé d'exploitations ce qui limite son utilisation dans le cas d'échantillons faibles d'exploitations tel que dans notre étude celui de Sikasso voire celui de la Réunion.

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## **Chapitre VIII**

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# **CONCLUSION ET PERSPECTIVES**





L'objectif de ce travail de thèse était d'analyser l'intérêt de la prise en compte de l'ensemble des dimensions énergétiques à travers des méthodes existantes ou originales afin d'analyser le fonctionnement de systèmes laitiers contrastés et de fournir des voies d'amélioration de l'efficacité d'utilisation des ressources.

Pour y répondre une revue préliminaire des différentes méthodes évaluant les consommations d'énergie comme indicateur d'évaluation environnementale a été menée. Elle a permis de mettre en lumière trois méthodes : l'Analyse énergétique fossile, la méthode Emery et l'Empreinte écologique. Leur intérêt pour analyser les différents flux d'énergie dans des systèmes d'élevage aussi contrastés que ceux présents à travers le monde a été discuté. Parmi ces trois méthodes, deux se sont révélés pertinentes :

- l'Analyse énergétique fossile sous condition qu'elle soit complétée par une prise en compte de l'ensemble des flux d'énergie présents dans un système d'élevage (énergie fossile énergie calorifique contenue dans la biomasse manipulée, énergie dépensée lors des travaux réalisés sur l'exploitation et l'énergie solaire reçue par les surfaces) dans le cadre de la conception d'une « Analyse pluri-énergétique » ;
- la méthode Emery en considérant les récentes améliorations dans sa méthodologie qui sont l'allocation de l'emery entrante entre les différents produits sur la base de leur teneur en énergie calorifique et la prise en compte de facteurs de renouvelabilité afin de considérer l'origine renouvelable et non renouvelable des ressources issues de l'économie.

Leur application à des systèmes contrastés issus de territoires différents est tout de même soumise à deux contraintes méthodologiques communes. Tout d'abord la délimitation du système doit inclure l'ensemble des composantes du système (cultures, animaux productifs, animaux de traction, parcours naturels et famille) alors qu'habituellement les méthodes d'évaluation ne se concentrent sur les composantes productives (cultures et troupeaux). De plus l'adaptation des facteurs de conversion (coefficients énergétiques et Unit Emery Values) au contexte local est nécessaire pour produire des résultats précis sur chacun des territoires et mener des comparaisons pertinentes. Cette nécessité a été démontrée à travers l'analyse de la variabilité dans la consommation énergétique fossile issue de l'incertitude des coefficients énergétiques menée sur des systèmes laitiers issus de la Réunion et de Poitou-Charentes. Les résultats obtenus à partir des valeurs minimales et maximales pour les coefficients énergétiques issus de la littérature ont ainsi démontré une variation de 3.6 à 5.0 MJ.l<sup>-1</sup> pour le Poitou-Charentes et de 5.8 à 8.2 MJ.l<sup>-1</sup>. Cette étude, appuyée par la variation

des UEVs trouvées dans la littérature nous a conduit à faire une hypothèse similaire sur la nécessité d'adaptation des UEVs.

L'application des deux méthodes sur des systèmes laitiers issus de quatre territoires contrastés (Mali Sud, Ile de la Réunion, Poitou-Charentes, Bretagne) a démontré leur intérêt pour mettre en lumière des modes de gestion différenciés de l'énergie (Analyse pluri-énergétique) ou des ressources (Emergy). Les systèmes familiaux en intégration agriculture - élevage sont ainsi apparus peu consommateur d'énergie fossile ( $0.1 \text{ MJ.l}^{-1}$ ) et peu consommateur de ressources non renouvelables (44% de renouvelabilité et ELR de 1.23 à 1.25). Ces résultats proviennent pour une grande part d'une valorisation par le troupeau de ressources naturelles à faible valeur agronomique mais peu impactantes sur l'environnement, d'une forte intégration entre cultures et élevage et de l'utilisation de force animale et humaine en substitution de la mécanisation. Parmi les systèmes intensifs des trois autres territoires, les systèmes de Bretagne sont moins consommateurs d'énergie fossile ( $3.6 \text{ MJ.l}^{-1}$ ) et moins impactants de par la mobilisation de ressources plus directes à travers le pâturage (24% de renouvelabilité et ELR de 3.25). La comparaison entre les systèmes de la Réunion et de Poitou-Charentes est un peu plus nuancée selon les méthodes. L'analyse pluri-énergétique discrimine clairement les systèmes de la Réunion lesquels du fait de leur import élevé de concentrés ont une consommation énergétique élevée ( $6.6 \text{ MJ.l}^{-1}$ ) alors que les systèmes de Poitou-Charentes se rapprochent des systèmes bretons ( $4.9 \text{ MJ.l}^{-1}$ ). La méthode emergy est moins discriminante et situe les systèmes de la Réunion et de Poitou-Charentes en terme de renouvelabilité (21%) du fait d'une utilisation moins directe des ressources à travers les concentrés pour la réunion l'ensilage maïs pour le Poitou-Charentes. Les systèmes de Poitou-Charentes apparaissent même plus impactant à travers le calcul de l'ELR (4.39) en comparaison de ceux de la Réunion (3.83 à 3.86).

Cette plus faible discrimination de la méthode Emergy sur les territoires intensifs semble poser les limites de cette méthode pour fournir des voies d'amélioration intra-territoire et nous a conduit à ne pas mener d'analyse de la diversité à l'intérieur des territoires. Cette analyse a donc été menée sur le territoire Mali Sud à partir de l'analyse pluri-énergétique. Celle-ci s'est montrée utile pour mettre en lumière différents modes de gestion de l'énergie directement reliée à l'efficacité des systèmes et notamment dans la valorisation de l'énergie fossile consommée afin d'augmenter la productivité des systèmes. Ainsi, le recours à une plus grande énergie liée au travail sous forme animale est apparue intéressante pour améliorer l'efficacité énergétique fossile des surfaces. Ceci a indirectement un intérêt important pour la gestion des troupeaux puisque ceci permet de diminuer le coût en énergie fossile des résidus de culture

qui constituent une part importante de leur alimentation. De plus l'import d'énergie fossile sous forme de concentrés pour compléter les animaux en production peut s'avérer une stratégie utile pour améliorer la productivité du troupeau.

La faible variabilité obtenue sur l'énergie liée au travail et l'énergie solaire et la forte corrélation entre l'énergie brute et l'énergie fossile entrante nous a conduit à n'analyser que la diversité des modes de gestion de l'énergie fossile complétée par la méthode DEA sur les systèmes de Poitou-Charentes et de Bretagne. Au-delà du constat déjà affiché de la plus grande éco-efficience des systèmes herbagers, cette méthode s'est avérée particulièrement utile pour mettre en lumière des voies d'amélioration propre à chaque type de système sur chacun des territoires.

Ce travail de thèse a donc permis de répondre à l'ensemble des questions précédemment posées. Cependant, les réponses fournies sont parfois partielles du fait de la non application systématique de l'ensemble des méthodes sur les différents territoires. Cette application incomplète qui résulte principalement des délais auxquels contraint un travail de thèse nous a donc conduit à émettre des hypothèses pour justifier ces choix. Afin de confirmer ces choix, un certain nombre de travaux doivent sans doute encore être menés :

- L'application de l'analyse d'incertitude sur les UEVs de manière similaire à celle menée sur les coefficients énergétiques fossiles (Chapitre IV) permettraient de confirmer ou d'infirmer l'hypothèse de leur nécessité d'adaptation aux différents territoires. Cette étude revêt d'autant plus un intérêt que nous n'avons encore trouvé aucune référence dans la littérature ayant mené des travaux similaires.
- Une analyse de la variabilité obtenue sur l'ensemble des territoires à partir de la méthode Emergy permettraient de conclure définitivement sur l'intérêt limitée de cette méthode pour mettre en lumière une diversité de gestion des ressources au sein de ces territoires. Dans le cas inverse, l'application de la méthode DEA sur les indicateurs obtenus permettrait de mettre en lumière des voies d'amélioration à l'efficience d'utilisation de ces ressources.
- L'analyse de la variabilité intra-territoire via l'analyse pluri-énergétique sur les territoires de la Réunion, de Poitou-Charentes et de Bretagne est à mener. Ceci permettrait sans doute de valider l'intérêt de la prise en compte des différentes formes d'énergie pour mettre en lumière des formes variables de gestion de l'énergie et des voies d'amélioration dans les systèmes intensifs. Cependant, une telle analyse nécessite des données plus précises, notamment concernant les travaux menés sur l'exploitation, que celles utilisées dans notre étude car propres à chaque exploitation.

De plus, le travail de thèse a démontré que si l'analyse pluri-énergétique s'est révélée pertinente pour l'évaluation du fonctionnement d'un système agricole, les diverses améliorations citées en discussion à apporter à sa méthodologie permettront d'en faire une méthode plus robuste. La prise en compte des différentes énergies indirectes, en particulier l'énergie solaire et l'énergie liée au travail, revêt un intérêt pour faire de la méthode d'analyse pluri-énergétique une méthode d'évaluation de la durabilité globale des systèmes.

Enfin, des perspectives plus locales peuvent être établies compte tenu des premiers résultats originaux proposés par le travail de thèse sur les systèmes familiaux en intégration agriculture – élevage de Sikasso. En effet, les résultats ont montré une variabilité importante dans le ratio « litre de lait produit par kilogramme de concentrés distribués ». Cette variabilité est sans doute une future clé de l'amélioration de la productivité des systèmes de ces zones notamment dans le cadre de leur intensification écologique. Les nombreux facteurs responsables de cette variabilité (facteurs sanitaires, calendrier de distribution, qualité de ces ressources) sont encore à étudier pour mettre en lumière des voies d'amélioration de l'efficacité de leur utilisation.

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# ANNEXES



## Impact du choix des coefficients énergétiques sur les résultats de l'analyse énergétique : Exemple de la consommation énergétique des élevages bovins laitiers réunionnais

### The impact of choice of energy coefficients on results of energy analysis: case of energy use on dairy farms of Reunion Island

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#### INTRODUCTION

L'analyse énergétique est une des premières méthodes d'évaluation environnementale menées sur des systèmes agricoles (Pimentel *et al.*, 1973). Elle consiste à mesurer l'énergie fossile consommée directement ou indirectement à travers les intrants pour faire fonctionner le système. Si dans les contextes de production intensifs elle ne représente qu'une part de l'évaluation environnementale à travers les analyses multicritère de type ACV, elle connaît un intérêt grandissant avec l'étude des impacts environnementaux des systèmes du Sud. Or, en l'absence de données précises sur les cycles de vie des intrants dans ces contextes peu informés, le choix des coefficients énergétiques s'est souvent porté sur des valeurs issues de la littérature parfois peu ou pas adaptées aux conditions réelles du contexte étudié et souvent issues de références anciennes (Vigne *et al.*, soumis). Cela pose donc la question du choix des coefficients énergétiques. Afin de mener une analyse précise des impacts en terme d'énergie, un coefficient énergétique se doit de traduire au plus juste la consommation énergétique nécessaire à la conception et la mise à disposition d'un intrant dans le contexte étudié. Notre objectif est ici de mettre en évidence le risque d'erreur sur les bilans globaux liés à ces choix.

#### 1. MATERIEL ET METHODES

##### 1.1. ECHANTILLON

Trente exploitations en production laitière de la Réunion ont été analysées. Les données de consommations d'intrants et de production pour l'année 2007 sont issues d'une précédente analyse énergétique menée grâce à la méthode PLANETE adaptée au contexte réunionnais (Vigne *et al.*, 2008).

##### 1.2. CHOIX DES COEFFICIENTS ENERGETIQUES

Chaque exploitation a été analysée selon 10 séries de coefficients énergétiques. Ces séries de coefficients comportent pour chacun des 25 intrants considérés une valeur choisie aléatoirement dans un intervalle établi à partir des valeurs les plus faibles et les plus hautes trouvées dans la littérature (28 références) (Tableau 1).

**Tableau 1.** Valeur faible et élevée des coefficients énergétiques trouvés dans la littérature pour 5 des 25 intrants considérés pour l'étude

| Intrants    | Coefficient énergétique (en MJ/unité) |       | Unité |
|-------------|---------------------------------------|-------|-------|
|             | faible                                | élevé |       |
| Diesel      | 35,9                                  | 56,3  | L     |
| Electricité | 5,7                                   | 12,7  | kWh   |
| Engrais N   | 44,0                                  | 78,2  | uN    |
| Herbicides  | 85,0                                  | 418,0 | kgMA  |
| Concentrés  | 1,1                                   | 6,3   | kg    |

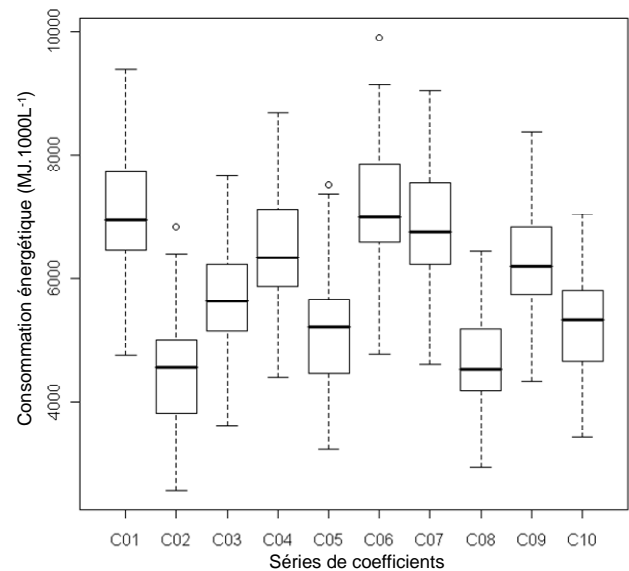
##### 1.3. TRAITEMENT DES RESULTATS

L'indicateur énergétique considéré est la consommation d'énergie fossile exprimée en Mégajoule (MJ) pour 1000 litres de lait produit. L'effet de la série de coefficient sur la consommation énergétique moyenne des 30 exploitations a été analysé par analyse de variance à un facteur.

#### 2. RESULTATS ET DISCUSSION

Les résultats obtenus montrent un effet important de la série de coefficients sur la consommation énergétique moyenne calculée ( $p < 0.001$ ). La consommation énergétique moyenne varie de 4 604 à 7 270 MJ/1000L en moyenne pour les 30 exploitations selon le set de coefficient (figure 1) choisi soit un écart de consommation de près de 60%

**Figure 1.** Consommation énergétique des 30 exploitations étudiées selon les 10 sets de coefficients énergétiques



Cette variation ne paraît pas limitante lorsque l'analyse énergétique a pour but de cerner la variabilité entre exploitations observée au sein d'un même contexte. Mais elle soulève la question de la validité des valeurs obtenues dans les différentes études n'utilisant pas des références adaptées aux contextes étudiés. L'incertitude liée au choix des coefficients conduit à remettre en cause la hiérarchisation observée lorsque des systèmes issus de contextes très variés sont comparés ce qui est souvent le cas dans la littérature.

#### 3. CONCLUSION

En appliquant différentes séries de coefficients énergétiques issus de la littérature sur un même panel d'exploitation, cette étude offre une première approche sur le risque d'erreur engendré par des choix de coefficients non adaptés au contexte étudié et/ou aux conditions de production actuelle. Il apparaît donc nécessaire lorsque l'on étudie des contextes pour lesquels des références ne sont pas disponibles de réadapter au plus juste les coefficients énergétiques aux conditions locales et actuelles.

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## Energy analysis of agricultural systems: Uncertainty associated to energy coefficients non-adapted to local conditions

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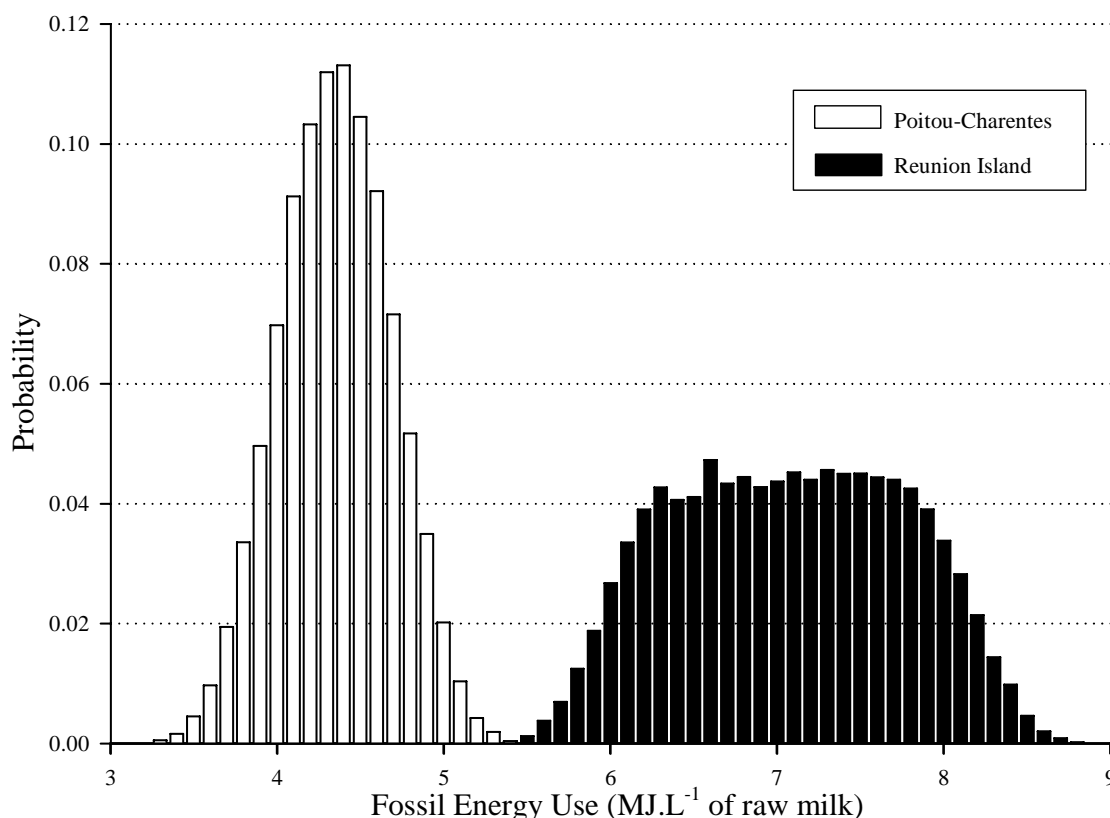
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### ABSTRACT

Among studied impacts in Life Cycle Analysis, fossil energy use has been widely considered. But choice of energy coefficients from the literature and their ability to express accurately local conditions is questioned for territories where references for inputs life-cycle are lacking. This study measured fossil energy use in dairy farms and assessed uncertainty associated to energy coefficients in order to improve energy analysis methodology of agricultural systems.

Fossil energy use for forty two dairy farms from Poitou-Charentes (PC) and thirty from Reunion Island (RI) have been analyzed using PLANETE for PC (Bochu, 2002) and PLANETE MASCAREIGNES for RI (Thevenot et al., 2010). Uncertainty analysis and sensitivity analysis has been conducted through the SIMLAB tool (Saltelli et al., 2004). Uncertainty analysis consisted in a Monte-Carlo methodology: 30,000 sets of energy coefficients have been randomly drawn from a uniform law between minimum and maximum values found in the literature for each energy coefficients. Uncertainty is expressed by 95% confidence interval of average fossil energy use in megajoule per litre of milk produced ( $\text{MJ.l}^{-1}$ ). Estimation of sensitivity of energy coefficients is based on similar drawn and has been studied through the calculation of the Standardized Regression Coefficient (SRC).

Estimated probability distribution is reported in Figure 1.



**Figure 1.** Probability distribution of energy use for dairy farms from (a) Poitou-Charentes and (b) Reunion Island calculated with the 30,000 sets of energy coefficients

Minimum and maximum values for 95% confidence interval are respectively 3.6 and 5.0  $\text{MJ.l}^{-1}$  for PC and 5.8 to 8.2  $\text{MJ.l}^{-1}$  for Run. The corresponding variabilities from mean were  $\pm 16\%$  and  $\pm 17\%$  respectively for PC and RI. Whereas they could appear low, these values question comparison of systems from different

territories. Among the set of coefficients chosen, difference between the territories could appear large or conversely equal when considering higher values for PC and lower values for RI. This results highlights need for a common methodology for calculation of energy coefficients. This could enable to calculate energy coefficients adapted to local conditions and to produce accurate values of energy use of agricultural systems. Such method should concern clear definition of system boundaries in indirect energy assessment and promote precise investigation of the technology used in the different processes.

SRCs obtained for the different energy coefficients (Table 1) showed that the most sensitive energy coefficients are not the same in the two territories.

**Table 1.** Standardized Regression Coefficients (SRC) of the five most influential energy coefficients for Poitou-Charentes and Reunion Island dairy farms

| <b>Poitou-Charentes</b>    |            | <b>Reunion Island</b>      |            |
|----------------------------|------------|----------------------------|------------|
| <b>Energy coefficients</b> | <b>SRC</b> | <b>Energy coefficients</b> | <b>SRC</b> |
| Electricity                | 0.53       | Concentrate feeds          | 0.91       |
| Concentrate feeds          | 0.51       | Tractor                    | 0.25       |
| Animal buildings           | 0.47       | Fuel                       | 0.17       |
| Fuel                       | 0.38       | Electricity                | 0.15       |
| N fertiliser               | 0.27       | Animal buildings           | 0.14       |

Energy coefficient for concentrate feeds is mainly responsible of this uncertainty for RI farms whereas it is a combination of several energy coefficients for PC farms (electricity, concentrate feeds, animal buildings, fuel, N fertilizer). Calculation of adapted energy coefficients could be associated to a preliminary sensitivity analysis through minimum and maximum values of energy coefficients found in the literature in order to focus on the most influential energy coefficients and to fit an appropriate value for them. This will avoid adapting all energy coefficients which could be time-consumer.

Nonetheless, energy coefficients do not represent the only source of uncertainty in energy analysis. Uncertainty related to inputs data could be decrease as done in our study with large surveys of real farms and individual economic follow-up surveys based on representative years. Uncertainty related to the methodology could be decrease, in addition to common methodology for energy coefficients, by common choice of allocation method.

**Keywords :** Energy analysis, agricultural systems, uncertainty

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## Efficiences énergétique des systèmes mixtes agriculture-élevage en zone périurbaine de Sikasso, Mali Sud

### Energy efficiency of mixed crop-livestock systems from periurban area of Sikasso, South Mali

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#### INTRODUCTION

L'impact environnemental des activités d'élevage est un sujet sociétal important. Il apparaît donc nécessaire de pouvoir fournir des méthodes d'analyse environnementale pertinentes et adaptées. L'analyse énergétique apparaît utile pour évaluer les systèmes agricoles. Cependant, si la méthode a été développée à travers le monde, aucune analyse énergétique sur les systèmes mixte agriculture - élevage dans les pays en développement n'a encore été menée. Cette étude propose donc une première référence sur les consommations en énergie fossile de ces systèmes à travers l'analyse énergétique de 14 exploitations mixtes agriculture - élevage de la zone périurbaine de Sikasso (Mali).

#### 1. MATERIEL ET METHODES

##### 1.1. DONNEES

L'étude a concerné 14 exploitations situées dans la zone périurbaine de Sikasso (Mali). Une partie des données est issue d'une étude préalable menée en 2006 (Coulibaly, 2008). Ces données ont été complétées en 2011 par des enquêtes menées auprès des chefs d'exploitation concernant les équipements agricoles. Elles concernent la campagne agricole 2005-2006 et prennent en compte les données structurelles, les consommations d'intrants pour le troupeau, les cultures et les productions de l'exploitation.

##### 1.2. ANALYSE ENERGETIQUE

L'analyse énergétique consiste à mesurer l'énergie fossile (EF) directement consommée sur l'exploitation et indirectement pour produire les intrants mobilisés sur l'exploitation. Le coût en EF des différents intrants est établi à partir des coefficients énergétiques. Les coefficients énergétiques fossiles utilisés dans cette étude sont issus de nos propres calculs ou proviennent de la littérature lorsque les cycles de vie étaient difficiles à définir. Les indicateurs calculés sont la consommation d'EF et l'efficacité énergétique (EE) correspondant au ratio entre l'énergie brute (EB) produite et l'EF consommée. Ces deux indicateurs ont été calculés à l'échelle globale de l'exploitation, à l'échelle des cultures et du troupeau. La consommation d'EF est exprimée en MJ.ha<sup>-1</sup> à l'échelle de l'exploitation et des cultures et en MJ.UBT<sup>-1</sup> (UBT = Unité Bovin Tropical) à l'échelle du troupeau. L'EE est sans dimension d'unité. A l'échelle du troupeau, la consommation d'EF par litre de lait a également été calculée selon une allocation entre le lait et la viande basée sur leur contenu énergétique.

#### 2. RESULTATS

Le tableau 1 présente les résultats pour les différents indicateurs énergétiques.

**Tableau 1** Indicateurs énergétiques moyens à l'échelle de l'exploitation, des cultures et du troupeau

| Indicateurs   | Echelle      |          |          |
|---|--------------|----------|----------|
|   | Exploitation | Cultures | Troupeau |
| Consommation d'EF en MJ.ha <sup>-1</sup> ou UBT <sup>-1</sup> | 967          | 745      | 524      |
| en MJ.L <sup>-1</sup>   | -            | -        | 2,9      |
| Efficiences énergétique                                       | 17,7         | 37,4     | 1,4      |

#### 3. DISCUSSION

##### 3.1. DES EXPLOITATIONS EFFICIENTES

A l'échelle de l'exploitation, les systèmes mixtes agriculture-élevage ont une consommation d'EF faible et une EE élevée. Cette EE globale résulte principalement de l'EE observée sur les surfaces qui est plus élevée que celle du troupeau. Cette EE est également supérieure aux références obtenus sur des systèmes de culture intensifs proches de 10 (Kuesters and Lammel, 1999 ; Rathke *et al.*, 2007) ou manuels inférieurs à 10 (Singh *et al.*, 2002 ; Canakci *et al.*, 2005).

##### 3.2. IMPORTANCE DES ENGRAIS DE FERME DANS LA PRODUCTION TOTALE

Si la consommation d'EF pour le troupeau est faible, l'EE est légèrement plus élevée que les systèmes d'élevage intensifs qui se situe entre 0,5 et 1 (Benoit and Laignel, 2010 ; Veysset *et al.*, 2010). La consommation d'EF par litre de lait produit se situe dans la partie inférieure des systèmes laitiers intensifs qui s'étend de 1,3 (Haas *et al.*, 2001) à 6,6 MJ.L<sup>-1</sup> (Grönroos *et al.*, 2006). Cependant, le lait est une partie infime de la production de ces troupeaux. Lorsque les effluents sont quantifiés en sortie, ceux-ci représentent en moyenne 95% de l'EB produite par le troupeau alors que la viande ne représente que 3% et le lait 2%. Cette proportion est élevée en comparaison des systèmes intensifs où le lait représente plus de 80% de la production énergétique du troupeau (Vigne *et al.*, soumis). Ceci confirme le rôle primordial que jouent les troupeaux dans ces zones au travers de leur production d'engrais de ferme en opposition à la source de revenus directe que représentent les troupeaux des systèmes intensifs. Ainsi, lorsque l'on considère les engrais de ferme comme production du troupeau, la consommation moyenne d'EF diminue à 0,1 MJ.L<sup>-1</sup> et l'EE s'élève alors à 26,5.

#### CONCLUSION

Les systèmes mixtes agriculture-élevage de la zone périurbaine de Sikasso ont des consommations en énergie fossile faibles par rapport à des systèmes agricoles intensifs. Ceci tend à contredire les débats actuels sur l'impact environnemental de ces systèmes. De plus, l'improductivité souvent mise en cause pour les troupeaux de ces zones est ici contrebalancée par l'importance des effluents dans la production d'énergie brute totale du troupeau. Ceci illustre l'un des multiples rôles de l'élevage dans ces zones en addition du rôle de capital économique ou de force de travail.

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## Analyse de la variabilité de l'efficacité énergétique fossile dans les systèmes laitiers de l'Ouest de la France

Analysis of the variability of fossil energy efficiency in dairy systems from West of France

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### INTRODUCTION

Les considérations environnementales et l'accroissement des prix du pétrole font aujourd'hui de l'efficacité d'utilisation de la ressource fossile un enjeu majeur de durabilité des systèmes agricoles. Des voies d'amélioration de cette efficacité sont donc à explorer pour les différents systèmes. Une analyse de la variabilité au sein de chaque territoire et une analyse plus fine des consommations à chaque composante du système permettraient de mettre en avant les marges de progrès les plus pertinentes.

### 1. MATERIEL ET METHODES

#### 1.1. ANALYSE ENERGETIQUE

Une analyse énergétique fossile a été appliquée sur des exploitations lait spécialisées de Bretagne (Bzh) et Poitou-Charentes (Pc). Elle a consisté à mesurer l'énergie fossile (EF) directement consommée sur l'exploitation (carburants, électricité) et indirectement pour produire les intrants (concentrés, fourrages, soins vétérinaires, engrais, phytosanitaires, semences, matériel et bâtiments). Cette analyse a été menée à l'échelle globale du système ainsi qu'à l'échelle de la Surface Fourragère Principale (SFP) et du troupeau. L'analyse à l'échelle de la SFP considère les intrants des surfaces. L'analyse à l'échelle du troupeau considère les intrants du Troupeau et l'EF indirecte des fourrages issus de la SFP. Les indicateurs calculés sont la consommation d'EF (CEF) par litre de lait produit ( $MJ.L^{-1}$ ), par hectare de SFP ( $MJ.ha^{-1}$ ) et par Unité Gros Bétail ( $MJ.UGB^{-1}$ ) et l'efficacité énergétique (EE) correspondant à l'énergie brute produite rapportée à l'EF consommée.

#### 1.2. DONNEES D'EXPLOITATION

Les données nécessaires à l'exploitation sont issues de la base de données DIAPASON. Elles regroupent pour les années 2008 et 2009 les données structurelles de l'exploitation, les consommations d'intrants pour les surfaces et le troupeau et les productions végétales et animales. Trois types de systèmes ont été identifiés selon la part de surface en maïs dans la SFP : les systèmes « herbagers » (H) (maïs < 10%), les systèmes « maïs-herbe » (MH) (10% < maïs < 30%) et les systèmes « maïs » (M) (maïs > 30%).

### 2. RESULTATS ET DISCUSSION

#### 2.1. VARIABILITE ENTRE TERRITOIRE

La CEF moyenne des systèmes laitiers s'élèvent à 4,1  $MJ.L^{-1}$  pour Bzh et 5,0  $MJ.L^{-1}$  pour Pc. Cette différence significative ( $p < 0.001$ ) s'explique en partie par une EE plus faible sur la SFP pour les exploitations de Pc ( $p = 0.01$ ) (Tableau 1). L'EE faible de la SFP résulte principalement d'une présence plus élevée d'ensilage maïs (38% vs 30% de la SFP) et

probablement d'une présence de légumineuses plus faibles entraînant une fertilisation minérale plus importante ( $76kgN.ha^{-1}$  vs  $34kgN.ha^{-1}$ ) et une CEF plus élevée ( $p < 0.001$ ). Cette relation est facilement observable au travers de la part de fourrages conservés dans la ration qui est une résultante directe du choix de système fourrager (Figure 1).

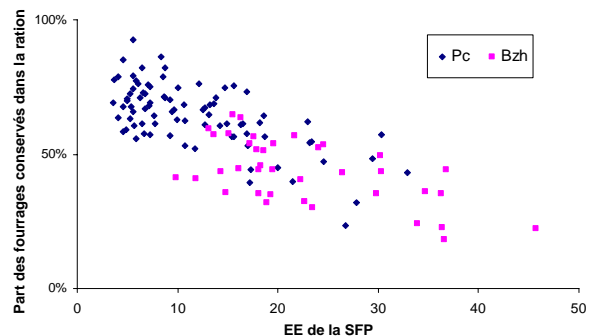


Figure 1 Relation entre l'EE de la SFP et la part de fourrages conservés dans la ration

#### 2.2. COMPARAISON ENTRE SYSTEMES

Les systèmes herbagers présentent une CEF par litre de lait plus faible que pour les autres systèmes, les systèmes maïs présentant la CEF la plus élevée ( $p < 0.001$  pour Bzh et Pc) (Tableau 1). Comme pour la comparaison entre les territoires, cette différence semble s'expliquer en grande partie par une EE plus élevée de la SFP ( $p = 0.02$  pour Bzh et  $p < 0.001$  pour Pc) liée à une part plus importante de surface en herbe dans ces systèmes (Bzh :  $R^2 = 0,47$  ; Pc :  $R^2 = 0,52$ )

### CONCLUSION

Cette étude met en lumière le rôle primordial du mode de gestion des surfaces fourragères dans l'efficacité énergétique globale de chaque système. La faible efficacité énergétique des systèmes ayant une part importante de la SFP en maïs s'explique par les augmentations de consommation énergétique nécessaire à la culture, mais aussi à une part de l'alimentation conservée supérieure. La recherche de sécurisation du système fourrager face aux aléas climatiques par une part importante d'ensilage de maïs se fait donc au détriment de l'autonomie énergétique et de l'impact environnemental de l'exploitation sous forme de consommation d'EF. Des voies d'amélioration de l'efficacité énergétique du lait produit dans les systèmes de l'Ouest de la France se situent donc dans un bon équilibre entre maïs et herbe et dans une amélioration de l'efficacité énergétique de la production d'ensilage maïs, mais aussi de l'herbe.

Tableau 1 Indicateurs énergétiques moyens pour les différents systèmes de Bretagne et Poitou-Charentes

| Indicateurs           | Bzh            |                |                | Pc             |                |                |
|-----------------------|----------------|----------------|----------------|----------------|----------------|----------------|
|                       | H (n=5)        | MH (n=13)      | M (n=20)       | H (n=10)       | MH (n=13)      | M (n=12)       |
| <b>Globale</b>        |                |                |                |                |                |                |
| CEF ( $MJ.L^{-1}$ )   | 2,8 ± 0,3      | 3,9 ± 0,8      | 4,6 ± 1,3      | 3,6 ± 0,7      | 4,9 ± 1,1      | 6,1 ± 1,3      |
| <b>SFP</b>            |                |                |                |                |                |                |
| CEF ( $MJ.ha^{-1}$ )  | 4 522 ± 2 701  | 7 324 ± 2 081  | 9 999 ± 6 348  | 5 516 ± 1 896  | 14 626 ± 4 619 | 18 351 ± 3 534 |
| EE                    | 34,8 ± 11,8    | 19,8 ± 5,9     | 17,2 ± 7,4     | 23,4 ± 13,7    | 9,8 ± 3,5      | 7,2 ± 2,7      |
| <b>Troupeau</b>       |                |                |                |                |                |                |
| CEF ( $MJ.UGB^{-1}$ ) | 13 947 ± 2 162 | 20 831 ± 6 159 | 24 830 ± 6 477 | 19 183 ± 3 919 | 31 523 ± 6 194 | 35 362 ± 7 701 |
| EE                    | 1,26 ± 0,10    | 0,91 ± 0,22    | 0,85 ± 0,19    | 0,96 ± 0,20    | 0,72 ± 0,17    | 0,59 ± 0,15    |

|   |
|---|
| <p><b>Cahier d'enquête</b><br/> <b>Récolte des données Mali Sud</b></p> |
|---|

**Description de l'exploitation en début du suivi**

Nom de l'éleveur : YACOUBA Youssouf

Date : \_\_\_\_\_

Village / Ville : \_\_\_\_\_

Eloignement de la ville : \_\_\_\_ km

Distance du parc de la route principale : \_\_\_\_ km

Surface totale cultivée (2005-2006) : \_\_\_\_ ha

**Composition de la MO Familiale**

| Type            | Nb | Présent en 2006 | Type de travaux sur l'exploitation |
|-----------------|----|-----------------|------------------------------------|
| Chef de famille |    |                 |                                    |
| Autres hommes   |    |                 |                                    |
| Femmes          |    |                 |                                    |
| Enfants         |    |                 |                                    |

**Inventaire des Equipements et Infrastructures – Campagne 2005-2006**

**- Matériel de culture -**

| Type      | Année acquisition | Etat d'origine | Valeur d'achat |
|-----------|-------------------|----------------|----------------|
| Charrette |                   |                |                |
| Charrue 1 |                   |                |                |
| Charrue 2 |                   |                |                |

**- Motorisation – Equipements Electriques -**

|  | Type (cylindrée, puissance, ...) | Année acquisition | Etat origine | Valeur d'achat |
|--|----------------------------------|-------------------|--------------|----------------|
|  |                                  |                   |              |                |
|  |                                  |                   |              |                |

**- Bâtiments -**

| Type            | Surface (ha) | Année construction | Matériaux |
|-----------------|--------------|--------------------|-----------|
| Parc à fumier 1 |              |                    |           |
| Parc à fumier 2 |              |                    |           |

|                     |  |  |  |
|---------------------|--|--|--|
| Hangar              |  |  |  |
| Magasin<br>stockage |  |  |  |
| Logement<br>salarié |  |  |  |
|                     |  |  |  |

### Abreuvement des animaux

Qui effectue l'abreuvement des animaux ?

---

Nb jour / an : \_\_\_\_\_ j/an

Durée moyenne : \_\_\_\_\_ h/j

### Alimentation des animaux (précision)

Origine Fane de Niébé :

Exploitation

Récolté sur une autre exploitation



## Inventaire des surfaces et des intrants agricoles – Campagne 2005-2006

**Maïs** Surface : 3 ha Distance : \_\_\_\_\_ km

| Type de FO | Semences |         | Herbicides |     | Complexe |           | Urée |         | Production totale |           |
|------------|----------|---------|------------|-----|----------|-----------|------|---------|-------------------|-----------|
|            | Qté      | Origine | Transport  | Qté | Origine  | Transport | Qté  | Origine |                   | Transport |
|            |          |         |            |     |          |           |      |         |                   |           |
|            |          |         |            |     |          |           |      |         |                   |           |

Type de Gestion des résidus :  Lissé sur le champ

Ramassé et stocké sur le champ

Ramassé et transporté

Si transport :

Type de transport : \_\_\_\_\_

Utilisation :  Aliment  Fumure

**Sorgho** Surface : 0,5 ha Distance : \_\_\_\_\_ km

| Type de FO | Semences |         | Herbicides |     | Complexe |           | Urée |         | Production totale |           |
|------------|----------|---------|------------|-----|----------|-----------|------|---------|-------------------|-----------|
|            | Qté      | Origine | Transport  | Qté | Origine  | Transport | Qté  | Origine |                   | Transport |
|            |          |         |            |     |          |           |      |         |                   |           |
|            |          |         |            |     |          |           |      |         |                   |           |

Type de Gestion des résidus :  Lissé sur le champ

Ramassé et stocké sur le champ

Ramassé et transporté

Si transport :

Type de transport : \_\_\_\_\_

Utilisation :  Aliment  Fumure

**Riz** Surface : 0,5 ha Distance : \_\_\_\_\_ km Pluvial / Bas-fonds ?

| Type de FO | Semences |         | Herbicides |     | Complexe |           | Urée |         | Production totale |           |
|------------|----------|---------|------------|-----|----------|-----------|------|---------|-------------------|-----------|
|            | Qté      | Origine | Transport  | Qté | Origine  | Transport | Qté  | Origine |                   | Transport |
|            |          |         |            |     |          |           |      |         |                   |           |
|            |          |         |            |     |          |           |      |         |                   |           |





## CALCUL DES COEFFICIENTS ENERGETIQUES FOSSILES SUR LE TERRITOIRE MALI SUD

### I. CARBURANTS

On sait que le carburant est totalement importé au Mali (source : site internet de la direction nationale de l'énergie du Mali, [www.dnemali.org](http://www.dnemali.org)). En l'absence de données précises sur l'origine de ces importations, on va considérer qu'à Sikasso le carburant provient pour une totalité de Lomé (Togo). On considère donc dans un premier temps un **coût de production** et de **transport jusqu'au port** pour les carburants de **40.37 MJ/L** pour l'essence et **41.17 MJ/L** pour le gasoil (Vigne, 2007).

Puis on considère un coût de transport camion entre Abidjan et Sikasso de 14000 km qui s'élève à 0.85 MJ/km.t (Risoud et Theobald, 2002) soit **1,19 MJ/kg**.

Le coût total s'élève à :

Essence :  $40,37 + 1,19 = \mathbf{41,56 \text{ MJ/L}}$

Gasoil :  $41,17 + 1,19 = \mathbf{42,36 \text{ MJ/L}}$

### II. ELECTRICITE

Selon l'OCDE, l'électricité consommée au Mali est issue à 80% de centrale hydraulique alors que les 20% restant sont issues de centrale thermique. On considère un rendement de production de l'énergie hydraulique de 100% et de 30% pour l'énergie thermique.

| Type de production | % age origine | Rdt de production |
|--------------------|---------------|-------------------|
| Hydraulique        | 80            | 100%              |
| Thermique          | 20            | 30%               |

On obtient donc un rendement global de 1,4 kWh consommé par kWh produit soit un coefficient énergétique de **5,04 MJ/kWh consommé**.

### III. ENGRAIS

On considère un coût de production industriel donné par Gaillard et al. (1997) :

| Type d'engrais | Coût énergétique | Unité      |
|----------------|------------------|------------|
| Urée           | 49.2             | MJ/unité N |
| Autres N       | 43.0             | MJ/unité N |
| Engrais P      | 11.4             | MJ/unité P |
| Engrais K      | 8.1              | MJ/unité K |

On ajoute ensuite :

- un coût de transport maritime Asie-Abidjan de 13000km qui s'élève à 0.025 MJ/km.t (Risoud et Theobald, 2002) soit 0.325 MJ/kg.
- Un coût de transport en camion d'Abidjan à Sikasso de 900 km qui s'élève à 0.85 MJ/km.t (Risoud et Theobald, 2002) soit 0.765 MJ/kg.

Compte-tenu de leur formulation (24-0-0 pour l'Urée, 14-22-12 pour le Complexe coton et 15-15-15 pour le complexe céréale (Gakou et al., 1996)), le coût total énergétique s'élève à :

- 12,90 MJ/kg pour l'Urée
- 10,62 MJ/kg pour le complexe Coton
- 10,59 MJ/kg pour le complexe Céréales

#### IV. PHYTOSANITAIRES

On considère 2 types d'herbicides et un type d'insecticides ainsi que des concentrations moyennes en matière active :

| Type                      | Concentration (g de matière active/L) | Coefficient énergétique (MJ/kgMA) | Coût énergétique (MJ/L) |
|---------------------------|---------------------------------------|-----------------------------------|-------------------------|
| Herbicide coton           | 440                                   | 414                               | 182                     |
| Herbicide autres cultures | 360                                   | 414                               | 149                     |
| Insecticides              | 88                                    | 359                               | 32                      |

#### V. SEMENCES

##### 5.1. Coton

En l'absence de données sur le coton OGM on considère un coefficient énergétique égal à celui du lin donné par PLANETE (Risoud et Theobald, 2002) soit **5.7 MJ/kg**.

##### 5.2. Niébé

On considère que la semence de Niébé est produit localement. En l'absence de données sur l'itinéraire technique on considère un coût de production nulle sur les exploitations (cf enquête) puis un transport local moyen de 25 km en moto pour 60kg. Pour ce transport on considère une consommation moyenne de 7L/100km soit 1,75L de carburants pour 60kg soit 0,03L/kg transporté. Compte-tenu du coefficient énergétique précédent calculé pour le carburant de 41,56 MJ/L, le coefficient énergétique de la semence de Niébé s'élève à  $41,56 \times 0,03 = 1,25$  **MJ/kg**.

##### 5.3. Riz

En l'absence de données sur l'origine des plants de riz on considère le coût énergétique donné par PLANETE qui s'élève à **8 MJ/kg**.

##### 5.4. Pomme de Terre

Les semences de Pomme de Terre sont originaire d'Europe. On considère donc le coefficient énergétique donné par PLANETE (2 MJ/kg) auquel on rajoute un transport maritime entre Brest et Abidjan estimé à 5329 km et un coût de transport de 0.025 MJ/km.t soit un coût énergétique de 0.133 MJ/kg.

On ajoute enfin un coût de transport en camion d'Abidjan à Sikasso de 900 km qui s'élève à 0.85 MJ/km.t (Risoud et Theobald, 2002) soit 0.765 MJ/kg.

Le coût énergétique de la semence de Pomme de Terre s'élève donc à  $2 + 0,133 + 0,765 = 2,90$  **MJ/kg**.

##### 5.5. Patate Douce

On considère l'itinéraire technique moyen trouvé sur les enquêtes :

| Intrants | Quantité | Coefficient énergétique (MJ/unité) | Coût énergétique (MJ/ha) |
|----------|----------|------------------------------------|--------------------------|
|          |          |                                    |                          |

|                   |        |       |      |
|-------------------|--------|-------|------|
| Herbicides        | 1L     | 149   | 149  |
| Complexe Céréales | 200 kg | 10,59 | 2118 |

**TOTAL : 2267 MJ/ha**

Si on considère un rendement moyen de 10 tonnes par hectare, un ratio tubercule/fanes de 1/0,6 et une valeur énergétique de 4,52 et 16,83 MJ/kg brut respectivement pour les tubercules et pour les fanes on obtient la production énergétique par hectare suivante :

| Produits   | Quantité | Valeur énergétique (MJ/unité) | Prod énergétique (MJ/ha) | Prop. (%) |
|------------|----------|-------------------------------|--------------------------|-----------|
| Tubercules | 10000    | 4,52                          | 45200                    | 31        |
| Fanes      | 6000     | 16,83                         | 100980                   | 69        |

Le coût énergétique pour la tubercule (considéré ici comme la semence) s'élève donc à  $(2267 \times 0,31)/10000 = \mathbf{0,07 \text{ MJ/kg}}$ .

### 5.6. Maïs

On se base dans un premier temps sur un itinéraire technique moyen du maïs trouvé dans les enquêtes.

| Intrants                          | Quantité | Coefficient énergétique (MJ/unité) | Coût énergétique (MJ/ha) |
|-----------------------------------|----------|------------------------------------|--------------------------|
| Semences issues de l'exploitation | 30 kg    | 0                                  | 0                        |
| Herbicides                        | 3 L      | 182                                | 546                      |
| Complexe céréales                 | 100 kg   | 10,59                              | 1059                     |
| Urée                              | 100 kg   | 12,90                              | 1290                     |

**TOTAL : 2895 MJ/ha**

Si on considère un rendement moyen de 4 tonnes par hectare, un ratio grain/paille de 1/3 et une valeur énergétique de 16,14 et 13,93 MJ/kg brut respectivement pour le grain et pour la paille on obtient la production énergétique par hectare suivante :

| Produits | Quantité | Valeur énergétique (MJ/unité) | Prod énergétique (MJ/ha) | Prop. (%) |
|----------|----------|-------------------------------|--------------------------|-----------|
| Grain    | 3000     | 16,14                         | 64560                    | 28%       |
| Paille   | 12000    | 13,93                         | 167160                   | 72%       |

Le coût énergétique pour le grain de maïs (considéré comme la semence ici) s'élève donc à  $(2895 \times 0,28)/4000 = \mathbf{0,203 \text{ MJ/kg}}$ .

### 5.7. Mil

Les enquêtes démontrent que le Mil ne fait l'objet d'aucun apport d'intrants. On ne considère que le coût de transport de la graine jusqu'au marché de façon identique au Niébé soit un coefficient énergétique de **1,25 MJ/kg**.

## VI. ALIMENTS ACHETES

### 6.1. Produits du coton

On va se baser sur un itinéraire technique moyen du coton trouvé dans les enquêtes et une allocation massique entre les différents produits du coton

| Intrants   | Quantité | Coefficient énergétique (MJ/unité) | Coût énergétique (MJ/ha) |
|------------|----------|------------------------------------|--------------------------|
| Semences   | 30 kg    | 5,7                                | 171                      |
| Herbicides | 3 L      | 182                                | 546                      |

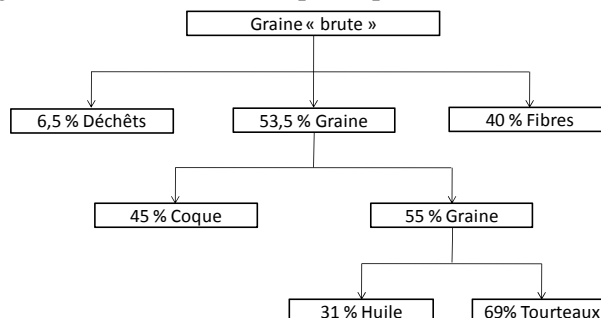
|                |        |       |      |
|----------------|--------|-------|------|
| Complexe coton | 150 kg | 10,62 | 1593 |
| Urée           | 100 kg | 12,90 | 1290 |

**TOTAL : 3600 MJ/ha**

On se base sur une production approximative de 2000kg/ha et un ratio grain paille de 42/58 (dire d'expert).

On obtient donc un coût énergétique de  $(3600 \times 0,42) / 2000 = 0,756$  MJ/kg pour la graine de coton entière.

Selon l'INERA, 1 kg de graine « brute » se décompose après traitement en matière brute comme suit :



Si on considère la valeur énergétique des différents sous-produits de la graine brute, la composition et les teneurs MS :

| Type de sous-produits | Composition (%) | Valeur énergétique (kcal/kgMS) | %MS  | Valeur énergétique (kcal/kg brut) | Apport énergétique dans 1kg de graine brute |
|-----------------------|-----------------|--------------------------------|------|-----------------------------------|---|
| Fibres                | 40              | 4063                           | 0,98 | 3982                              | 1592  |
| Graines triées        | 53,5            | 5739                           | 0,89 | 4409                              | 2359  |
| Déchets               | 6,5             | 0                              |      |                                   |   |

Le coût énergétique de la graine après triage s'élève donc à  $0,756 \times (2359/3951) \times 1/0,535 = 0,844$  MJ/kg + un coût de triage de 0,067 MJ/kg (source PLANETE) soit **0,911 MJ/kg de graines triées**.

Si on considère maintenant la composition en différents sous-produits de la graine triée, leur valeur énergétique et leur teneur MS :

| Type de sous-produits | Composition (%) | Valeur énergétique (kcal/kgMS) | %MS  | Valeur énergétique (kcal/kg brut) | Apport énergétique dans 1 kg de graine triée |
|-----------------------|-----------------|--------------------------------|------|-----------------------------------|--|
| Coques                | 45              | 3893                           | 0,90 | 3504                              | 1576   |
| Graine nue            | 55              | 5853                           | 0,88 | 5151                              | 2833   |

Le coût énergétique de la coque s'élève à  $0,911 \times (1576/4409) \times (1/0,45) = 0,724$  MJ/kg + un coût de trituration de 0,067 MJ/kg soit **0,791 MJ/kg de coques de coton** alors que le coût énergétique de la graine « nue » s'élève à  $0,911 \times (2833/4409) \times (1/0,55) = 1,064$  MJ/kg + un coût de trituration de 0,067 MJ/kg soit **1,131 MJ/kg de graine de coton « nue »**

Enfin, si on considère maintenant la composition en différents sous-produits de la graine pressée, leur valeur énergétique et leur teneur MS :

| Type de sous-produits | Composition (%) | Valeur énergétique (kcal/kgMS) | %MS  | Valeur énergétique (kcal/kg brut) | Apport énergétique dans 1 kg de graine « nue » |
|-----------------------|-----------------|--------------------------------|------|-----------------------------------|--|
| Huile                 | 31              | 9380                           | 0,80 | 7504                              | 2326   |
| Tourteaux             | 69              | 4450                           | 0,92 | 4094                              | 2825   |

Le coût énergétique du Tourteaux de coton s'élève à  $1,131 \times (2825/5151) \times (1/0,69) = 0,899$  MJ/kg + un coût de pressage de 0,067 MJ/kg (source PLANETE) soit **0,966 MJ/kg de Tourteaux de coton**.

### 6.2. Fanes de Niébé

On se base sur un itinéraire technique moyen trouvé dans les enquêtes (seulement des semences) et un rendement moyen de 1000 kg de fanes (grain pas valorisé dans la majeure partie du temps).

| Intrants | Quantité | Coefficient énergétique (MJ/unité) | Coût énergétique (MJ/ha) |
|----------|----------|------------------------------------|--------------------------|
| Semences | 10 kg    | 1,23                               | 12,3                     |

On obtient un coût énergétique de  $12,3 / 1000 = 0,01$  MJ/kg de fanes de Niébé.

### 6.3. Fanes d'Arachide

On se base sur un itinéraire technique moyen trouvé dans les enquêtes.

| Intrants   | Quantité | Coefficient énergétique (MJ/unité) | Coût énergétique (MJ/ha) |
|------------|----------|------------------------------------|--------------------------|
| Herbicides | 2L       | 182                                | 364                      |

**TOTAL : 364 MJ/ha**

Si on considère une valeur énergétique de 17,89 MJ/kg pour l'arachide et de 17,92 MJ/kg pour les fanes, un rendement moyen de 3500 kg de graines décortiquées et un ratio grain/fane de 47/63.

| Produits | Quantité | Valeur énergétique (MJ/unité) | Prod énergétique (MJ/ha) | Prop. (%) |
|----------|----------|-------------------------------|--------------------------|-----------|
| Coques   | 3500     | 17,89                         | 62615                    | 47%       |
| Paille   | 3950     | 17,92                         | 70784                    | 53%       |

On obtient un coût énergétique de  $(364 \times 0,53) / 3950 = 0,05$  MJ/kg de fanes d'Arachide.

### 6.4. Paille de Riz

On se base sur un itinéraire technique moyen trouvé dans les enquêtes

| Intrants   | Quantité | Coefficient énergétique (MJ/unité) | Coût énergétique (MJ/ha) |
|------------|----------|------------------------------------|--------------------------|
| Semences   | 50 kg    | 8                                  | 400                      |
| Herbicides | 3 L      | 182                                | 546                      |
| Urée       | 100 kg   | 12,90                              | 1290                     |

**TOTAL : 2236 MJ/ha**

Si on considère maintenant, un rendement moyen de 2000 kg de grains, un ratio grain/paille de 25%/75% et une valeur énergétique du grain de 15,73 MJ/kg brut et de la paille de 13,85 MJ/kg brut, on obtient la production énergétique par hectare suivant :

| Produits | Quantité | Valeur énergétique (MJ/unité) | Prod énergétique (MJ/ha) | Prop. (%) |
|----------|----------|-------------------------------|--------------------------|-----------|
| Grain    | 2000     | 15,73                         | 31460                    | 27%       |
| Paille   | 6000     | 13,87                         | 83220                    | 73%       |

On obtient un coût énergétique de  $(2236 \times 0,73) / 6000 = 0,272$  MJ/kg de paille de Riz.

### 6.5. Son de céréales

On se base dans un premier temps sur un itinéraire technique moyen du maïs trouvé dans les enquêtes.

| Intrants                          | Quantité | Coefficient énergétique (MJ/unité) | Coût énergétique (MJ/ha) |
|-----------------------------------|----------|------------------------------------|--------------------------|
| Semences issues de l'exploitation | 30 kg    | 0                                  | 0                        |
| Herbicides                        | 3 L      | 182                                | 546                      |
| Complexe céréales                 | 100 kg   | 10,59                              | 1059                     |
| Urée                              | 100 kg   | 12,90                              | 1290                     |
| <b>TOTAL :</b>                    |          |                                    | <b>2895 MJ/ha</b>        |

Si on considère un rendement moyen de 4 tonnes par hectare, un ratio grain/paille de 1/3 et une valeur énergétique de 16,14 et 13,93 MJ/kg brut respectivement pour le grain et pour la paille on obtient la production énergétique par hectare suivante :

| Produits | Quantité | Valeur énergétique (MJ/unité) | Prod énergétique (MJ/ha) | Prop. (%) |
|----------|----------|-------------------------------|--------------------------|-----------|
| Grain    | 3000     | 16,14                         | 64560                    | 28%       |
| Paille   | 12000    | 13,93                         | 167160                   | 72%       |

Le coût énergétique pour le grain de maïs s'élève donc à  $(2895 \times 0,28) / 4000 = 0,203$  MJ/kg.

On considère ensuite un rendement de concassage au pilon de 61% grain /39% son (Ndjouenkeu et al., 1989) et des valeurs énergétiques de 4506 kcal/kg brut pour le son de maïs et de 4480 pour le grain.

On obtient donc un coût énergétique de  $0,203 \times (2733/4490) \times (1/0,61) = 0,203$  MJ/kg de son de céréales.

## VII. BÂTIMENTS

Pour les bâtiments, on considère que les bâtiments en bois ou banco ont un coût énergétique nul. Les autres valeurs sont issues de PLANETE (Risoud et Theobald, 2002) ou Vigne (2007).

| Type de bâtiment         | Coût énergétique | Unité             | Références                                    |
|--------------------------|------------------|-------------------|---|
| Etable bois              | 0                | MJ/m <sup>2</sup> | PLANETE<br>Vigne (2007) : coef fosse à lisier |
| Etable banco             | 0                | MJ/m <sup>2</sup> |   |
| Etable en ciment         | 790              | MJ/m <sup>2</sup> |   |
| Fosse en dure            | 268.5            | MJ/m <sup>2</sup> |   |
| Fosse sans consolidation | 0                | MJ/m <sup>2</sup> |   |
| Hangar en bois           | 0                | MJ/m <sup>2</sup> |   |
| Hangar en banco          | 0                | MJ/m <sup>2</sup> |   |
| Hangar en ciment         | 790              | MJ/m <sup>2</sup> |   |
| Laiterie                 | 2970             | MJ/m <sup>2</sup> |   |
| Parc en bois             | 0                | MJ/unité          |   |
| Parc en fer barbelé      | 2,82             | MJ/m linéaire     | Bilan Carbone : coef fer <sup>3</sup>         |

<sup>3</sup> On considère ici une bobine de 50kg pour 250 m et 2 lignes de fil soit pour un parc de 0.125ha (périmètre ~ 140m) approximativement 56 kg de fer

## VIII. MATERIELS

On considère des coefficients énergétiques identiques à ceux de PLANETE (Risoud et Theobald, 2002).

| Type de matériel          | Coefficient énergétique (MJ/kg) |
|---------------------------|---------------------------------|
| Tracteur 4 Roues Motrices | 91.9                            |
| Tracteur 2 Roues Motrices | 95.7                            |
| Automotrices / Véhicules  | 83.5                            |
| Travail du sol            | 99.2                            |
| Autres                    | 95.4                            |

| Type de matériel | Poids (kg) | Coef. énerg. (MJ/kg) | Coût énergétique total (MJ) | Coût énergétique par an (MJ/an) <sup>4</sup> |
|------------------|------------|----------------------|-----------------------------|--|
| Appareil à dos   | 10         | 95.4                 | 954                         | 47,7   |
| Camion           | 3500       | 83.5                 | 292250                      | 14612,5                                      |
| Charrette asine  | 60         | 95.4                 | 5724                        | 286,2  |
| Charrette bovine | 150        | 95.4                 | 14310                       | 715,5  |
| Tombereau        | 100        | 95.4                 | 9540                        | 477  |
| Charrue          | 50         | 99.2                 | 4960                        | 248  |
| Congélateur      | 80         | 95.4                 | 6680                        | 334  |
| Corps butteur    | 40         | 99.2                 | 3968                        | 198,4  |
| Ensileuse        | 1700       | 95.4                 | 162180                      | 8109   |
| Fourgonnette     | 1500       | 83.5                 | 125250                      | 6262,5                                       |
| Moto             | 80         | 83.5                 | 6680                        | 334  |
| Remorque         | 1500       | 95.4                 | 143100                      | 7155   |
| Sarcler          | 60         | 99.2                 | 5952                        | 297,6  |
| Vélo             | 15         | 95.4                 | 1431                        | 71,55  |
| Voiture          | 800        | 83.5                 | 66800                       | 3340   |

<sup>4</sup> On considère ici un amortissement moyen de 20 ans

### *Autres frais*

On considère les coefficients énergétiques donnés par PLANETE (Risoud et Theobald, 2002) pour les frais vétérinaires (1.14 MJ/F) et les frais d'élevage (0.76 MJ/F).

Converti en FCFA, le coût énergétique s'élève à **0.0114 MJ/FCFA** pour les frais de vaccination et à **0.0076 MJ/FCFA** pour les frais de déparasitage et les frais d'insémination.

Pour le Sel, en l'absence de données sur l'origine on considère un coût de **0.99 MJ/kg** (Benagabou, 2011).

## **IX. RESIDUS DE CULTURES**

### **9.1. Résidus de Céréales**

On va faire une moyenne des coûts énergétiques pour les 3 grandes cultures céréalières de plateaux : Maïs, Mil et Sorgho.

Pour le Maïs, on considère un itinéraire technique et des ratios identiques au calcul du son de céréales. Le coût énergétique de la paille de maïs s'élève donc à  $(2895 \times 0,72) / 12000 = 0,174$  MJ/kg.

Pour le Mil et le Sorgho, les enquêtes montrent que les champs ne font l'objet d'aucun ajout d'intrant.

On va donc considérer que le coût de production des résidus de mil est nul.

On fait une moyenne entre les trois cultures pondéré par les teneurs matière sèche moyennes et le pourcentage de présence des cultures dans l'assolement total des 14 exploitations. On obtient un coût énergétique pour les résidus de céréales de  $(0,174 \times 0,841 \times 0,6 + 0 \times 0,95 \times 0,33 + 0 \times 0,95 \times 0,07 = 0,088$  MJ/kgMS consommé.

### **9.2. Résidus de Cultures de bas-fonds**



On va faire une moyenne des coûts énergétiques pour les 3 grandes cultures de bas-fond : Riz, Pomme de Terre et Patate Douce.

Pour le Riz, on considère le coefficient énergétique précédemment calculé pour la Paille de Riz soit **0,27 MJ/kg de paille de Riz.**

Pour la Pomme de Terre, on considère l’itinéraire technique moyen trouvé sur les enquêtes :

| Intrants          | Quantité | Coefficient énergétique (MJ/unité) | Coût énergétique (MJ/ha) |
|-------------------|----------|------------------------------------|--------------------------|
| Semences achetées | 650 kg   | 2,90                               | 1885                     |
| Complexe Céréales | 1500 kg  | 10,59                              | 15585                    |

**TOTAL : 17770 MJ/ha**

Si on considère un rendement moyen de 45 tonnes par hectare, un ratio tubercule/fanes de 1/0,6 et une valeur énergétique de 3,35 et 16,83 MJ/kg brut respectivement pour les tubercules et pour les fanes on obtient la production énergétique par hectare suivante :

| Produits   | Quantité | Valeur énergétique (MJ/unité) | Prod énergétique (MJ/ha) | Prop. (%) |
|------------|----------|-------------------------------|--------------------------|-----------|
| Tubercules | 45000    | 3,35                          | 150750                   | 25%       |
| Fanes      | 27000    | 16,83                         | 454410                   | 75%       |

Le coût énergétique pour les fanes de Pomme de Terre s’élève donc à  $(17770 \times 0,75) / 27000 = \mathbf{0,49 \text{ MJ/kg}}$ .

Pour la Patate Douce, on considère l’itinéraire technique moyen trouvé sur les enquêtes :

| Intrants          | Quantité | Coefficient énergétique (MJ/unité) | Coût énergétique (MJ/ha) |
|-------------------|----------|------------------------------------|--------------------------|
| Herbicides        | 1L       | 149                                | 149                      |
| Complexe Céréales | 200 kg   | 10,59                              | 2118                     |

**TOTAL : 2267 MJ/ha**

Si on considère un rendement moyen de 10 tonnes par hectare, un ratio tubercule/fanes de 1/0,6 et une valeur énergétique de 4,52 et 16,83 MJ/kg brut respectivement pour les tubercules et pour les fanes on obtient la production énergétique par hectare suivante :

| Produits   | Quantité | Valeur énergétique (MJ/unité) | Prod énergétique (MJ/ha) | Prop. (%) |
|------------|----------|-------------------------------|--------------------------|-----------|
| Tubercules | 10000    | 4,52                          | 45200                    | 31        |
| Fanes      | 6000     | 16,83                         | 100980                   | 69        |

Le coût énergétique pour la paille de riz s’élève donc à  $(2267 \times 0,69) / 6000 = \mathbf{0,26 \text{ MJ/kg}}$ .

On fait une moyenne entre les trois cultures pondéré par leur valeur en MS et leur pourcentage de présence dans l’assolement total des 14 exploitations étudiées. On obtient un coût énergétique pour les résidus de bas-fonds de  $0,27 \times 0,923 \times 0,37 + 0,49 \times 0,907 \times 0,43 + 0,26 \times 0,907 \times 0,20 = \mathbf{0,330 \text{ MJ/kgMS consommé}}$ .

## **X. ANIMAUX ACHETES**

On se base sur la précédente étude de Benagabou et al. (2011) menée au Burkina sur des systèmes intégrés agriculture-élevage qui montre une consommation énergétique moyenne par kg d'animaux vendu de **0,8 MJ/kg vendu**.

## ***XI. FUMIER***

### ***11.1. Fumure déposée par pâturage***

On va se baser sur le coût énergétique des résidus de cultures et une moyenne de teneur en énergie digestible de 60%. On va donc affecter 40% du coût énergétique des résidus soit pour la fumure déposée sur les céréales  $0,088 \times 0,4 = 0,035$  MJ/kgMS et pour la fumure déposée sur les bas-fonds  $0,330 \times 0,4 = 0,132$  MJ/kgMS.

### ***11.2. Fumure épandue***

On se base sur la moyenne des deux précédents calculs soit 0.084 MJ/kgMS

## **XII. TRAVAIL**

### ***12.1. Travail Humain***

Recherche d'équilibre des efficacités à partir des 14 exploitations d'abord sans coefficient pour le travail puis à chaque fois en recalculant avec le coefficient trouvé: 0.9MJ d'énergie fossile consommée pour 1MJ d'énergie produite sous forme de productions animales (EE = 1.1) et de 0.02 MJ d'énergie fossile consommée pour 1MJ d'énergie produite sous forme de productions animales (EE=42.7) (On considère également un rapport énergie produite sur énergie consommée de 50%).

On se base également sur le rapport Agrimonde qui donne une consommation quotidienne en Afrique de 2366 kcal/hab/j soit 9.9 MJ/hab/j dont 5% d'origine animale (soit 9.4 MJ d'origine végétale et 0.5 MJ d'origine animale).

Il faut donc pour produire ces 9.9 MJ d'énergie alimentaire  $(9.4 \times 0.02) + (0.5 \times 0.9) = 1$  MJ d'énergie fossile soit 0.1 MJ d'énergie fossile par énergie alimentaire. Sachant qu'il faut 2 MJ d'énergie alimentaire pour fournir 1 MJ, s'élève donc à 0.2 MJ/MJ de travail.

### ***12.2. Travail Animal***

On prend ici l'efficacité moyenne fossile du troupeau de 35 MJ.MJ-1. Donc il faut approximativement 0.03 MJ d'EF par MJ de travail.

**ENQUÊTE : EVALUATION DES DEGRES DE PENIBILITE**

Nom : \_\_\_\_\_

Date : \_\_\_\_\_

Selon vous, quelle activité demande le plus d'énergie par heure travaillée : \_\_\_\_\_

Selon vous, quelle activité demande le moins d'énergie par heure travaillée : \_\_\_\_\_

Donnez une valeur de la demande énergétique des différents travaux réalisés sur l'exploitation de 1 (facile, peu demandeur d'énergie) à 5 (difficile, très demandeur en énergie). Veuillez également indiquer qui réalise ces travaux.

| Type de travaux              | Difficulté   | Travaux réalisés par : |
|------------------------------|--|------------------------|
| Abreuvement des animaux      | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Apport d'herbicides          | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Apport de fumure organique   | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Arrosage                     | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Buttage avec animaux         | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Buttage manuel               | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Conduite des Animaux         | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Déplacement des parcs        | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Distribution des aliments    | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Egrenage                     | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Epandage du complexe         | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Implantation du Riz          | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Implantation des tubercules  | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Labour avec animaux          | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Labour manuel                | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Nettoyage des champs         | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Nettoyage des parcs          | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Pilage Poudre de Néré        | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Récolte des grains           | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Récolte des résidus          | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Sarclage avec animaux        | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Sarclage manuel              | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Semis de grains avec animaux | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Semis de grain Manuel        | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Traite                       | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Transport à pied avec charge | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Transport avec animaux       | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Transport avec moto          | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |
| Transport autres véhicules   | <input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 | _____                  |

|   |
|---|
| <b>Mode de calcul et valeurs retenues des Unit Energy Values sur l'ensemble des territoires</b> |
|---|

**I. ÉLECTRICITÉ****1.1. France Métropolitaine**

| Énergie primaire | %  | Transformity | Renew. | Ref.              |
|------------------|----|--------------|--------|-------------------|
| Nucléaire        | 74 | 4.37E+04     | 5      | Odum (1996)       |
| Hydraulique      | 12 | 6.23E+04     | 68.84  | Brown and Ulgiati |
| Gaz              | 6  | 1.70E+05     | 6.60   | (2002)            |
| Charbon          | 4  | 1.71E+05     | 8.79   |                   |
| Fioul            | 2  | 2.00E+05     | 6.56   |                   |
| Eolien           | 2  | 6.21E+04     | 86.61  |                   |

La transformité moyenne s'élève à **6.21E+04** et la renouvelabilité moyenne s'élève à **11%**.

**1.2. Ile de la Réunion**

Avant de recalculer la transformité selon le profil d'énergie primaire on calcule la transformité de l'électricité issue de la bagasse. Selon l'OER (2008), 510 128 t de bagasse permettent de produire 262.6 GWh d'électricité soit  $9.45E+14$  J. Compte-tenu de sa transformité ( $3.34E+11$  sej.kg<sup>-1</sup>), la bagasse représente une énergie totale de  $17.03E+19$  sej. La transformité de l'électricité issue de la bagasse s'élève donc à **18.02E+04 sej.J<sup>-1</sup>**

A partir de cette donnée on peut recalculer la transformité de l'électricité totale grâce au profil de consommation en énergie primaire totale.

| Énergie primaire | % Prod | Transformity | Renew. | Ref.                     |
|------------------|--------|--------------|--------|--------------------------|
| Fioul / Gazole   | 13     | 20.00E+04    | 6.56   | Brown and Ulgiati (2002) |
| Charbon          | 51     | 17.10E+04    | 8.79   | Brown and Ulgiati (2002) |
| Bagasse          | 10     | 18.02E+04    | 27.00  | Own calculation          |
| Hydraulique      | 25     | 6.23E+04     | 68.84  | Brown and Ulgiati (2002) |
| Eolien           | 1      | 6.21E+04     | 86.61  | Brown and Ulgiati (2002) |

On obtient **1.48E+05 sej.J<sup>-1</sup>** et une renouvelabilité de **26%**.

**1.3. Mali**

| Energie primaire | %  | Transformity | Renewability | Ref.                                      |
|------------------|----|--------------|--------------|---|
| Hydraulique      | 80 | 6.23E+04     | 70%          | Odum (1996) for transformity and          |
| Charbon          | 20 | 1.71E+05     | 9%           | Brown and Ulgiati (2002) for renewability |

On obtient : **8.40E+04 sej.J<sup>-1</sup>** et une renouvelabilité de **58%**.

**II. FOURRAGES****2.1. France Métropolitaine**

**2.1.1. Ensilage de Maïs**

| Note                     | Item                  | Quantité | Unité | Transformity    | Emergy flow | Renew. |
|--------------------------|-----------------------|----------|-------|-----------------|-------------|--------|
| Renewable Inputs (R)     |                       |          |       |                 |             |        |
| 1                        | Solar radiation       | 3.72E+13 | J     | 1               | 3.72E+13    | 1      |
| 2                        | Rain                  | 4.20E+10 | J     | 3.06E+04        | 128.52E+13  | 1      |
| 3                        | Wind                  | 1.62E+09 | J     | 2.52E+03        | 0.41E+13    | 1      |
| Non-Renewable Inputs (N) |                       |          |       |                 |             |        |
| 4                        | Soil Loss             | 2.71E+08 | J     | 1.24E+05        | 3.36E+13    | 0      |
| Materials (M)            |                       |          |       |                 |             |        |
| 5                        | Fuel                  | 4.07E+09 | J     | 1.30E+05        | 52.91E+13   | 0.05   |
| 6                        | Herbicides            | 7.00E+03 | g     | 2.48E+10        | 17.36E+13   | 0.05   |
| 7                        | Insecticides          | 4.00E+03 | g     | 2.48E+10        | 9.92E+13    | 0.05   |
| 8                        | Nitrogen              | 9.00E+04 | g     | 4.05E+10        | 364.50E+13  | 0.05   |
| 9                        | Manure                | 3.00E+07 | g     | 1.13E+08        | 339.00E+13  | 0.18   |
| 10                       | Plastics              | 5.80E+04 | g     | 1.87E+09        | 10.85E+13   | 0.05   |
| 11                       | Seeds                 | 6.48E+08 | J     | 1.82E+04        | 1.18E+13    | 0.20   |
| 12                       | Material depreciation | 1.43E+04 | g     | 1.13E+10        | 16.16E+13   | 0.05   |
| Services (S)             |                       |          |       |                 |             |        |
| 13                       | Travail humain        | 3.24E+06 | J     | 3.36E+06        | 1.09E+13    | 0.27   |
| Total R                  |                       |          |       |                 | 132.65E+13  |        |
| Total N                  |                       |          |       |                 | 3.36E+13    |        |
| Total M                  |                       |          |       |                 | 811.88E+13  |        |
| Total S                  |                       |          |       |                 | 1.09E+13    |        |
| Total Emergy (Y)         |                       |          |       |                 | 948.98E+13  |        |
| Renewable Emergy         |                       |          |       |                 | 217.79E+13  |        |
| Non-Renewable Emergy     |                       |          |       |                 | 731.19E+13  |        |
| Renew. (%)               |                       |          |       |                 | 23          |        |
| Outputs (O)              |                       |          |       |                 |             |        |
| 14                       | Ensilage Maïs         | 1.50E+04 | kgMS  | <b>6.33E+11</b> | 948.98E+13  |        |

**2.1.2. Paille de blé**

On calcule d'abord le coût de la culture du blé + récolte

| Note                     | Item            | Quantité | Unité | Transformity | Emergy flow | Renew. |
|--------------------------|-----------------|----------|-------|--------------|-------------|--------|
| Renewable Inputs (R)     |                 |          |       |              |             |        |
| 1                        | Solar radiation | 3.72E+13 | J     | 1            | 3.72E+13    | 1      |
| 2                        | Rain            | 4.20E+10 | J     | 3.06E+04     | 128.52E+13  | 1      |
| 3                        | Wind            | 1.62E+09 | J     | 2.52E+03     | 0.41E+13    | 1      |
| Non-Renewable Inputs (N) |                 |          |       |              |             |        |
| 4                        | Soil Loss       | 2.71E+08 | J     | 1.24E+05     | 3.36E+13    | 0      |
| Materials (M)            |                 |          |       |              |             |        |
| 5                        | Fuel            | 2.62E+09 | J     | 1.30E+05     | 34.06E+13   | 0.05   |
| 6                        | Herbicides      | 2.00E+03 | g     | 2.48E+10     | 4.96E+13    | 0.05   |
| 7                        | Insecticides    | 2.00E+03 | g     | 2.48E+10     | 4.96E+13    | 0.05   |

|                      |                       |          |    |                 |            |      |
|----------------------|-----------------------|----------|----|-----------------|------------|------|
| 8                    | Nitrogen              | 1.67E+05 | g  | 4.05E+10        | 676.35E+13 | 0.05 |
| 9                    | Seeds                 | 2.10E+09 | J  | 7.90E+04        | 16.61E+13  | 0.20 |
| 10                   | Material depreciation | 1.05E+04 | g  | 1.13E+10        | 11.87E+13  | 0.05 |
| Services (S)         |                       |          |    |                 |            |      |
| 11                   | Travail humain        | 2.16E+06 | J  | 3.36E+06        | 0.73E+13   | 0.27 |
| Total R              |                       |          |    |                 | 132.65E+13 |      |
| Total N              |                       |          |    |                 | 3.36E+13   |      |
| Total M              |                       |          |    |                 | 748.81E+13 |      |
| Total S              |                       |          |    |                 | 0.73E+13   |      |
| Total Emergy (Y)     |                       |          |    |                 | 885.55E+13 |      |
| Renewable Emergy     |                       |          |    |                 | 172.45E+13 |      |
| Non-Renewable Emergy |                       |          |    |                 | 713.10E+13 |      |
| Renew. (%)           |                       |          |    |                 |            | 19   |
| Outputs (O)          |                       |          |    |                 |            |      |
| 12                   | Blé                   | 6.20E+03 | Kg | <b>1.43E+12</b> | 885.55E+13 |      |
| 13                   | Paille de Blé         | 1.14E+04 | kg | <b>7.77E+11</b> | 885.55E+13 |      |

Il faut maintenant rajouter un coût de pressage :

| Note                 | Item                  | Quantité | Unité | Transformity    | Emergy flow | Renew. flow |
|----------------------|-----------------------|----------|-------|-----------------|-------------|-------------|
| Materials (M)        |                       |          |       |                 |             |             |
| 1                    | Paille au sol         | 1.14+04  | Kg    | 7.77E+11        | 885.55E+13  | 0.19        |
| 2                    | Fuel                  | 4.03E+08 | J     | 1.30E+05        | 5.59E+13    | 0.05        |
| 3                    | Material Depreciation | 3.88E+04 | g     | 1.13E+10        | 43.84E+13   | 0.05        |
| Services (S)         |                       |          |       |                 |             |             |
| 4                    | Human labour          | 6.36E+05 | J     | 3.36E+06        | 0.21E+13    | 0.27        |
| Total R              |                       |          |       |                 | 0           |             |
| Total N              |                       |          |       |                 | 0           |             |
| Total M              |                       |          |       |                 | 934.98E+13  |             |
| Total S              |                       |          |       |                 | 0.21E+13    |             |
| Total Emergy (Y)     |                       |          |       |                 | 935.19E+13  |             |
| Renewable Emergy     |                       |          |       |                 | 170.78E+13  |             |
| Non-Renewable Emergy |                       |          |       |                 | 764.41E+13  |             |
| Renew. (%)           |                       |          |       |                 |             | 18          |
| Outputs (O)          |                       |          |       |                 |             |             |
| 5                    | Paille de Blé         | 1.14E+04 | Kg    | <b>8.20E+11</b> | 935.19E+13  |             |
|                      |                       | 1.00E+04 | kgMS  | <b>9.35E+11</b> | 935.19E+13  |             |

## 2.2. Ile de la Réunion

### 2.2.1. Ensilage et Foin

On considère l'itinéraire technique donné par Barbet-Massin (2004) et un rendement de 30tB/ha

| Note | Item | Quantité | Unité | Transformity | Emergy flow | Renew. flow |
|------|------|----------|-------|--------------|-------------|-------------|
|------|------|----------|-------|--------------|-------------|-------------|

|                          |                       |          |    |                 |            |      |
|--------------------------|-----------------------|----------|----|-----------------|------------|------|
| Renewable Inputs (R)     |                       |          |    |                 |            |      |
| 1                        | Solar radiation       | 5.33E+13 | J  | 1               | 0.53E+14   | 1    |
| 2                        | Rain                  | 1.48E+11 | J  | 3.06E+04        | 45.29E+14  | 1    |
| 3                        | Wind                  | 2.59E+09 | J  | 2.52E+03        | 0.07E+14   | 1    |
| Non-Renewable Inputs (N) |                       |          |    |                 |            |      |
| 4                        | Soil Loss             | 2.40E+10 | J  | 1.24E+05        | 29.76E+14  | 0    |
| Materials (M)            |                       |          |    |                 |            |      |
| 5                        | Seeds                 | 4.00E+04 | g  | 2.26E+05        | 0.00E+14   | 0.20 |
| 6                        | Fuel                  | 4.43E+10 | J  | 1.30E+05        | 57.59E+14  | 0.05 |
| 7                        | Herbicides            | 4.30E+04 | g  | 2.51E+10        | 10.79E+14  | 0.05 |
| 8                        | Nitrogen              | 3.00E+05 | g  | 4.08E+10        | 122.40E+14 | 0.05 |
| 9                        | Phosphate             | 2.40E+05 | g  | 3.73E+10        | 89.52E+14  | 0.05 |
| 10                       | Potash                | 4.80E+05 | g  | 3.26E+09        | 15.65E+14  | 0.05 |
| 11                       | Plastics              | 1.28E+04 | g  | 3.20E+09        | 0.41E+14   | 0.05 |
| 12                       | Material depreciation | 1.20E+03 | g  | 1.13E+10        | 0.14E+14   | 0.05 |
| Services (S)             |                       |          |    |                 |            |      |
| 13                       | Human labour          | 3.31E+07 | J  | 3.36E+06        | 1.11E+14   | 0.27 |
| Total R                  |                       |          |    |                 | 45.89E+14  |      |
| Total N                  |                       |          |    |                 | 29.76E+14  |      |
| Total M                  |                       |          |    |                 | 326.50E+14 |      |
| Total S                  |                       |          |    |                 | 1.11E+14   |      |
| Total Emergy (Y)         |                       |          |    |                 | 403.26E+14 |      |
| Renewable Emergy         |                       |          |    |                 | 62.51E+14  |      |
| Non-Renewable Emergy     |                       |          |    |                 | 340.75E+14 |      |
| Renew. (%)               |                       |          |    |                 | 16         |      |
| Outputs (O)              |                       |          |    |                 |            |      |
| 13                       | Fourrages             | 3.00E+04 | kg | <b>1.34E+12</b> | 403.26E+14 |      |

### 2.2.2. Produits de la canne

On se base sur :

- l'itinéraire de Rondeau (2002) avec ramassage manuel
- un rendement en 2010 de 75 t/ha de canne soit 133 m<sup>2</sup> pour une tonne et un rendement en paille de canne de 10 t/ha soit 0.133 t/133m<sup>2</sup>
- Une production à partir d'une t de canne de 860 kg de bagasse, 30 kg de mélasse et 110 kg de sucre.

| Note                     | Item            | Quantité | Unité | Transformity | Emergy flow | Renew. |
|--------------------------|-----------------|----------|-------|--------------|-------------|--------|
| Renewable Inputs (R)     |                 |          |       |              |             |        |
| 1                        | Solar radiation | 7.11E+13 | J     | 1            | 0.71E+12    | 1      |
| 2                        | Rain            | 1.97E+09 | J     | 3.06E+04     | 60.28E+12   | 1      |
| 3                        | Wind            | 3.47E+07 | J     | 2.52E+03     | 0.87E+12    | 1      |
| Non-Renewable Inputs (N) |                 |          |       |              |             |        |
| 4                        | Soil Loss       | 3.19E+08 | J     | 1.24E+05     | 39.56E+12   | 0      |
| Materials (M)            |                 |          |       |              |             |        |
| 5                        | Fuel            | 3.18E+08 | J     | 1.30E+05     | 41.34E+12   | 0.05   |

|                      |                       |          |    |                  |            |      |
|----------------------|-----------------------|----------|----|------------------|------------|------|
| 6                    | Herbicides            | 0.11E+03 | g  | 2.51E+10         | 2.76E+12   | 0.05 |
| 7                    | Nitrogen              | 1.80E+03 | g  | 4.08E+10         | 73.44E+12  | 0.05 |
| 8                    | Phosphate             | 0.80E+03 | g  | 3.73E+10         | 29.84E+12  | 0.05 |
| 9                    | Potash                | 3.00E+03 | g  | 3.26E+09         | 9.78E+12   | 0.05 |
| 10                   | Material depreciation | 3.90E+02 | g  | 1.13E+10         | 4.41E+12   | 0.05 |
| Services (S)         |                       |          |    |                  |            |      |
| 11                   | Human labour          | 7.21E+06 | J  | 3.36E+06         | 24.22E+12  | 0.27 |
| Total R              |                       |          |    |                  | 61.86E+12  |      |
| Total N              |                       |          |    |                  | 39.56E+12  |      |
| Total M              |                       |          |    |                  | 161.57E+12 |      |
| Total S              |                       |          |    |                  | 24.22E+12  |      |
| Total Emergy (Y)     |                       |          |    |                  | 287.21E+12 |      |
| Renewable Emergy     |                       |          |    |                  | 76.48E+12  |      |
| Non-Renewable Emergy |                       |          |    |                  | 210.73E+12 |      |
| Renew. (%)           |                       |          |    |                  | 27         |      |
| Outputs (O)          |                       |          |    |                  |            |      |
| 11                   | Paille                | 1.33E+02 | kg | <b>21.59E+11</b> | 287.21E+12 |      |
| 12                   | Canne brute           | 1.0E+03  | kg | <b>2.87E+11</b>  | 287.21E+12 |      |

On rajoute ensuite un coût de pressage de la canne :

| Note                 | Item                  | Quantité | Unité | Transformity    | Emergy flow | Renew. |
|----------------------|-----------------------|----------|-------|-----------------|-------------|--------|
| Materials (M)        |                       |          |       |                 |             |        |
| 1                    | Paille au sol         | 1.00+03  | Kg    | 21.59E+11       | 215.90E+13  | 0.27   |
| 2                    | Fuel                  | 4.03E+08 | J     | 1.30E+05        | 5.59E+13    | 0.05   |
| 3                    | Material Depreciation | 3.88E+04 | g     | 1.13E+10        | 43.84E+13   | 0.05   |
| Services (S)         |                       |          |       |                 |             |        |
| 4                    | Human labour          | 6.36E+05 | J     | 3.36E+06        | 0.21E+13    | 0.27   |
| Total R              |                       |          |       |                 | 0           |        |
| Total N              |                       |          |       |                 | 0           |        |
| Total M              |                       |          |       |                 | 265.33E+13  |        |
| Total S              |                       |          |       |                 | 0.21E+13    |        |
| Total Emergy (Y)     |                       |          |       |                 | 265.54E+13  |        |
| Renewable Emergy     |                       |          |       |                 | 60.82E+13   |        |
| Non-Renewable Emergy |                       |          |       |                 | 265.54E+13  |        |
| Renew. (%)           |                       |          |       |                 | 23          |        |
| Outputs (O)          |                       |          |       |                 |             |        |
| 5                    | Paille de Canne       | 1.00E+03 | Kg    | <b>2.66E+12</b> | 265.54E+13  |        |

Pour la bagasse on considère le coût de broyage de la canne :

| Note          | Item        | Quantité | Unité | Transformity | Emergy flow | Renew. |
|---------------|-------------|----------|-------|--------------|-------------|--------|
| Materials (M) |             |          |       |              |             |        |
| 1             | Canne brute | 1.00E+03 | Kg    | 2.87E+11     | 2.87E+14    | 0.27   |
| 2             | Fuel        | 0.67E+05 | J     | 1.30E+05     | 0.00E+14    | 0.05   |



|                      |          |
|----------------------|----------|
| Total Energy (Y)     | 2.87E+14 |
| Renewable Energy     | 0.69E+15 |
| Non-Renewable Energy | 2.18E+15 |
| Renew. (%)           | 27       |

|             |              |          |    |                  |          |
|-------------|--------------|----------|----|------------------|----------|
| Outputs (O) |              |          |    |                  |          |
| 1           | Bagasse      | 0.86E+03 | kg | <b>3.34E+11</b>  | 2.87E+14 |
| 2           | Jus de Canne | 0.14E+03 | kg | <b>20.50E+11</b> | 2.87E+14 |

## 2.3. Mali

### 2.3.1. Résidus de céréales

On va faire une moyenne des coûts énergétiques pour les 3 grandes cultures céréalières de plateaux (Maïs, Mil et Sorgho) à partir des itinéraires techniques moyens trouvés dans les enquêtes.

| - Maïs -                 |                 |           |       |                  |             |       |
|--------------------------|-----------------|-----------|-------|------------------|-------------|-------|
| Note                     | Item            | Quantité  | Unité | Transformity     | Energy flow | Renew |
| Renewable Inputs (R)     |                 |           |       |                  |             |       |
| 1                        | Solar radiation | 6.19E+13  | J     | 1                | 0.62E+14    | 1     |
| 2                        | Rain            | 5.43E+10  | J     | 3.06E+04         | 16.62E+14   | 1     |
| 3                        | Wind            | 2.59E+10  | J     | 2.52E+03         | 0.65E+14    | 1     |
| Non-Renewable Inputs (N) |                 |           |       |                  |             |       |
| 4                        | Soil Loss       | 2.86E+09  | J     | 1.24E+05         | 3.55E+14    | 0     |
| Materials (M)            |                 |           |       |                  |             |       |
| 5                        | Seeds           | 4.84E+08  | J     | 1.82E+04         | 0.09E+14    | 0.17  |
| 6                        | Herbicides      | 3E+03     | g     | 2.48E+10         | 0.74E+14    | 0.05  |
| 7                        | Nitrogen        | 1.5E+04   | g     | 4.05E+10         | 6.08E+14    | 0.05  |
| 8                        | Phosphate       | 1.5E+04   | g     | 3.70E+10         | 5.55E+14    | 0.05  |
| 9                        | Potash          | 1.5E+04   | g     | 2.92E+09         | 0.44E+14    | 0.05  |
| 10                       | Urea            | 1.0E+05   | g     | 6.62E+09         | 6.62E+14    | 0.05  |
| Services (S)             |                 |           |       |                  |             |       |
| 11                       | Human Labour    | 6.26E+08  | J     | 6.72E+05         | 4.21E+14    | 0.50  |
| 12                       | Animal Labour   | 2.51E+08  | J     | 6.94E+06         | 17.42E+14   | 0.26  |
| Total R                  |                 |           |       |                  | 17.89E+14   |       |
| Total N                  |                 |           |       |                  | 3.55E+14    |       |
| Total M                  |                 |           |       |                  | 19.52E+14   |       |
| Total S                  |                 |           |       |                  | 21.63E+14   |       |
| Total Energy (Y)         |                 |           |       |                  | 62.59E+14   |       |
| Renewable Energy         |                 |           |       |                  | 25.51E+14   |       |
| Non-Renewable Energy     |                 |           |       |                  | 37.08E+14   |       |
| Renew. (%)               |                 |           |       |                  | 41          |       |
| Outputs (O)              |                 |           |       |                  |             |       |
| 13                       | Grain           | 3.50E+03  | kg    | <b>17.88E+11</b> | 62.59E+14   |       |
| 14                       | Straw           | 12.00E+03 | kg    | <b>5.22E+11</b>  | 62.59E+14   |       |

| - Mil -                  |                 |          |       |                  |             |        |
|--------------------------|-----------------|----------|-------|------------------|-------------|--------|
| Note                     | Item            | Quantité | Unité | Transformity     | Emergy flow | Renew. |
| Renewable Inputs (R)     |                 |          |       |                  |             |        |
| 1                        | Solar radiation | 6.19E+13 | J     | 1                | 0.62E+14    | 1      |
| 2                        | Rain            | 5.43E+10 | J     | 3.06E+04         | 16.62E+14   | 1      |
| 3                        | Wind            | 2.59E+10 | J     | 2.52E+03         | 0.65E+14    | 1      |
| Non-Renewable Inputs (N) |                 |          |       |                  |             |        |
| 4                        | Soil Loss       | 2.86E+09 | J     | 1.24E+05         | 3.55E+14    | 0      |
| Services (S)             |                 |          |       |                  |             |        |
| 5                        | Human Labour    | 1.42E+08 | J     | 6.72E+05         | 0.95E+14    | 0.50   |
| 6                        | Animal Labour   | 0.37E+08 | J     | 6.94E+06         | 2.57E+14    | 0.26   |
| Total R                  |                 |          |       |                  | 17.89E+14   |        |
| Total N                  |                 |          |       |                  | 3.55E+14    |        |
| Total M                  |                 |          |       |                  | 0           |        |
| Total S                  |                 |          |       |                  | 3.52E+14    |        |
| Total Emergy (Y)         |                 |          |       |                  | 24.96E+14   |        |
| Renewable Emergy         |                 |          |       |                  | 19.06E+14   |        |
| Non-Renewable Emergy     |                 |          |       |                  | 5.90E+14    |        |
| Renew. (%)               |                 |          |       |                  | 76          |        |
| Outputs (O)              |                 |          |       |                  |             |        |
| 7                        | Grain           | 1.00E+03 | kg    | <b>24.96E+11</b> | 24.96E+14   |        |
| 8                        | Straw           | 4.00E+03 | kg    | <b>6.24E+11</b>  | 24.96E+14   |        |

| - Sorgho -               |                 |          |       |                  |             |        |
|--------------------------|-----------------|----------|-------|------------------|-------------|--------|
| Note                     | Item            | Quantité | Unité | Transformity     | Emergy flow | Renew. |
| Renewable Inputs (R)     |                 |          |       |                  |             |        |
| 1                        | Solar radiation | 6.19E+13 | J     | 1                | 0.62E+14    | 1      |
| 2                        | Rain            | 5.43E+10 | J     | 3.06E+04         | 16.62E+14   | 1      |
| 3                        | Wind            | 2.59E+10 | J     | 2.52E+03         | 0.65E+14    | 1      |
| Non-Renewable Inputs (N) |                 |          |       |                  |             |        |
| 4                        | Soil Loss       | 2.86E+09 | J     | 1.24E+05         | 3.55E+14    | 0      |
| Services (S)             |                 |          |       |                  |             |        |
| 5                        | Human Labour    | 1.90E+08 | J     | 6.72E+05         | 1.28E+14    | 0.50   |
| 6                        | Animal Labour   | 0.94E+08 | J     | 6.94E+06         | 6.52E+14    | 0.26   |
| Total R                  |                 |          |       |                  | 17.89E+14   |        |
| Total N                  |                 |          |       |                  | 3.55E+14    |        |
| Total M                  |                 |          |       |                  | 0           |        |
| Total S                  |                 |          |       |                  | 7.80E+14    |        |
| Total Emergy (Y)         |                 |          |       |                  | 29.24E+14   |        |
| Renewable Emergy         |                 |          |       |                  | 20.29E+14   |        |
| Non-Renewable Emergy     |                 |          |       |                  | 8.95E+14    |        |
| Renew. (%)               |                 |          |       |                  | 69          |        |
| Outputs (O)              |                 |          |       |                  |             |        |
| 7                        | Grain           | 0.90E+03 | kg    | <b>32.49E+11</b> | 29.24E+14   |        |

|   |       |          |    |                 |           |
|---|-------|----------|----|-----------------|-----------|
| 8 | Straw | 3.20E+03 | kg | <b>9.14E+11</b> | 29.24E+14 |
|---|-------|----------|----|-----------------|-----------|

On fait une moyenne entre les trois cultures pondéré par le pourcentage de présence des cultures dans l'assolement total des 14 exploitations. On obtient un coût énergétique pour les résidus de céréales de  $5.22E+11 \times 0,6 + 6.24E+11 \times 0,33 + 9.14E+11 \times 0,07 = \mathbf{5.83E+11}$  sej.kg<sup>-1</sup>.

La renouvelabilité s'élève à **55%**.

### 2.3.2. Cultures de bas-fonds

On va faire une moyenne des coûts énergétiques pour les 3 grandes cultures de bas-fond (Riz, Pomme de Terre et Patate Douce) à partir des itinéraires techniques trouvés dans les enquêtes.

#### - Riz -

| Note                     | Item                       | Quantité | Unité | Transformity     | Emergy flow | Renew. |
|--------------------------|----------------------------|----------|-------|------------------|-------------|--------|
| Renewable Inputs (R)     |                            |          |       |                  |             |        |
| 1                        | Solar radiation            | 6.19E+13 | J     | 1                | 0.62E+14    | 1      |
| 2                        | Rain                       | 5.43E+10 | J     | 3.06E+04         | 16.62E+14   | 1      |
| 3                        | Wind                       | 2.59E+10 | J     | 2.52E+03         | 0.65E+14    | 1      |
| Non-Renewable Inputs (N) |                            |          |       |                  |             |        |
| 4                        | Soil Loss                  | 2.86E+09 | J     | 1.24E+05         | 3.55E+14    | 0      |
| Materials (M)            |                            |          |       |                  |             |        |
| 5                        | Seeds                      | 7.87E+08 | J     | 8.30E+04         | 0.65E+14    | 0.20   |
| 6                        | Herbicides                 | 3E+03    | g     | 2.48E+10         | 0.74E+14    | 0.05   |
| 7                        | Urea                       | 1.0E+05  | g     | 6.62E+09         | 6.62E+14    | 0.05   |
| Services (S)             |                            |          |       |                  |             |        |
| 8                        | Human                      | 6.67E+08 | J     | 6.72E+05         | 4.48E+14    | 0.50   |
| 9                        | Labour<br>Animal<br>Labour | 2.98E+08 | J     | 6.94E+06         | 20.68E+14   | 0.26   |
| Total R                  |                            |          |       |                  | 17.89E+14   |        |
| Total N                  |                            |          |       |                  | 3.55E+14    |        |
| Total M                  |                            |          |       |                  | 8.01E+14    |        |
| Total S                  |                            |          |       |                  | 25.16E+14   |        |
| Renewable Emergy         |                            |          |       |                  | 26.21E+14   |        |
| Non-Renewable<br>Emergy  |                            |          |       |                  | 28.40E+14   |        |
| Total Emergy (Y)         |                            |          |       |                  | 54.61E+14   |        |
| Renew. (%)*              |                            |          |       |                  | 48          |        |
| Outputs (O)              |                            |          |       |                  |             |        |
| 10                       | Grain                      | 2.00E+03 | kg    | <b>27.31E+11</b> | 54.61E+14   |        |
| 11                       | Straw                      | 6.00E+03 | kg    | <b>9.10E+11</b>  | 54.61E+14   |        |

#### - Pomme de Terre -

| Note                 | Item            | Quantité | Unité | Transformity | Emergy flow | Renew. |
|----------------------|-----------------|----------|-------|--------------|-------------|--------|
| Renewable Inputs (R) |                 |          |       |              |             |        |
| 1                    | Solar radiation | 6.19E+13 | J     | 1            | 0.62E+14    | 1      |
| 2                    | Rain            | 5.43E+10 | J     | 3.06E+04     | 16.62E+14   | 1      |

|                          |                            |          |    |                  |            |      |
|--------------------------|----------------------------|----------|----|------------------|------------|------|
| 3                        | Wind                       | 2.59E+10 | J  | 2.52E+03         | 0.65E+14   | 1    |
| Non-Renewable Inputs (N) |                            |          |    |                  |            |      |
| 4                        | Soil Loss                  | 2.86E+09 | J  | 1.24E+05         | 3.55E+14   | 0    |
| Materials (M)            |                            |          |    |                  |            |      |
| 5                        | Seeds                      | 6.50E+05 | g  | 2.80E+09         | 18.20E+14  | 0.20 |
| 6                        | Nitrogen                   | 2.25E+05 | g  | 4.05E+10         | 91.12E+14  | 0.05 |
| 7                        | Phosphate                  | 2.25E+05 | g  | 3.70E+10         | 83.25E+14  | 0.05 |
| 8                        | Potash                     | 2.25E+05 | g  | 2.92E+09         | 65.70E+14  | 0.05 |
| Services (S)             |                            |          |    |                  |            |      |
| 9                        | Human                      | 1.44E+09 | J  | 6.72E+05         | 9.68E+14   | 0.50 |
| 10                       | Labour<br>Animal<br>Labour | 0.45E+09 | J  | 6.94E+06         | 31.23E+14  | 0.26 |
| Total R                  |                            |          |    |                  | 17.89E+14  |      |
| Total N                  |                            |          |    |                  | 3.55E+14   |      |
| Total M                  |                            |          |    |                  | 258.27E+14 |      |
| Total S                  |                            |          |    |                  | 40.91E+14  |      |
| Total Energy (Y)         |                            |          |    |                  | 320.62E+14 |      |
| Renewable Energy         |                            |          |    |                  | 46.81E+14  |      |
| Non-Renewable<br>Energy  |                            |          |    |                  | 273.81E+14 | 15   |
| Renew. (%)               |                            |          |    |                  |            |      |
| Outputs (O)              |                            |          |    |                  |            |      |
| 11                       | Grain                      | 4.50E+04 | kg | <b>7.12E+11</b>  | 320.62E+14 |      |
| 12                       | Straw                      | 2.70E+04 | kg | <b>11.87E+11</b> | 320.62E+14 |      |

**- Patate douce -**

| Note                     | Item                       | Quantité | Unité | Transformity | Emergy<br>flow | Renew. |
|--------------------------|----------------------------|----------|-------|--------------|----------------|--------|
| Renewable Inputs (R)     |                            |          |       |              |                |        |
| 1                        | Solar                      | 6.19E+13 | J     | 1            | 0.62E+14       | 1      |
| 2                        | radiation                  | 5.43E+10 | J     | 3.06E+04     | 16.62E+14      | 1      |
| 3                        | Rain<br>Wind               | 2.59E+10 | J     | 2.52E+03     | 0.65E+14       | 1      |
| Non-Renewable Inputs (N) |                            |          |       |              |                |        |
| 4                        | Soil Loss                  | 2.86E+09 | J     | 1.24E+05     | 3.55E+14       | 0      |
| Materials (M)            |                            |          |       |              |                |        |
| 5                        | Herbicides                 | 1.00E+04 | g     | 2.48E+10     | 2.48E+14       | 0.05   |
| 6                        | Nitrogen                   | 3.00E+04 | g     | 4.05E+10     | 12.15E+14      | 0.05   |
| 7                        | Phosphate                  | 3.00E+04 | g     | 3.70E+10     | 11.10E+14      | 0.05   |
| 8                        | Potash                     | 3.00E+04 | g     | 2.92E+09     | 0.87E+14       | 0.05   |
| Services (S)             |                            |          |       |              |                |        |
| 9                        | Human                      | 3.20E+08 | J     | 6.72E+05     | 2.15E+14       | 0.50   |
| 10                       | Labour<br>Animal<br>Labour | 1.36E+08 | J     | 6.94E+06     | 9.44E+14       | 0.26   |
| Total R                  |                            |          |       |              | 17.89E+14      |        |

|                  |          |    |                 |           |
|------------------|----------|----|-----------------|-----------|
| Total N          |          |    |                 | 3.55E+14  |
| Total M          |          |    |                 | 26.60E+14 |
| Total S          |          |    |                 | 11.59E+14 |
| Renewable Emergy |          |    |                 | 22.84E+14 |
| Non-Renewable    |          |    |                 | 36.79E+14 |
| Emergy           |          |    |                 | 59.63E+14 |
| Total Emergy (Y) |          |    |                 | 38        |
| Renew. (%)       |          |    |                 |           |
| Outputs (O)      |          |    |                 |           |
| 12 Grain         | 1.00E+04 | kg | <b>5.96E+11</b> | 59.63E+14 |
| 13 Straw         | 6.00E+03 | kg | <b>9.94E+11</b> | 59.63E+14 |

On fait une moyenne entre les trois cultures pondéré par leur pourcentage de présence dans l'assolement total des 14 exploitations étudiées. On obtient un coût énergétique pour les résidus de bas-fonds de  $9.10E+11 \times 0,37 + 11.87E+11 \times 0,43 + 9.94E+11 \times 0,20 =$   
**10.46E+11 sej/kg<sup>-1</sup>.**

La renouvelabilité s'élève à  $48 \times 0,37 + 15 \times 0,43 + 38 \times 0,20 =$  **32%**.

### 2.3.3. Niébé

| Note                     | Item      | Quantité | Unité | Transformity     | Emergy flow | Renew. |
|--------------------------|-----------|----------|-------|------------------|-------------|--------|
| Renewable Inputs (R)     |           |          |       |                  |             |        |
| 1                        | Solar     | 6.19E+13 | J     | 1                | 0.62E+14    | 1      |
| 2                        | radiation | 5.43E+10 | J     | 3.06E+04         | 16.62E+14   | 1      |
| 3                        | Rain      | 2.59E+10 | J     | 2.52E+03         | 0.65E+14    | 1      |
|                          | Wind      |          |       |                  |             |        |
| Non-Renewable Inputs (N) |           |          |       |                  |             |        |
| 4                        | Soil Loss | 2.86E+09 | J     | 1.24E+05         | 3.55E+14    | 0      |
| Materials (M)            |           |          |       |                  |             |        |
| 5                        | Seeds     | 1.66E+07 | J     | 6.60E+04         | 0.01E+14    | 0.20   |
| Services (S)             |           |          |       |                  |             |        |
| 6                        | Human     | 2.18E+08 | J     | 6.72E+05         | 1.46E+14    | 0.50   |
| 7                        | Labour    | 0.40E+08 | J     | 6.94E+06         | 2.78E+14    | 0.26   |
|                          | Animal    |          |       |                  |             |        |
|                          | Labour    |          |       |                  |             |        |
| Total R                  |           |          |       |                  | 17.89E+14   |        |
| Total N                  |           |          |       |                  | 3.55E+14    |        |
| Total M                  |           |          |       |                  | 0.01E+14    |        |
| Total S                  |           |          |       |                  | 4.24E+14    |        |
| Total Emergy (Y)         |           |          |       |                  | 25.69E+14   |        |
| Renewable Emergy         |           |          |       |                  | 19.37E+14   |        |
| Non-Renewable Emergy     |           |          |       |                  | 6.32E+14    |        |
| Renew. (%)               |           |          |       |                  | 75          |        |
| Outputs (O)              |           |          |       |                  |             |        |
| 11                       | Grain     | 6.00E+03 | kg    | <b>4.28E+11</b>  | 25.69E+14   |        |
| 12                       | Straw     | 0.80E+03 | kg    | <b>32.11E+11</b> | 25.69E+14   |        |

### 2.3.4. Arachide

| Note                     | Item            | Quantité | Unité | Transformity     | Emergy flow | Renew. |
|--------------------------|-----------------|----------|-------|------------------|-------------|--------|
| Renewable Inputs (R)     |                 |          |       |                  |             |        |
| 1                        | Solar radiation | 6.19E+13 | J     | 1                | 0.62E+14    | 1      |
| 2                        | Rain            | 5.43E+10 | J     | 3.06E+04         | 16.62E+14   | 1      |
| 3                        | Wind            | 2.59E+10 | J     | 2.52E+03         | 0.65E+14    | 1      |
| Non-Renewable Inputs (N) |                 |          |       |                  |             |        |
| 4                        | Soil Loss       | 2.86E+09 | J     | 1.24E+05         | 3.55E+14    | 0      |
| Materials (M)            |                 |          |       |                  |             |        |
| 5                        | Semences        | 4.22E+08 | J     | 6.60E+04         | 0.28E+14    | 0.20   |
| 6                        | Herbicides      | 2.00E+04 | g     | 2.48E+10         | 4.48E+14    | 0.05   |
| Services (S)             |                 |          |       |                  |             |        |
| 7                        | Human Labour    | 3.79E+08 | J     | 6.72E+05         | 2.55E+14    | 0.50   |
| 8                        | Animal Labour   | 0.90E+08 | J     | 6.94E+06         | 6.25E+14    | 0.26   |
| Total R                  |                 |          |       |                  | 17.89E+14   |        |
| Total N                  |                 |          |       |                  | 3.55E+14    |        |
| Total M                  |                 |          |       |                  | 4.76E+14    |        |
| Total S                  |                 |          |       |                  | 8.80E+14    |        |
| Total Emergy (Y)         |                 |          |       |                  | 35.00E+14   |        |
| Renewable Emergy         |                 |          |       |                  | 21.13E+14   |        |
| Non-Renewable Emergy     |                 |          |       |                  | 13.87E+14   |        |
| Renew. (%)               |                 |          |       |                  | 60          |        |
| Outputs (O)              |                 |          |       |                  |             |        |
| 9                        | Grain           | 0.70E+03 | kg    | <b>50.00E+11</b> | 35.00E+14   |        |
| 10                       | Straw           | 0.80E+03 | kg    | <b>43.75E+11</b> | 35.00E+14   |        |

### 2.3.5. Coton

| Note                     | Item       | Quantité  | Unité | Transformity | Emergy flow | Renew. |
|--------------------------|------------|-----------|-------|--------------|-------------|--------|
| Renewable Inputs (R)     |            |           |       |              |             |        |
| 1                        | Solar      | 6.19E+13  | J     | 1            | 0.62E+14    | 1      |
| 2                        | radiation  | 5.43E+10  | J     | 3.06E+04     | 16.62E+14   | 1      |
| 3                        | Rain       | 2.59E+10  | J     | 2.52E+03     | 0.65E+14    | 1      |
|                          | Wind       |           |       |              |             |        |
| Non-Renewable Inputs (N) |            |           |       |              |             |        |
| 4                        | Soil Loss  | 2.86E+09  | J     | 1.24E+05     | 3.55E+14    | 0      |
| Materials (M)            |            |           |       |              |             |        |
| 5                        | Herbicides | 3.01E+04  | g     | 2.48E+10     | 7.46E+14    | 0.05   |
| 6                        | Urea       | 46.00E+04 | g     | 6.62E+09     | 30.45E+14   | 0.05   |
| 7                        | Nitrogen   | 6.00E+04  | gN    | 4.05E+10     | 24.30E+14   | 0.05   |
| 8                        | Phosphate  | 10.00E+04 | gP    | 3.70E+10     | 37.00E+14   | 0.05   |
| 9                        | Potash     | 7.50E+04  | gK    | 2.92E+09     | 2.19E+14    | 0.05   |
| Services (S)             |            |           |       |              |             |        |
| 10                       | Human      | 5.01E+08  | J     | 6.72E+05     | 3.37E+14    | 0.50   |
| 11                       | Labour     | 1.42E+08  | J     | 6.94E+06     | 9.85E+14    | 0.26   |

|                     |               |          |    |                  |            |
|---------------------|---------------|----------|----|------------------|------------|
|                     | Animal Labour |          |    |                  |            |
| Total R             |               |          |    |                  | 17.89E+14  |
| Total N             |               |          |    |                  | 3.55E+14   |
| Total M             |               |          |    |                  | 101.40E+14 |
| Total S             |               |          |    |                  | 13.22E+14  |
| Total Emery (Y)     |               |          |    |                  | 136.06E+14 |
| Renewable Emery     |               |          |    |                  | 28.20E+14  |
| Non-Renewable Emery |               |          |    |                  | 107.86E+14 |
| Renew. (%)          |               |          |    |                  | 21         |
| Outputs (O)         |               |          |    |                  |            |
| 11                  | Grain         | 2.00E+03 | Kg | <b>68.03E+11</b> | 136.06E+14 |
| 12                  | Straw         | 2.80E+03 | kg | <b>48.59E+11</b> | 136.06E+14 |

### 2.3.6. Biomasse pâturée sur les parcours

| Note                     | Item            | Quantité | Unité | Transformity    | Emery flow | Renew. |
|--------------------------|-----------------|----------|-------|-----------------|------------|--------|
| Renewable Inputs (R)     |                 |          |       |                 |            |        |
| 1                        | Solar radiation | 6.19E+13 | J     | 1               | 0.62E+14   | 1      |
| 2                        | Rain            | 5.43E+10 | J     | 3.06E+04        | 16.62E+14  | 1      |
| 3                        | Wind            | 2.59E+10 | J     | 2.52E+03        | 0.65E+14   | 1      |
| Non-Renewable Inputs (N) |                 |          |       |                 |            |        |
| 4                        | Soil Loss       | 1.01E+09 | J     | 1.24E+05        | 1.25E+14   | 0      |
| Total R                  |                 |          |       |                 | 17.89E+14  |        |
| Total N                  |                 |          |       |                 | 1.25E+14   |        |
| Total M                  |                 |          |       |                 | 0.00E+14   |        |
| Total S                  |                 |          |       |                 | 0.00E+14   |        |
| Total Emery (Y)          |                 |          |       |                 | 19.14E+14  |        |
| Renewable Emery          |                 |          |       |                 | 17.89E+14  |        |
| Non-Renewable Emery      |                 |          |       |                 | 1.25E+14   |        |
| Renew. (%)               |                 |          |       |                 |            | 93     |
| Outputs (O)              |                 |          |       |                 |            |        |
| 5                        | Biomasse        | 3E+03    | kgMS  | <b>6.38E+11</b> | 19.14E+14  |        |

## III. CONCENTRÉS

### 3.1. France Métropolitaine

#### 3.1.1. Concentrés commerciaux

Recalculer selon un mix 75 % Blé et 25% tourteaux de soja :

| Energie primaire  | %  | Transformity | Références               |
|-------------------|----|--------------|--------------------------|
| Blé               | 75 | 1.40E+09     | Castellini et al. (2006) |
| Tourteaux de Soja | 25 | 1.82E+09     | Castellini et al. (2006) |

On obtient  $0.75 \times 1.40E+09 + 0.25 \times 1.82E+09 = 1.51 E+09 \text{ sej.kg}^{-1}$ .

**3.1.2. Pulpes de betteraves**

On calcule un coût à partir de la transformité donnée par Ulgiati et al. (1994) et un cycle de vie de transformation de la betterave sucrière (Ecoinvent 2.0)

| Note                 | Item                 | Quantité | Unité | Transformity    | Emergy flow | Renew. |
|----------------------|----------------------|----------|-------|-----------------|-------------|--------|
| <b>Materials (M)</b> |                      |          |       |                 |             |        |
| 1                    | Betteraves           | 5.85E+00 | Kg    | 20.50E+11       | 119.93E+1   | 0.17   |
| 2                    | Natural Gas          | 1.78E+06 | J     | 8.06E+04        | 1           | 0.05   |
| 3                    | Electricity          | 6.87E+05 | J     | 6.21E+04        | 1.43E+11    | 0.12   |
| 4                    | Water                | 6.44E+03 | g     | 5.12E+05        | 0.43E+11    | 0.00   |
| 5                    | Chemicals            | 3.86E+00 | g     | 1.48E+10        | 0.03E+11    | 0.05   |
| 6                    | Limestone            | 1.76E+02 | g     | 1.68E+09        | 0.57E+11    | 0.05   |
| 7                    | Coal                 | 1.53E+04 | J     | 6.69E+04        | 2.96E+11    | 0.05   |
|                      |                      |          |       |                 | 0.01E+11    |        |
| Total Emergy (Y)     |                      |          |       |                 | 125.36E+1   |        |
| Renewable Emergy     |                      |          |       |                 | 1           |        |
| Non-Renewable Emergy |                      |          |       |                 | 20.68E+11   |        |
| Renew. (%)           |                      |          |       |                 | 104.68E+1   |        |
|                      |                      |          |       |                 | 1           |        |
|                      |                      |          |       |                 | 16          |        |
| <b>Outputs (O)</b>   |                      |          |       |                 |             |        |
| 8                    | Sucre                | 1.00E+00 | kg    | <b>1.25E+13</b> | 125.36E+1   |        |
| 9                    | Mélasses             | 0.22E+00 | kg    | <b>5.70E+13</b> | 1           |        |
| 10                   | Pulpes de betteraves | 1.30E+00 | kg    | <b>9.64E+12</b> | 125.36E+1   |        |
|                      |                      |          |       |                 | 1           |        |
|                      |                      |          |       |                 | 125.36E+1   |        |
|                      |                      |          |       |                 | 1           |        |

**3.1.3. Luzerne déshydratée**

On part sur une transformité du foin de Luzerne de  $3.03E+11 \text{ sej.kg}^{-1}$  (Castellini et al., 1996), un coût de  $1.06E+07 \text{ J/kg}$  de luzerne déshydratée (US Department of Energy, 1977) et un besoin de 1.18 kg de foin de luzerne (85%MS) pour produire 1 kg de luzerne déshydratée (100%MS).

| Note                 | Item                | Quantité | Unité | Transformity    | Emergy flow | Renew. |
|----------------------|---------------------|----------|-------|-----------------|-------------|--------|
| <b>Materials (M)</b> |                     |          |       |                 |             |        |
| 1                    | Foin                | 5.85E+00 | Kg    | 3.03E+11        | 17.73E+11   | 0.17   |
| 2                    | Natural Gas         | 1.06E+07 | J     | 8.06E+04        | 8.54E+11    | 0.05   |
| Total Emergy (Y)     |                     |          |       |                 | 26.27E+11   |        |
| Renewable Emergy     |                     |          |       |                 | 3.44E+11    |        |
| Non-Renewable Emergy |                     |          |       |                 | 22.83E+11   |        |
| Renew. (%)           |                     |          |       |                 | 13          |        |
| <b>Outputs (O)</b>   |                     |          |       |                 |             |        |
| 3                    | Luzerne déshydratée | 1.00E+00 | kg    | <b>2.63E+12</b> | 26.27E+11   |        |

**3.1.4. Poudre de Lait**

On se base sur une transformité du lait calculé sans la poudre de lait puis un coût énergétique de transformation du lait donné par Vigne (2007) :



| Note                 | Item           | Quantité  | Unité | Transformity    | Emergy flow | Renew. |
|----------------------|----------------|-----------|-------|-----------------|-------------|--------|
| Materials (M)        |                |           |       |                 |             |        |
| 1                    | Lait           | 11.20E+00 | L     | 2.00E+12        | 22.40E+12   | 0.32   |
| 2                    | Fuel           | 11.89E+06 | J     | 1.30E+05        | 1.55E+12    | 0.05   |
| Total Emergy (Y)     |                |           |       |                 | 23.95E+12   |        |
| Renewable Emergy     |                |           |       |                 | 7.25E+12    |        |
| Non-Renewable Emergy |                |           |       |                 | 16.70E+12   |        |
| Renew. (%)           |                |           |       |                 | 17          |        |
| Outputs (O)          |                |           |       |                 |             |        |
| 3                    | Poudre de Lait | 1.00E+00  | kg    | <b>2.40E+13</b> | 23.95E+12   |        |

### 3.2. Ile de la Réunion

#### 3.2.1. Concentrés commerciaux

Recalculer à partir des compositions données par les provendiers et des transformités suivantes auxquelles on a rajouté un coût de transport pour ceux qui ont été importés de 2.68KJ/g de fuel soit un coût supplémentaire de 3.48E+08 sej.g<sup>-1</sup>.

| Matières premières | Transformité (en seJ.g-1) | Renew. | refs                     | Transformité (en seJ.g-1) | Renew. |
|--------------------|---------------------------|--------|--------------------------|---------------------------|--------|
| Maïs               | 1.40E+09                  | 0.22   | Castellini et al. (2006) | 1.75E+09                  | 0.22   |
| Son de Blé         | 3.02E+09                  | 0.42   | Castellini et al. (2006) | 3.37E+09                  | 0.42   |
| Blé                | 4.21E+08                  | 0.22   | Castellini et al. (2006) | 7.56E+08                  | 0.21   |
| Tx Soja            | 2.98E+09                  | 0.10   | Cavalett et al. (2006)   | 3.33E+09                  | 0.10   |
| Tx Colza           | 2.98E+09                  | 0.10   | Cavalett et al. (2006)   | 3.33E+09                  | 0.10   |
| Mélasses           | 9.73E+09                  | 0.13   | Own calculation          | -                         | -      |
| Tx Tournesol       | 2.98 E+09                 | 0.10   | Cavalett et al. (2006)   | 3.33E+09                  | 0.10   |
| Orge               | 4.21E+08                  | 0.22   | Castellini et al. (2006) | 7.56E+08                  | 0.21   |
| Son de Riz         | 3.02E+09                  | 0.42   | Castellini et al. (2006) | 3.37E+09                  | 0.42   |
| Huile de Soja      | 0.65E+08                  | 0.10   | Castellini et al. (2006) | 4.00E+08                  | 0.08   |
| Coques de Soja     | 2.98E+09                  | 0.10   | Cavalett et al. (2006)   | 3.33E+09                  | 0.10   |

<sup>a</sup> sej.J<sup>-1</sup>

#### 3.2.2. Mélasses

Calculer selon le processus de transformation du jus de canne en sucre :

| Note                 | Item         | Quantité | Unité | Transformity | Emergy flow | Renew. |
|----------------------|--------------|----------|-------|--------------|-------------|--------|
| Materials (M)        |              |          |       |              |             |        |
| 1                    | Jus de Canne | 0.14E+03 | Kg    | 20.50E+11    | 2.87E+14    | 0.27   |
| 2                    | Fuel         | 0.67E+05 | J     | 1.30E+05     | 0.00E+14    | 0.05   |
| Total Emergy (Y)     |              |          |       |              | 2.87E+14    |        |
| Renewable Emergy     |              |          |       |              | 0.69E+14    |        |
| Non-Renewable Emergy |              |          |       |              | 2.18E+14    |        |
| Renew. (%)           |              |          |       |              | 27          |        |

| Outputs (O) |         |          |    |                 |          |  |
|-------------|---------|----------|----|-----------------|----------|--|
| 1           | Sucre   | 0.11E+03 | kg | <b>2.61E+12</b> | 2.87E+14 |  |
| 2           | Mélasse | 0.03E+03 | kg | <b>9.57E+12</b> | 2.87E+14 |  |

### 3.2.3. Poudre de Lait

On se base sur une transformité du lait calculé sans la poudre de lait puis un coût énergétique de transformation du lait donné par Vigne (2007) :

| Note                 | Item           | Quantité  | Unité | Transformity    | Emergy flow | Renew. |
|----------------------|----------------|-----------|-------|-----------------|-------------|--------|
| Materials (M)        |                |           |       |                 |             |        |
| 1                    | Lait           | 11.20E+00 | L     | 4.70E+12        | 52.64E+12   | 0.32   |
| 2                    | Fuel           | 11.89E+06 | J     | 1.30E+05        | 1.55E+12    | 0.05   |
| Total Emergy (Y)     |                |           |       |                 | 54.19E+12   |        |
| Renewable Emergy     |                |           |       |                 | 10.61E+12   |        |
| Non-Renewable Emergy |                |           |       |                 | 43.58E+12   |        |
| Renew. (%)           |                |           |       |                 | 11          |        |
| Outputs (O)          |                |           |       |                 |             |        |
| 3                    | Poudre de Lait | 1.00E+00  | kg    | <b>5.42E+13</b> | 54.19E+12   |        |

## 3.3. Mali

### 3.3.1. Sous-produit du coton

La graine entière se divise en 40% de fibres, 24% de coques et 29.5 % de graine décoquée et 6.5 % de déchets :

| Note                 | Item            | Quantité | Unité | Transformity     | Emergy flow | Renew. |
|----------------------|-----------------|----------|-------|------------------|-------------|--------|
| Materials (M)        |                 |          |       |                  |             |        |
| 1                    | Gross grain of  | 1.00E+00 | kg    | 68.03E+11        | 68.03E+11   | 0.21   |
| 2                    | cotton Fuel     | 0.67E+05 | J     | 1.30E+05         | 0.09E+11    | 0.05   |
| Total R              |                 |          |       |                  | 0           |        |
| Total N              |                 |          |       |                  | 0           |        |
| Total M              |                 |          |       |                  | 68.12E+11   |        |
| Total S              |                 |          |       |                  | 0           |        |
| Total Emergy (Y)     |                 |          |       |                  | 68.12E+11   |        |
| Renewable Emergy     |                 |          |       |                  | 14.29E+11   |        |
| Non-Renewable Emergy |                 |          |       |                  | 53.83E+11   |        |
| Renew. (%)           |                 |          |       |                  | 21          |        |
| Outputs (O)          |                 |          |       |                  |             |        |
| 3                    | Fibres          | 0.40E+00 | kg    | <b>17.03E+12</b> | 68.12E+11   |        |
| 4                    | Graine décoquée | 0.24E+00 | kg    | <b>28.38E+12</b> | 68.12E+11   |        |
| 5                    | Coques          | 0.30E+00 | kg    | <b>22.71E+12</b> | 68.12E+11   |        |

La graine décoquée se divise ensuite en 31% d'huile et 69% de tourteaux :

| Note                 | Item            | Quantité | Unité | Transformity    | Emergy flow | Renew. |
|----------------------|-----------------|----------|-------|-----------------|-------------|--------|
| Materials (M)        |                 |          |       |                 |             |        |
| 1                    | Graine décoquée | 1.00E+00 | kg    | 28.38E+12       | 28.38E+12   | 0.21   |
| 2                    | Fuel            | 0.67E+05 | J     | 1.30E+05        | 0.01E+12    | 0.05   |
| Total R              |                 |          |       |                 | 0           |        |
| Total N              |                 |          |       |                 | 0           |        |
| Total M              |                 |          |       |                 | 28.39E+12   |        |
| Total S              |                 |          |       |                 | 0           |        |
| Total Emergy (Y)     |                 |          |       |                 | 28.39E+12   |        |
| Renewable Emergy     |                 |          |       |                 | 5.96E+12    |        |
| Non-Renewable Emergy |                 |          |       |                 | 22.43E+12   |        |
| Renew. (%)           |                 |          |       |                 | 21          |        |
| Outputs (O)          |                 |          |       |                 |             |        |
| 3                    | Huile           | 0.31E+00 | kg    | <b>9.16E+13</b> | 28.39E+12   |        |
| 4                    | Tourteaux       | 0.69E+00 | kg    | <b>4.11E+13</b> | 28.39E+12   |        |

### 3.3.2. Son de céréales

On va se baser sur la transformité du grain de maïs et un rendement au concassage de 61% grain / 39% son (Ndjouenkeu et al., 1989) et des valeurs énergétiques de 5165 kcal/kg brut pour la graine entière, de 5132 kcal/kg brut pour le son de maïs et de 5186 pour le grain décortiqué. On se base sur un rendement de pillage de 1.5 kg/h (Dendy and Dobraszczuk, 2000).

| Note                 | Item             | Quantité | Unité | Transformity    | Emergy flow | Renew. |
|----------------------|------------------|----------|-------|-----------------|-------------|--------|
| Materials (M)        |                  |          |       |                 |             |        |
| 1                    | Grain de maïs    | 1.00E+00 | kg    | 17.88E+11       | 17.88E+11   | 0.41   |
| Services (S)         |                  |          |       |                 |             |        |
| 2                    | Human Labour     | 5.69E+05 | J     | 6.72E+05        | 3.82E+11    | 0.50   |
| Total R              |                  |          |       |                 | 0           |        |
| Total N              |                  |          |       |                 | 0           |        |
| Total M              |                  |          |       |                 | 17.88E+11   |        |
| Total S              |                  |          |       |                 | 3.82E+11    |        |
| Total Emergy (Y)     |                  |          |       |                 | 21.70E+11   |        |
| Renewable Emergy     |                  |          |       |                 | 9.24E+11    |        |
| Non-Renewable Emergy |                  |          |       |                 | 12.46E+11   |        |
| Renew. (%)           |                  |          |       |                 | 43          |        |
| Outputs (O)          |                  |          |       |                 |             |        |
| 3                    | Grain décortiqué | 0.61E+00 | kg    | <b>3.56E+12</b> | 21.70E+11   |        |
| 4                    | Son              | 0.39E+00 | kg    | <b>5.56E+12</b> | 21.70E+11   |        |

## IV. ENGRAIS

### 4.1. Ile de la Réunion

#### 4.1.1. Engrais et Phytosanitaires

On se base sur des transformités de bases auxquelles on rajoute un coût de transport de 2.6KJ/g de fuel soit un coût supplémentaire de 3.38E+08 sej.g<sup>-1</sup>.

| Intrants     | Transformité originale (sej.g <sup>-1</sup> ) | Références             | Transformité recalculé (sej.g <sup>-1</sup> ) |
|--------------|---|------------------------|---|
| Nitrogen     | 4.05E+10                                      | Cavalett et al. (2006) | 4.08E+10                                      |
| Phosphate    | 3.70E+10                                      | Cavalett et al. (2006) | 3.73E+10                                      |
| Potash       | 2.92E+09                                      | Cavalett et al. (2006) | 3.26E+09                                      |
| Urea         | 6.62E+09                                      | Cuarta and Rydberg     | 6.96E+09                                      |
| Herbicides   | 2.48E+10                                      | (2006)                 | 2.51E+10                                      |
| Fungicides   | 2.48E+10                                      | Cavalett and Ortega    | 2.51E+10                                      |
| Insecticides | 2.48E+10                                      | (2009)                 | 2.51E+10                                      |
|              |   | Cavalett and Ortega    |   |
|              |   | (2009)                 |   |
|              |   | Cavalett and Ortega    |   |
|              |   | (2009)                 |   |

#### V. FRAIS VETERINAIRES

On se base sur les transformités données par la base nationale sahel pour les services (Energy Money Ratio) en 2000 et un taux de change moyen entre le \$ et les monnaies locales

| Territoires | Transformité originale | Taux de change en 2000 | Transformité finale |
|-------------|------------------------|------------------------|---------------------|
| Mali        | 3.79E+13 sej/\$        | 500 FCFA/\$            | 7.58 E+10 sej/FCFA  |
| La Réunion  | 2.92E+12 sej/\$        | 1.01 €/\$              | 2.89 E+12 sej/€     |
| Grand Ouest | 2.92E+12 sej/\$        | 1.01 €/\$              | 2.89 E+12 sej/€     |

#### VI. ANIMAUX

##### 6.1. Ile de la Réunion

Les animaux sont des génisses. On se base sur le bilan énergétique réalisé sur la ferme à génisse de la SicaLait.

| Note                     | Item            | Quantité | Unité | Transformity | Emergy flow | Renew. |
|--------------------------|-----------------|----------|-------|--------------|-------------|--------|
| Renewable Inputs (R)     |                 |          |       |              |             |        |
| 1                        | Solar radiation | 5.11E+15 | J     | 1            | 0.53E+16    | 1      |
| 2                        | Rain            | 1.42E+13 | J     | 3.06E+04     | 43.45E+16   | 1      |
| 3                        | Wind            | 2.48E+11 | J     | 2.52E+03     | 0.06E+16    | 1      |
| Non-Renewable Inputs (N) |                 |          |       |              |             |        |
| 4                        | Soil Loss       | 2.40E+10 | J     | 1.24E+05     | 29.76E+16   | 0      |

|                      |                       |          |    |                 |            |      |
|----------------------|-----------------------|----------|----|-----------------|------------|------|
| 5                    | Water                 | 6.94E+09 | g  | 5.12E+05        | 3.55E+16   | 0    |
| Materials (M)        |                       |          |    |                 |            |      |
| 6                    | Fuel                  | 7.84E+11 | J  | 1.30E+05        | 10.19E+16  | 0.05 |
| 7                    | Electricity           | 9.04E+10 | J  | 1.48E+05        | 1.34E+16   | 0.26 |
| 8                    | Chemicals             | 9.28E+00 | kg | 2.48E+13        | 0.02E+16   | 0.05 |
| 9                    | M49 mash              | 8.12E+08 | g  | 2.78E+09        | 225.74E+16 | 0.17 |
| 10                   | B20                   | 4.27E+07 | g  | 2.44E+09        | 10.42E+16  | 0.19 |
| 11                   | Milk Powder           | 1.36E+04 | kg | 5.42E+13        | 73.71E+16  | 0.11 |
| 12                   | Bagasse               | 2.35E+05 | kg | 3.34E+11        | 7.85E+16   | 0.27 |
| 13                   | Cane Straw            | 3.25E+05 | kg | 2.16E+12        | 70.20E+16  | 0.27 |
| 14                   | Hay                   | 5.43E+04 | kg | 1.34E+12        | 7.28E+16   | 0.16 |
| 15                   | Plastics              | 1.20E+05 | g  | 3.20E+09        | 0.04E+16   | 0.05 |
| 16                   | Building – Concrete   | 3.01E+06 | g  | 1.54E+09        | 0.46E+16   | 0.05 |
| 17                   | Building - Steel      | 4.93E+04 | g  | 1.13E+10        | 0.06E+16   | 0.05 |
| 18                   | Material depreciation | 2.81E+06 | g  | 1.13E+10        | 3.18E+16   | 0.05 |
| Services (S)         |                       |          |    |                 |            |      |
| 19                   | Vet costs             | 7.05E+04 | €  | 2.89E+12        | 20.38E+16  | 0.05 |
| 20                   | Travail humain        | 3.05E+10 | J  | 3.36E+06        | 22.51E+16  | 0.36 |
| Total R              |                       |          |    |                 | 44.04E+16  |      |
| Total N              |                       |          |    |                 | 33.31E+16  |      |
| Total M              |                       |          |    |                 | 410.49E+16 |      |
| Total S              |                       |          |    |                 | 42.89E+16  |      |
| Total Energy (Y)     |                       |          |    |                 | 530.73E+16 |      |
| Renewable Emergy     |                       |          |    |                 | 124.91E+16 |      |
| Non-Renewable Emergy |                       |          |    |                 | 405.82E+16 |      |
| Renew. (%)           |                       |          |    |                 | 24         |      |
| Outputs (O)          |                       |          |    |                 |            |      |
| 19                   | Fourrages             | 1.82E+05 | kg | <b>2.92E+13</b> | 530.73E+16 |      |

## 6.2. Mali

On a calculé une transformité moyenne pour les 14 troupeaux. On se base sur la consommation alimentaire totale des 14 troupeaux et le nombre d'animaux totaux multiplié par le poids moyen des différentes catégories soit :

Transformité animaux (sej/kg) = transformité totale des aliments consommés (sej) / Poids total du troupeau (kg)

On obtient une transformité de **3.18E+13 sej.kg<sup>-1</sup>** et une renouvelabilité de **51%**.

## VII. BÂTIMENTS

### 7.1. Bâtiments en Banco

Les bâtiments en banco sont composés de terre, de paille et d'eau.

On va d'abord calculer une transformité pour la terre. Pour cela, on se base sur la transformité de l'érosion de **1.24E+05 sej.J<sup>-1</sup>**, et une teneur en MO de la terre utilisée de 1.66% (teneur en MO de la terre rouge utilisé pour la construction - Blanchard, 2010).

Pour la paille on se base sur une moyenne de la transformité des résidus de céréales soit **1.80E+09 sej.g<sup>-1</sup>**.

Pour l'eau on se base sur la transformité de l'eau du sol donné par Brown and Arding (1991) de  $2.55E+05 \text{ sej.J}^{-1}$ .

Pour la durée du chantier, on considère 20 personnes (le « village ») travaillant 14 h par jour (durée moyenne d'une journée) pendant 3 jours (Déverin, Geo-phile.net) et un coût de dépense énergétique 1 MJ/h. On considère ensuite que 4.5 t de banco sont manipulés (25 briques de 15 kg par rangées sur 12 rangées).

On se base ensuite sur une composition assez aléatoire de 75% de terre, 20% de paille et 5% d'eau soit :

| Note                 | Item            | Quantité | Unité | Transformity    | Emergy flow | Renew. |
|----------------------|-----------------|----------|-------|-----------------|-------------|--------|
| Materials (M)        |                 |          |       |                 |             |        |
| 1                    | Terre           | 2.81E+05 | J     | 1.24E+05        | 3.48E+10    | 0.00   |
| 2                    | Paille          | 2.00E+02 | g     | 1.80E+09        | 36.00E+10   | 0.18   |
| 3                    | Eau             | 2.47E+02 | J     | 2.55E+05        | 0.01E+10    | 0.00   |
| Services (S)         |                 |          |       |                 |             |        |
| 4                    | Human Labour    | 1.87E+05 | J     | 6.72E+05        | 12.57E+10   | 0.50   |
| Total Emergy (Y)     |                 |          |       |                 | 52.06E+10   |        |
| Renewable Emergy     |                 |          |       |                 | 12.77E+10   |        |
| Non-Renewable Emergy |                 |          |       |                 | 39.30E+10   |        |
| Renew. (%)           |                 |          |       |                 | 25          |        |
| Outputs (O)          |                 |          |       |                 |             |        |
| 5                    | Bâtiments banco | 1.00E+03 | g     | <b>5.21E+08</b> | 52.06E+10   |        |

## VIII. TRACTION ANIMALE

On va se baser sur un bilan énergétique pour une journée de travail de labour d'un bœuf de labour. On considère qu'une journée de labour comporte 6h de travail entraînant une dépense énergétique de  $1.5 \text{ MJ/h} \times 6 = 9.00E+06 \text{ J}$ .

On considère une alimentation quotidienne d'un bœuf de labour de 6.5 kgMS sur parcours naturels + une supplémentation de 1.5 kg de tourteaux de coton

| Note                 | Item          | Quantité | Unité | Transformity    | Emergy flow | Renew. |
|----------------------|---------------|----------|-------|-----------------|-------------|--------|
| Materials (M)        |               |          |       |                 |             |        |
| 1                    | Pasture       | 6.50E+00 | kgMS  | 6.38E+11        | 4.15E+12    | 0.93   |
| 2                    | Cotton meal   | 1.50E+00 | kg    | 3.89E+13        | 58.35E+12   | 0.21   |
| Total Emergy (Y)     |               |          |       |                 | 62.50E+12   |        |
| Renewable Emergy     |               |          |       |                 | 16.11E+12   |        |
| Non-Renewable Emergy |               |          |       |                 | 46.39E+12   |        |
| Renew. (%)           |               |          |       |                 | 26          |        |
| Outputs (O)          |               |          |       |                 |             |        |
| 5                    | Animal labour | 9.00E+06 | J     | <b>6.94E+06</b> | 62.50E+12   |        |

## IX. EFFLUENTS

Pour tous les territoires on va faire une moyenne des différentes exploitations du ratio entre la transformité totale lié à l'alimentation et les effluents produits

On obtient :

- Une transformité de **6.51E+11 sej.kg** et une renouvelabilité de **23%** pour le Grand-Ouest
- Une transformité de **1.10E+12 sej.kg** et une renouvelabilité de **19%** pour la Réunion
- Une transformité de **9.61E+12 sej.kgMS<sup>-1</sup>** et une renouvelabilité de **51%** pour le Mali

|   |
|---|
| <b>FACTEURS DE RENOUVELABILITE UTILISES DANS<br/>L'ANALYSE EMERGY</b> |
|---|

| <b>Flux d'emergy</b>                           | <b>ML</b> | <b>Refs</b> | <b>RI</b> | <b>Refs</b> | <b>PC / BR</b> | <b>Refs</b> |
|--|-----------|-------------|-----------|-------------|----------------|-------------|
| <i>Ressources naturelles renouvelables</i>     |           |             |           |             |                |             |
| Rayonnement Solaire                            | 1,00      | [1]         | 1,00      | [1]         | 1,00           | [1]         |
| Vent   | 1,00      | [1]         | 1,00      | [1]         | 1,00           | [1]         |
| Rain   | 1,00      | [1]         | 1,00      | [1]         | 1,00           | [1]         |
| <i>Ressources naturelles non-renouvelables</i> |           |             |           |             |                |             |
| Erosion  | 0,00      | [1]         | 0,00      | [1]         | 0,00           | [1]         |
| Eau du sol                                     | 0,00      | [1]         | 0,00      | [1]         | 0,00           | [1]         |
| <i>Materials</i>                               |           |             |           |             |                |             |
| Carburants                                     | 0,05      | [3]         | 0,05      | [3]         | 0,05           | [3]         |
| Électricité                                    | 0,58      | [2]         | 0,26      | [2]         | 0,11           | [2]         |
| Fertilisation N                                | 0,05      | [3]         | 0,05      | [3]         | 0,05           | [3]         |
| Fertilisation P                                | 0,05      | [3]         | 0,05      | [3]         | 0,05           | [3]         |
| Fertilisation K                                | 0,05      | [3]         | 0,05      | [3]         | 0,05           | [3]         |
| Effluents                                      | 0,51      | [2]         | 0,19      | [2]         | 0,23           | [2]         |
| Phyosanitaires                                 | 0,05      | [3]         | 0,05      | [3]         | 0,05           | [3]         |
| Semences de Coton                              | 0,21      | [2]         | -         |             | -              |             |
| Semences de Niébé                              | 0,75      | [2]         | -         |             | -              |             |
| Semences de Riz                                | 0,48      | [2]         | -         |             | -              |             |
| Semences de Pomme de Terre                     | 0,15      | [2]         | -         |             | -              |             |
| Semences de Patate Douce                       | 0,38      | [2]         | -         |             | -              |             |
| Semences de Maïs                               | 0,41      | [2]         | 0,20      | [4]         | 0,20           | [4]         |
| Semences de Mil                                | 0,76      | [2]         | -         |             | -              |             |
| Semences de Blé                                | -         |             | 0,20      | [4]         | 0,20           | [4]         |
| Semences Prairies                              | -         |             | 0,20      | [4]         | 0,20           | [4]         |
| Coques de coton                                | 0,21      | [2]         | -         |             | -              |             |
| Graine de coton                                | 0,21      | [2]         | -         |             | -              |             |
| Tourteaux de coton                             | 0,21      | [2]         | -         |             | -              |             |
| Tourteaux de Soja                              | -         |             | -         |             | 0,17           | [3]         |
| Concentrés commerciaux                         | -         |             | 0,19      | [2]         | 0,17           | [3]         |
| Pulpes de betteraves                           | -         |             | -         |             | 0,16           | [2]         |
| Son de céréales                                | 0,43      | [2]         | -         |             | -              |             |
| Bagasse  | -         |             | 0,27      | [2]         | -              |             |
| Luzerne déshydratée                            | -         |             | -         |             | 0,13           | [2]         |
| Ensilage d'Herbe                               | -         |             | 0,16      | [2]         | -              |             |
| Ensilage de Maïs                               | -         |             | -         |             | 0,23           | [2]         |
| Foin   | -         |             | 0,16      | [2]         | 0,64           | [5]         |
| Paille de Canne                                | -         |             | 0,23      | [2]         | -              |             |
| Paille de Blé                                  | -         |             | -         |             | 0,18           | [2]         |
| Paille de Riz                                  | 0,48      | [2]         | -         |             | -              |             |
| Fanes de Niébé                                 | 0,60      | [2]         | -         |             | -              |             |
| Résidus de céréales                            | 0,55      | [2]         | -         |             | -              |             |
| Résidus de bas-fonds                           | 0,32      | [2]         | -         |             | -              |             |
| Biomasse de Parcours                           | 0,93      | [2]         | -         |             | -              |             |
| Mélasse  | -         |             | 0,27      | [2]         | -              |             |
| Poudre de Lait                                 | -         |             | 0,11      | [2]         | 0,17           | [2]         |
| Minéraux                                       | 0,05      | [2]         | 0,05      | [2]         | 0,05           | [2]         |
| Plastiques                                     | 0,05      | [2]         | 0,05      | [2]         | 0,05           | [2]         |
| Dépréciation du matériel                       | 0,05      | [3]         | 0,05      | [3]         | 0,05           | [3]         |
| Bâtiments - Banco                              | 0,25      | [2]         | -         |             | -              |             |
| Bâtiment - Bois                                | 0,25      | [2]         | -         |             | -              |             |
| Bâtiments - Béton                              | 0,05      | [3]         | 0,05      | [3]         | 0,05           | [3]         |
| Bâtiments - Acier                              | 0,05      | [3]         | 0,05      | [3]         | 0,05           | [3]         |
| Animaux  | 0,51      | [2]         | 0,24      | [2]         | -              |             |
| <i>Services</i>                                |           |             |           |             |                |             |
| Frais vétérinaires                             | 0,05      | [2]         | 0,05      | [2]         | 0,05           | [2]         |
| Travail Humain                                 | 0,27      | [3]         | 0,27      | [6]         | 0,27           | [6]         |
| Travail Animal                                 | 0,26      | [2]         | -         |             | -              |             |



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**DETAILS DES CALCULS REALISES DANS LE CADRE DE  
L'APPLICATION DE LA METHODE EMERGY SUR LES QUATRE  
TERRITOIRES**

**A. CALCUL A L'ECHELLE GLOBALE DE L'EXPLOITATION**

**1. Sunlight**

Emergy (seJ) = 10 000 m<sup>2</sup>.ha<sup>-1</sup> x solar radiation (J.m<sup>2</sup>.yr<sup>-1</sup>) x (1 - 0.20 (albedo)) x Transformity (seJ.J<sup>-1</sup>)<sup>1</sup>

With:

- Solar radiation: 7.13E+09 J.m<sup>2</sup>.yr<sup>-1</sup> for SM; 6.00E+09 J.m<sup>2</sup>.yr<sup>-1</sup> for RI, 4.63E+09 J.m<sup>2</sup>.yr<sup>-1</sup> for PC and 4.00E+09 J.m<sup>2</sup>.yr<sup>-1</sup> for BR

**2. Wind**

Emergy (seJ) = 10 000 m<sup>2</sup>.ha<sup>-1</sup> x air density (1.23 kg.m<sup>-3</sup>) x drag coefficient (0.001 na) x (surface windspeed (m.s<sup>-1</sup>) x 0.6)<sup>3</sup> x 31 536 000 s.an<sup>-1</sup> x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup>

With:

- Surface windspeed: 4.0 m.s<sup>-1</sup> for SM, 3.0 m.s<sup>-1</sup> for RI, 2.5 m.s<sup>-1</sup> for PC and 2.2 m.s<sup>-1</sup> for BR

**3. Rain**

Emergy (seJ) = rain (m.m<sup>2</sup>.yr<sup>-1</sup>) x density water (1000 kg.m<sup>-3</sup>) x Gibbs free energy of water ( 4940 J.kg<sup>-1</sup>) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup>

With:

- rain: 1.02 m.m<sup>2</sup>.yr<sup>-1</sup> for SM, 2.50 m.m<sup>2</sup>.yr<sup>-1</sup> for RI, 0.90 m.m<sup>2</sup>.yr<sup>-1</sup> for PC and 0.95 m.m<sup>2</sup>.yr<sup>-1</sup> for BR

**4. Erosion**

Emergy (seJ) = average soil loss (g.ha<sup>-1</sup>.yr<sup>-1</sup>) x average organic content (%) x energy content of organic matter (22,604 J.g<sup>-1</sup>) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup>

With:

- Average soil loss: 6.80E+06 g.ha<sup>-1</sup>.yr<sup>-1</sup> for SM, 2.20E+07 g.ha<sup>-1</sup>.yr<sup>-1</sup> for RI, 5.00E+05 g.ha<sup>-1</sup>.yr<sup>-1</sup> for PC and 5.00E+05 g.ha<sup>-1</sup>.yr<sup>-1</sup> for BR.

- Average organic content: 1.0% for SM, 4.5% for RI, 4.0% for PC and 4.0% for BR

**5. Water**

Emergy (seJ) = Quantity (J or g) x Transformity (seJ.J<sup>-1</sup> or seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 1.92E+08 J for SM, 1.28E+09 g for RI, 3.29E+10 g for PC, 4.93E+09 g for BR.

- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

**6. Fuel**

Emergy (seJ) = Quantity (J) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 5.12E+08 J for SM, 5.52E+11 J for RI, 8.56E+11 J for PC, 4.48E+11 J for BR.

- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

**7. Electricity**

Emergy (seJ) = Quantity (J) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 0.00E+00 J for SM, 5.49E+10 J for RI, 1.49E+12 J for PC, 8.85E+11 J for BR.

- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

<sup>1</sup> Transformities are given in Appendix B

### **8. N Fertiliser**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.kg<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 2.79E+02 kg for SM, 1.87E+03 kg for RI, 1.45E+04 kg for PC, 4.01E+03 kg for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### **9. P Fertiliser**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.kg<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 2.57E+02 kg for SM, 6.33E+02 kg for RI, 2.60E+03 kg for PC, 3.58E+02 kg for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### **10. K Fertiliser**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.kg<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 1.60E+02 kg for SM, 6.28E+02 kg for RI, 1.68E+03 kg for PC, 2.97E+02 kg for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### **11. Manure**

Emergy (seJ) = Quantity (kgDM) x Transformity (seJ.kgDM<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 2.69E+03 kgDM for SM, 8.33E+03 kgDM for RI, 2.10E+05 kgDM for PC, 1.68E+05 kgDM for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### **12. Chemicals**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 1.64E+01 kg for SM, 9.08E+00 kg for RI, 9.59E+01 kg for PC, 3.11E+01 kg for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### **13. Plastics**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 0.00E+00 kg for SM, 4.25E+02 kg for RI, 5.59E+03 kg for PC, 2.67E+03 kg for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### **14. Feed concentrates**

Emergy (seJ) = Quantity (g or kg) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity of cotton hull: 2.17E+02 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR
- Quantity of cottonseed: 1.53E+03 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR
- Quantity of cottonseed meal: 4.50E+02 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR
- Quantity of cereal bran: 4.47E+03 kg for SM, 0.00E+00 kg for RI, 0.00E+00 for PC and 0.00E+00 kg for BR
- Quantity of soybean meal: 0.00E+00 kg for SM, 0.00E+00 kg for RI, 7.28E+04 kg for PC and 3.90E+04 kg for BR
- Quantity of beet pulp: 0.00E+00 kg for SM, 0.00E+00 kg for RI, 2.42E+03 kg for PC and 1.03E+03 kg for BR
- Commercial feed concentrates: 0.00E+00 kg for SM, 2.62E+05 kg for RI, 8.30E+04 kg for PC, 5.03E+04 kg for BR
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### 15. Milk powder

Emergy (seJ) = Quantity (kg) x Transformity (seJ.kg<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 0.00E+00 kg for SM, 3.88E+02 kg for RI, 7.95E+02 kg for PC, 1.34E+02 kg for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### 16. External pasture

Emergy (seJ) = Quantity (kg) x Transformity (seJ.kg<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity of crops residues from cereal crops: 2.98E+03 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.
- Quantity of rcrop residues from shallow crops: 4.96E+03 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### 17. Forages

Emergy (seJ) = Quantity (kg) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity of Rice straw: 6.43E+01 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.
- Quantity of Groundnut haulms: 2.21E+01 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.
- Quantity of Sugarcane bagasse: 0.00E+00 kg for SM, 7.71E+03 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.
- Quantity of Silage: 0.00E+00 kg for SM, 1.09E+04 kg for RI, 1.06E+04 kg for PC, 4.62E+03 kg for BR.
- Quantity of Sugarcane straw: 0.00E+00 kg for SM, 3.86E+04 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.
- Quantity of Wheat straw: 0.00E+00 kg for SM, 0.00E+00 kg for RI, 3.90E+04 kg for PC, 2.54E+04 kg for BR.
- Quantity of Hay: 0.00E+00 kg for SM, 5.29E+03 kg for RI, 0.00E+00 kg for PC, 3.08E+06 kg for BR.

### 18. Animals

Emergy (seJ) = Quantity (kg) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 1.43E+02 kg for SM, 2.92E+03 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### 19. Minerals

Emergy (seJ) = Quantity (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 3.00E+05 g for SM, 2.20E+04 g for RI, 9.49E+04 g for PC, 1.31E+05 g for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### 20. Seeds

Emergy (seJ) = Quantity (kg) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity of Coton seeds: 4.93E+01 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR
- Quantity of Cowpea seeds: 1.17E+01 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR
- Quantity of Rice seeds: 5.36E+00 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR

- Quantity of Potato seeds: 1.57E+02 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR
- Quantity of Sweet potato seeds: 2.39E+02 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR
- Quantity of Corn seeds: 1.79E+01 kg for SM, 0.00E+00 kg for RI, 1.29E+10 J for PC and 6.73E+10 J for BR.
- Quantity of Millet seeds: 3.21E+00kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR
- Quantity of Wheat seeds: 0.00E+00 J for SM, 0.00E+00 J for RI, 7.15E+10 J for PC and 2.93E+10 J for BR.
- Quantity of Grassland seeds (en J): 0.00E+00 J for SM, 2.06E+10 J for RI, 1.95E+10 J for PC and 3.48E+10 J for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### **21. Machinery depreciation**

Emergy (seJ) = quantity of machinery depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)  
With:

- Quantity: 2.49E+04 g for SM, 1.59E+06 g for RI, 2.86E+06 g for PC and 1.81E+06 g for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### **22. Buildings - Wood**

Emergy (seJ) = quantity of wood depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)  
With:

- Quantity: 3.01E+08 g for SM, 0.00E+00 g for RI, 0.00E+00 g for PC and 0.00E+00 g for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### **23. Buildings – Mud**

Emergy (seJ) = quantity of mud depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)  
With:

- Quantity: 9.60E+02 g for SM, 0.00E+00 g for RI, 0.00E+00 g for PC and 0.00E+00 g for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### **24. Buildings – Concrete**

Emergy (seJ) = quantity of concrete depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)  
With:

- Quantity: 2.34E+05 g for SM, 1.43E+07 g for RI, 3.34E+07 g for PC and 2.81E+07 g for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### **25. Buildings – Steel**

Emergy (seJ) = quantity of steel depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)  
With:

- Quantity: 5.76E+02 g for SM, 1.63E+06 g for RI, 4.62E+06 g for PC and 2.37E+06 g for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### **26. Veterinary costs**

Emergy (seJ) = amount of veterinary costs (in different money unit) x Transformity (seJ.FCFA<sup>-1</sup> or seJ.€<sup>1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 1.12E+05 FCFA for SM, 1.33E+04 €for RI, 1.48E+04 €for PC and 1.53E+04 €for BR.
- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

### **27. Human labour**

Emergy (seJ) = quantity of human labour (J) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup> / Land area (ha)  
With:

- Quantity: 8.84E+09 J for SM, 2.81E+09 J for RI, 3.52E+09 J for PC and 3.25E+09 J for BR.

- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

## **28. Animal labour**

Emergy (seJ) = quantity of animal labour (J) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 1.16E+08 J for SM, 0.00E+00 J for RI, 0.00E+00 J for PC and 0.00E+00 J for BR.

- Land area: 36.5 ha for SM, 22.0 ha for RI, 135.2 ha for PC and 80.3 ha for BR

## **B. CALCUL A L'ECHELLE DU SYSTEME LAITIER**

### **1. Sunlight**

Emergy (seJ) = 10 000 m<sup>2</sup>.ha<sup>-1</sup> x solar radiation (J.m<sup>-2</sup>.yr<sup>-1</sup>) x (1 - 0.20 (albedo)) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup>

With:

- Solar radiation: 7.13E+09 J.m<sup>-2</sup>.yr<sup>-1</sup> for SM; 6.00E+09 J.m<sup>-2</sup>.yr<sup>-1</sup> for RI, 4.63E+09 J.m<sup>-2</sup>.yr<sup>-1</sup> for PC and 4.00E+09 J.m<sup>-2</sup>.yr<sup>-1</sup> for BR

### **2. Wind**

Emergy (seJ) = 10 000 m<sup>2</sup>.ha<sup>-1</sup> x air density (1.23 kg.m<sup>-3</sup>) x drag coefficient (0.001 na) x (surface windspeed (m.s<sup>-1</sup>) x 0.6)<sup>3</sup> x 31 536 000 s.an<sup>-1</sup> x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup>

With:

- Surface windspeed: 4.0 m.s<sup>-1</sup> for SM, 3.0 m.s<sup>-1</sup> for RI, 2.5 m.s<sup>-1</sup> for PC and 2.2 m.s<sup>-1</sup> for BR

### **3. Rain**

Emergy (seJ) = rain (m.m<sup>2</sup>.yr<sup>-1</sup>) x density water (1000 kg.m<sup>-3</sup>) x Gibbs free energy of water ( 4940 J.kg<sup>-1</sup>) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup>

With:

- rain: 1.02 m.m<sup>2</sup>.yr<sup>-1</sup> for SM, 2.50 m.m<sup>2</sup>.yr<sup>-1</sup> for RI, 0.90 m.m<sup>2</sup>.yr<sup>-1</sup> for PC and 0.95 m.m<sup>2</sup>.yr<sup>-1</sup> for BR

### **4. Erosion**

Emergy (seJ) = average soil loss (g.ha<sup>-1</sup>.yr<sup>-1</sup>) x average organic content (%) x energy content of organic matter (22,604 J.g<sup>-1</sup>) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup>

With:

- Average soil loss: 6.80E+06 g.ha<sup>-1</sup>.yr<sup>-1</sup> for SM, 2.20E+07 g.ha<sup>-1</sup>.yr<sup>-1</sup> for RI, 5.00E+05 g.ha<sup>-1</sup>.yr<sup>-1</sup> for PC and 5.00E+05 g.ha<sup>-1</sup>.yr<sup>-1</sup> for BR.

- Average organic content: 1.0% for SM, 4.5% for RI, 4.0% for PC and 4.0% for BR

### **5. Water**

Emergy (seJ) = Quantity (J or g) x Transformity (seJ.J<sup>-1</sup> or seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 1.92E+08 J for SM, 1.28E+09 g for RI, 2.76E+10 g for PC, 2.48E+09 g for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **6. Fuel**

Emergy (seJ) = Quantity (J) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 5.12E+08 J for SM, 5.52E+11 J for RI, 3.84E+11 J for PC, 2.49E+11 J for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **7. Electricity**

Emergy (seJ) = Quantity (J) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 0.00E+00 J for SM, 5.49E+10 J for RI, 1.41E+12 J for PC, 8.17E+11 J for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **8. N Fertiliser**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.kg<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 0.00E+00 kg for SM, 1.87E+03 kg for RI, 5.88E+03 kg for PC, 1.97E+03 kg for BR.
- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **9. P Fertiliser**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.kg<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 0.00E+00 kg for SM, 6.33E+02 kg for RI, 9.45E+02 kg for PC, 3.12E+02 kg for BR.
- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **10. K Fertiliser**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.kg<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 0.00E+00 kg for SM, 6.28E+02 kg for RI, 8.70E+02 kg for PC, 2.27E+02 kg for BR.
- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **11. Manure**

Emergy (seJ) = Quantity (kgDM) x Transformity (seJ.kgDM<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 0.00E+00 kgDM for SM, 8.33E+03 kgDM for RI, 3.24E+03 kgDM for PC, 7.12E+03 kgDM for BR.
- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **12. Chemicals**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 0.00E+00 kg for SM, 9.08E+00 kg for RI, 1.64E+01 kg for PC, 1.51E+01 kg for BR.
- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **13. Plastics**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 0.00E+00 kg for SM, 4.25E+02 kg for RI, 5.59E+03 kg for PC, 2.67E+03 kg for BR.
- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **14. Feed concentrates**

Emergy (seJ) = Quantity (g or kg) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity of cotton hull: 2.17E+02 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR
- Quantity of cottonseed: 1.53E+03 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR
- Quantity of cottonseed meal: 4.50E+02 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR
- Quantity of cereal bran: 4.47E+03 kg for SM, 0.00E+00 kg for RI, 0.00E+00 for PC and 0.00E+00 kg for BR
- Quantity of soybean meal: 0.00E+00 kg for SM, 0.00E+00 kg for RI, 7.28E+04 kg for PC and 3.90E+04 kg for BR
- Quantity of beet pulp: 0.00E+00 kg for SM, 0.00E+00 kg for RI, 2.42E+03 kg for PC and 1.03E+03 kg for BR
- - Quantity of internal wheat: 0.00E+00 kg for SM, 0.00E+00 kg for RI, 2.84E+04 kg for PC and 1.36E+04 kg for BR

- Quantity of Commercial feed concentrates: 0.00E+00 kg for SM, 2.62E+05 kg for RI, 8.30E+04 kg for PC, 5.03E+04 kg for BR

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **15. Milk powder**

$\text{Emergy (seJ)} = \text{Quantity (kg)} \times \text{Transformity (seJ.kg}^{-1}\text{)}^a / \text{Land area (ha)}$

With:

- Quantity: 0.00E+00 kg for SM, 3.88E+02 kg for RI, 7.95E+02 kg for PC, 1.34E+02 kg for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **16. Crop residues grazing**

$\text{Emergy (seJ)} = \text{Quantity (kg)} \times \text{Transformity (seJ.kg}^{-1}\text{)}^a / \text{Land area (ha)}$

With:

- Quantity of crops residues from cereal crops: 2.98E+03 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Quantity of crop residues from shallow crops: 4.96E+03 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Quantity of crop residues from internal crops: 4.68E+09 J for SM, 0.00E+00 J for RI, 0.00E+00 J for PC, 0.00E+00 J for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **17. Given forages**

$\text{Emergy (seJ)} = \text{Quantity (kg)} \times \text{Transformity (seJ.g}^{-1}\text{)}^a / \text{Land area (ha)}$

With:

- Quantity of Rice straw: 6.43E+01 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Quantity of Groundnut haulms: 2.21E+01 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Quantity of Sugarcane bagasse: 0.00E+00 kg for SM, 7.71E+03 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Quantity of Silage: 0.00E+00 kg for SM, 1.09E+04 kg for RI, 1.06E+04 kg for PC, 4.62E+03 kg for BR.

- Quantity of Sugarcane straw: 0.00E+00 kg for SM, 3.86E+04 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Quantity of External wheat straw: 0.00E+00 kg for SM, 0.00E+00 kg for RI, 3.90E+04 kg for PC, 2.54E+04 kg for BR.

- Quantity of Internal wheat straw: 0.00E+00 kg for SM, 0.00E+00 kg for RI, 5.89E+04 kg for PC, 5.10E+04 kg for BR.

- Quantity of Hay: 0.00E+00 kg for SM, 5.29E+03 kg for RI, 0.00E+00 kg for PC, 3.08E+06 kg for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **18. Animals**

$\text{Emergy (seJ)} = \text{Quantity (kg)} \times \text{Transformity (seJ.g}^{-1}\text{)}^a / \text{Land area (ha)}$

With:

- Quantity: 1.43E+02 kg for SM, 2.92E+03 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **19. Minerals**

$\text{Emergy (seJ)} = \text{Quantity (g)} \times \text{Transformity (seJ.g}^{-1}\text{)}^a / \text{Land area (ha)}$

With:

- Quantity: 3.00E+05 g for SM, 2.20E+04 g for RI, 9.49E+04 g for PC, 1.31E+05 g for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **20. Seeds**



Emergy (seJ) = Quantity (kg) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity of Corn seeds: 1.79E+01 kg for SM, 0.00E+00 kg for RI, 1.29E+10 J for PC and 6.73E+10 J for BR.

- Quantity of Grassland seeds (en J): 0.00E+00 J for SM, 2.06E+10 J for RI, 1.95E+10 J for PC and 3.48E+10 J for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **21. Machinery depreciation**

Emergy (seJ) = quantity of machinery depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 2.03E+03 g for SM, 1.59E+06 g for RI, 1.51E+06 g for PC and 1.17E+06 g for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **22. Buildings - Wood**

Emergy (seJ) = quantity of wood depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 2.14E+08 g for SM, 0.00E+00 g for RI, 0.00E+00 g for PC and 0.00E+00 g for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **23. Buildings – Mud**

Emergy (seJ) = quantity of mud depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 5.02E+02 g for SM, 0.00E+00 g for RI, 0.00E+00 g for PC and 0.00E+00 g for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **24. Buildings – Concrete**

Emergy (seJ) = quantity of concrete depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 0.33E+05 g for SM, 1.43E+07 g for RI, 2.25E+07 g for PC and 1.29E+07 g for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **25. Buildings – Steel**

Emergy (seJ) = quantity of steel depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 3.42E+02 g for SM, 1.63E+06 g for RI, 3.54E+06 g for PC and 1.92E+06 g for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **26. Veterinary costs**

Emergy (seJ) = amount of veterinary costs (in different money unit) x Transformity (seJ.FCFA<sup>-1</sup> or seJ.€<sup>1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 1.12E+05 FCFA for SM, 1.33E+04 €for RI, 1.48E+04 €for PC and 1.53E+04 €for BR.

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **27. Human labour**

Emergy (seJ) = quantity of human labour (J) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 4.20E+09 J for SM, 2.81E+09 J for RI, 3.09E+09 J for PC and 3.05E+09 J for BR

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **28. Animal labour**

Emergy (seJ) = quantity of animal labour (J) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup> / Land area (ha)

With:

- Quantity: 4.60E+07 J for SM, 0.00E+00 J for RI, 0.00E+00 J for PC and 0.00E+00 J for BR

- Land area: 25.6 ha for SM, 22.0 ha for RI, 81.2 ha for PC and 62.6 ha for BR

### **C. CALCUL A L'ECHELLE DU TROUPEAU**

#### **1. Biomass from natural pasture**

Emergy (seJ) = Quantity (kgMS) x Transformity (seJ.kgMS<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

- Quantity: 6.93E+04 kgMS for SM, 0.00E+00 kgMS for RI, 0.00E+00 kgMS for PC and 0.00E+00 kgMS for BR

- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

#### **2. Water**

Emergy (seJ) = Quantity (J or g) x Transformity (seJ.J<sup>-1</sup> or seJ.g<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 1.20E+06 J for SM, 1.28E+09 g for RI, 2.76E+10 g for PC, 2.48E+09 g for BR.

- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

#### **3. Fuel**

Emergy (seJ) = Quantity (J) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 2.95E+08 J for SM, 6.00E+09 J for RI, 6.63E+10 J for PC, 9.63E+10 J for BR.

- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

#### **4. Electricity**

Emergy (seJ) = Quantity (J) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 0.00E+00 J for SM, 5.49E+10 J for RI, 1.41E+12 J for PC, 8.17E+11 J for BR.

- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

#### **5. Feed concentrates**

Emergy (seJ) = Quantity (g or kg) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity of cotton hull: 2.17E+02 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR

- Quantity of cottonseed: 1.53E+03 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR

- Quantity of cottonseed meal: 4.50E+02 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC and 0.00E+00 kg for BR

- Quantity of cereal bran: 4.47E+03 kg for SM, 0.00E+00 kg for RI, 0.00E+00 for PC and 0.00E+00 kg for BR

- Quantity of soybean meal: 0.00E+00 kg for SM, 0.00E+00 kg for RI, 7.28E+04 kg for PC and 3.90E+04 kg for BR

- Quantity of beet pulp: 0.00E+00 kg for SM, 0.00E+00 kg for RI, 2.42E+03 kg for PC and 1.03E+03 kg for BR

- - Quantity of internal wheat: 0.00E+00 kg for SM, 0.00E+00 kg for RI, 2.84E+04 kg for PC and 1.36E+04 kg for BR

- Quantity of Commercial feed concentrates: 0.00E+00 kg for SM, 2.62E+05 kg for RI, 8.30E+04 kg for PC, 5.03E+04 kg for BR

- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

#### **6. Milk powder**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.kg<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 0.00E+00 kg for SM, 3.88E+02 kg for RI, 7.95E+02 kg for PC, 1.34E+02 kg for BR.

- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

### **7. Grassland grazing**

Emergy (seJ) = Quantity (kgMS) x Transformity (seJ.kgMS<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

- Quantity: 0.00E+00 kgMS for SM, 1.14E+05 kgMS for RI, 1.22E+05 kgMS for PC and 2.63E+05 kgMS for BR

- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

### **8. Crop residues grazing**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.kg<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity of crops residues from cereal crops: 2.98E+03 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Quantity of crop residues from shallow crops: 4.96E+03 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Quantity of crop residues from internal crops: 4.68E+09 J for SM, 0.00E+00 J for RI, 0.00E+00 J for PC, 0.00E+00 J for BR.

- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

### **9. Given forages**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity of Rice straw: 6.43E+01 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Quantity of Groundnut haulms: 2.21E+01 kg for SM, 0.00E+00 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Quantity of Sugarcane bagasse: 0.00E+00 kg for SM, 7.71E+03 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Quantity of External silage: 0.00E+00 kg for SM, 1.09E+04 kg for RI, 1.06E+04 kg for PC, 4.62E+03 kg for BR.

- Quantity of Internal silage: 0.00E+00 kg for SM, 3.42E+05 kg for RI, 6.07E+05 kg for PC, 2.99E+05 kg for BR.

- Quantity of Sugarcane straw: 0.00E+00 kg for SM, 3.86E+04 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Quantity of External wheat straw: 0.00E+00 kg for SM, 0.00E+00 kg for RI, 3.90E+04 kg for PC, 2.54E+04 kg for BR.

- Quantity of Internal wheat straw: 0.00E+00 kg for SM, 0.00E+00 kg for RI, 5.89E+04 kg for PC, 5.10E+04 kg for BR.

- Quantity of Hay: 0.00E+00 kg for SM, 5.29E+03 kg for RI, 0.00E+00 kg for PC, 3.08E+06 kg for BR.

- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

### **10. Animals**

Emergy (seJ) = Quantity (kg) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 1.43E+02 kg for SM, 2.92E+03 kg for RI, 0.00E+00 kg for PC, 0.00E+00 kg for BR.

- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

### **11. Minerals**

Emergy (seJ) = Quantity (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 3.00E+05 g for SM, 2.20E+04 g for RI, 9.49E+04 g for PC, 1.31E+05 g for BR.

- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

### **12. Machinery depreciation**

Emergy (seJ) = quantity of machinery depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 2.03E+03 g for SM, 1.06E+04 g for RI, 2.90E+05 g for PC and 3.40E+05 g for BR.
- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

### **13. Buildings - Wood**

Emergy (seJ) = quantity of wood depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 0.00E+00 g for SM, 0.00E+00 g for RI, 0.00E+00 g for PC and 0.00E+00 g for BR.
- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

### **14. Buildings – Mud**

Emergy (seJ) = quantity of mud depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 0.00E+00 g for SM, 0.00E+00 g for RI, 0.00E+00 g for PC and 0.00E+00 g for BR.
- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

### **15. Buildings – Concrete**

Emergy (seJ) = quantity of concrete depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 0.00E+00 g for SM, 8.78E+06 g for RI, 2.18E+07 g for PC and 1.29E+07 g for BR.
- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

### **16. Buildings – Steel**

Emergy (seJ) = quantity of steel depreciation (g) x Transformity (seJ.g<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 0.00E+00g for SM, 1.39E+06 g for RI, 3.46E+06 g for PC and 1.92E+06 g for BR.
- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

### **17. Veterinary costs**

Emergy (seJ) = amount of veterinary costs (in different money unit) x Transformity (seJ.FCFA<sup>-1</sup> or seJ.€<sup>1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 1.12E+05 FCFA for SM, 1.33E+04 €for RI, 1.48E+04 €for PC and 1.53E+04 €for BR.
- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

### **18. Human labour**

Emergy (seJ) = quantity of human labour (J) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 4.20E+09 J for SM, 2.19E+09 J for RI, 3.09E+09 J for PC and 2.86E+09 J for BR
- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR

### **19. Animal labour**

Emergy (seJ) = quantity of animal labour (J) x Transformity (seJ.J<sup>-1</sup>)<sup>a</sup> / Number of animals (LU)

With:

- Quantity: 4.60E+07 J for SM, 0.00E+00 J for RI, 0.00E+00 J for PC and 0.00E+00 J for BR
- Number of animals: 32.8 LU for SM, 55.5 LU for RI, 94.4 LU for PC and 79.2 LU for BR