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Consider the energy flows in the farm - Development of an energy analysis method encompassing the agroecosystem

Jean Hercher-Pasteur

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THÈSE POUR OBTENIR LE GRADE DE DOCTEUR DE MONTPELLIER SUPAGRO

En Génie des Procédés

École doctorale GAIA – Biodiversité, Agriculture, Alimentation, Environnement, Terre, Eau
Portée par l'Université de Montpellier

Unité de recherche UMR ITAP (INRAE)

Consider the energy flows in the farm

- Development of an energy analysis method encompassing the agroecosystem

Présentée par jean HERCHER-PASTEUR

Le 14 décembre 2020

Sous la direction de Arnaud HELIAS et Carole SINFORT

Devant le jury composé de

Mr Thomas NESME, Professeur, Bordeaux Sciences Agro

Mr Enric TELLO, Directeur de recherche, Universitat de Barcelona

Mme Aurélie METAY, Maître de conférences, L'institut Agro – Montpellier SupAgro

Mr Mathieu VIGNE, Chercheur, CIRAD

Mr Arnaud HELIAS, Directeur de recherche, INRAE

Mme Carole SINFORT, Professeur, L'institut Agro – Montpellier SupAgro

Rapporteur

Rapporteur

Examinatrice

Examineur

Directeur de thèse

Co-Directeur de thèse

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A Martín et Emilio.

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- Preamble -

A la fin de mes études d'agronomie à l'ISTOM en 2008, j'ai eu l'opportunité de travailler dans les énergies renouvelables. C'était pour moi l'occasion d'apprendre un domaine peu abordé lors de ma formation, mais qu'il me semblait essentiel de maîtriser afin de l'intégrer à l'agriculture. Ce travail m'a amené à m'intéresser aux maisons économes en énergie et à la construction de maison en ossature bois. En 2010, je décide d'en faire l'expérience proprement dite et part sur un voilier énergétiquement autonome pour un tour de l'Amérique latine qui me conduira en Uruguay, ma nouvelle terre d'accueil depuis 2012. La question énergétique a toujours été présente dans mes pensées et je me souviens encore de mon échange avec le responsable de la WWF de « Isla Isabela » des Galapagos où l'on se disait que la valeur d'échange universelle devrait être l'énergie ! Ce n'est au final qu'en 2016 que je décide de revenir à l'agronomie et d'y intégrer cet acquis sur l'énergie au cours de ces dernières années. Je commence alors à développer le concept d'efficacité énergétique dans l'agriculture en Uruguay auprès d'entreprises de conseil en économie d'énergie. L'idée les séduit, mais je manque d'épaisseur et d'un « business model » ... C'est alors qu'une opportunité se présente au travers d'un appel à candidatures pour réaliser une thèse en France. Même étranger, en tant que résident permanent, je peux concourir. Bravo et merci l'Uruguay ! Et puis j'y vois une belle occasion de partager ma culture avec mon épouse uruguayenne (Mariana) et mes deux enfants, Martin et Emilio, dans l'âge où apprendre des langues est une question de mois. C'est avec tous ces espoirs en tête que je commence à écrire mon sujet de thèse. J'ai la chance de compter sur mon ami Fabien Charbonnier, ancien collègue de l'ISTOM, ayant réalisé une thèse quelques années auparavant, pour m'initier à l'écriture scientifique, à ses outils de gestion de la bibliographie et qui me transmet quelques références sur l'énergie et l'agriculture. La suite est heureuse puisque j'arrive à obtenir cette bourse et à trouver une directrice de thèse pour m'encadrer. Une nouvelle aventure commence.

Cette thèse est le fruit de ce cheminement et de ce retour aux études. La suite est dans ce manuscrit, où il aura fallu concilier les événements de cette dernière année 2020, mais qui ne sauront entacher le plaisir que j'ai eu à découvrir le monde scientifique et explorer plus en profondeur ces thématiques qui me passionnent.

English version :

At the end of my agronomy studies at ISTOM in 2008, I had the opportunity to work in renewable energies. It was an occasion for me to learn a field that I had not studied during my training, but which I felt it was essential to understand, in order to integrate it into agriculture. This work brought me to be involved in energy efficient houses and wood-framing construction. In 2010, I decided to experience it by myself and set off on an energy self-sufficient sailboat for a tour of Latin America that will take me to Uruguay, my new homeland since 2012. The energy question has always been present in my thoughts and I still remember my exchange with the WWF head of "Isla Isabela" in the Galapagos Islands where we said that the universal exchange value should be energy! In the end, it was only in 2016 that I decided to return to agronomy and to integrate the knowledge I had acquired about energy over the last years. I then began to develop the concept of energy efficiency in agriculture in Uruguay with an energy saving consulting company. The idea seduced them, but I lack recognition and a business model... Then an opportunity arose through a call for applications to carry out a PhD thesis in France. Even if I am a foreigner, as a permanent resident, I can apply. Bravo and thank you Uruguay! I also see it as a great opportunity to share my culture with my Uruguayan wife (Mariana) and my two children, Martín and Emilio, at the age where learning languages is a matter of months. It is with all these hopes in mind that I start writing my thesis topic. I am lucky to count on my friend Fabien Charbonnier, a former colleague of ISTOM, who wrote a thesis a few years ago, to introduce me to scientific writing, to its tools for managing bibliography and who is giving me some references on energy and agriculture. The following is a happy continuation since I succeed in obtaining the scholarship and in finding a thesis director to supervise me. A new adventure begins.

This PhD thesis is the result of all this. The continuation is in this manuscript, where it was necessary to reconcile the events of this last year 2020, but that will in no case affect the pleasure that I had to discover the scientific world and explore more deeply these topics that fascinate me.

Caminante no hay camino, se hace camino al andar.
(Antonio Machado)

- Abstract / Résumé -

Comme l'ensemble de la société, les systèmes de production agricole sont actuellement soumis à une forte pression en raison de la forte consommation en énergie fossile, de l'impact sur le climat que cela engendre et de la faible durabilité de certaines pratiques qui dégradent la biodiversité et les ressources naturelles. Le système de production agricole est au carrefour du monde socio-économique et de l'agroécosystème et doit être abordé à travers ces deux composantes. Nous pensons qu'un point de vue énergétique permet de concilier les deux (les deux étant soumis aux lois de la thermodynamique) et d'appréhender la durabilité du système de production agricole dans son ensemble. En ce sens, cette thèse tente de répondre à la question suivante : "Comment l'analyse énergétique permet-elle d'évaluer et de concevoir un système de production agricole performant et durable ? ", avec pour objectif opérationnel de développer une évaluation de l'exploitation agricole en termes de flux énergétique.

Cette méthode a été construite au travers d'une approche systémique qui différencie les processus de stockage (le capital fixe et le capital naturel), qui fournissent des services, et les processus de production (la biomasse cultivée, la production animale), qui transforment un produit en un autre. Une attention toute particulière a été portée à la circularité des flux entre l'activité agricole et son capital naturel à travers la biomasse investie pour maintenir les fonctionnalités de l'agroécosystème. Tout comme nos machines et nos outils constituent un capital fixe pour la production, le sol et la biomasse représentent un stock intrinsèque de l'agroécosystème et qui contribue à la fourniture de services écosystémiques. La matière organique du sol est perçue comme la "bio-batterie" de l'agroécosystème, dont la capacité à fournir des services est mesurée à travers la minéralisation du sol, reflet de l'activité microbienne des sols.

Cette méthode a été appliquée sur une exploitation polyculture-élevage réelle en France. Trois scénarios contrastés de gestion agricole ont été proposés afin de tester l'outil. La méthode a ensuite été utilisée pour comparer deux régions contrastées, pour tester l'outil à une autre échelle. Les perspectives et les potentialités de cette approche sont ensuite présentées et discutées dans l'objectif d'un futur usage de conseils agricoles.

Mots clés : Système de production agricole ; agroécosystème ; analyse énergétique ; circularité ; stock énergétique ; sol

English version :

Like all human activities, agricultural production systems are currently under great pressure due to the high consumption of fossil fuels, the impact on the climate that this generates, and the low sustainability of certain practices that degrade biodiversity and natural resources. The agricultural production system is at the crossroads of the socio-economic world and the agroecosystem and must be addressed through these two components. We believe that an energy point of view would make it possible to reconcile the two (both being subject to the laws of thermodynamics) and to apprehend the sustainability of the agricultural production system as a whole. In this sense, this thesis tries to answer the following question: "How can energy analysis be used to assess and design an efficient and sustainable agricultural production system? ", with the operational objective of developing an evaluation of the farm in terms of energy flow.

This method has been built through a systemic approach that differentiates storage processes (fixed capital and natural capital), which provide services, and production processes (cultivated biomass, animal production), which transform one product into another. Special attention was paid to the circularity of flows between agricultural activity and its natural capital through the biomass invested in it maintaining the functionalities of the agroecosystem. Just as our machines and tools constitute fixed capital for production, soil and biomass represent an intrinsic stock of the agroecosystem and contribute to the provision of ecosystem services. Soil organic matter is seen as the "bio-battery" of the agroecosystem, whose capacity to provide services is measured through soil mineralization, a mirror of soil microbial activity.

This method has been applied to a real case study in France. Three contrasting farm management scenarios are proposed in order to test the tool. The method was then used to compare two contrasting regions to assess its adaptability on a larger scale. The perspectives and potentialities of this approach are then presented and discussed with a view to future use of agricultural advice.

Key words: Agricultural production system ; agroecosystem ; energy assessment ; circularity ; energy stock ; soil

- Lay abstract / Résumé grand public -

L'agriculture met en œuvre des processus qui correspondent à des flux issus de la société humaine et des flux issus de l'écosystème. L'énergie est une unité de mesure qui permet d'apprécier ces deux aspects. Ce travail de thèse propose de développer une nouvelle méthode d'analyse énergétique, afin d'appréhender la durabilité de l'exploitation agricole. Pour cela, il est mis en avant le capital fixe (technique) tout comme le capital naturel (les écosystèmes), tous deux consommateurs d'énergies et producteurs de services. Une attention toute particulière est donnée aux flux circulaires nécessaires pour maintenir le capital naturel. Le sol est vu comme la « bio-batterie » du système agricole. La méthode est appliquée à l'échelle de l'exploitation et du département, et permet d'apprécier la durabilité des systèmes agricoles.

English version :

Agriculture involves processes that correspond to flows from human society and flows from the ecosystem. Energy is a metric that allows assessing these two aspects. This thesis work proposes to develop a new method of energy analysis in order to apprehend the sustainability of the farm. To do this, the research emphasizes the fixed (technical) capital as well as the natural capital (ecosystems), both consumers of energy and producers of services. Special attention is given to the circular flows necessary to maintain natural capital. Soil is seen as the "bio-battery" of the agricultural system. The method is applied to the farm and French department levels, and allows the sustainability of agricultural systems to be assessed.

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- List of abbreviations -

AE	Associated ecosystem
AEA	Agroecological energy analysis
CB	Cultivated biomass
CED	Cumulative energy demand
CEENE	Cumulative exergy extraction from the natural environment
CExC	Cumulative exergy consumption
DA	Domestic animal
EA	energy assessment
EEA	Extended exergy accounting
EREA	energy resources exergy accounting
EROI	Energy return on energy invest
FT	Facilities and Tools
GCV	Gross calorific value
GHG	Grenhouse gas
GJ	Giga Joule
GMO	Genetic modified organism
ha	hectar
K2	Mineralization coefficient
KJ	Kilo Joule
LCA	Life cycle assessment
LCI	Life cycle inventory
LU	Livestock unit
MJ	Mega Joule
NPP	Net primary production
NREA	natural resources exergy accounting
SAFRA	Sustainable agroecological farm reproductive analysis
SOM	Soil organic matter

- Scientific production -

Scientific publications

This thesis has three core chapters, out of which one was accepted in an international peer-reviewed journal, another was submitted and the last is ready for submission:

- Chapter 2 has been accepted: Hercher-Pasteur, J., Loiseau, E., L., Sinfort, C., Helias, A. “Energetic assessment of the agricultural production system. A review”. *Agronomy for Sustainable Development*.
- Chapter 3 has been submitted : Hercher-Pasteur, J., Loiseau, E., Astigarraga, L., Sinfort, C., Helias, A. “Identifying the resource use and circularity into the farm systems: focus on the energy analysis of agroecosystem”. *Resources, Conservation & Recycling*.
- Chapter 4 will soon be submitted as: “Agroecosystem energy assessment of two contrasting territories”

Oral presentation

6th International Symposium for Farming Systems Design, Montevideo, August 2019

Agroecological Energy Analysis method designed at farm scale: case study of a French mixed-farming system

Hercher-Pasteur, J., Loiseau, E., Astigarraga, L., Sinfort, C., Helias, A.

Chapter 1: General introduction

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This chapter presents the challenges of the agricultural production system in respect to its limits and the opportunities of new practices and approaches. Then, it introduces the research question, the objectives and the general structure of the thesis.

1.1 Challenges for the agricultural system

Agriculture resulting from the Green revolution has enabled a sharp increase in food production and in its productivity thanks to a high use of external inputs (synthetic fertilizers and crop protection products), seed improvement, mechanization and irrigation. This has helped respond to a global increase in food demand, as in the mid-1960s with Asia threatened by hunger, and boosted the human population as a result (Gomiero, 2016). More recently it also allowed the increase in animal production and consumption, mainly in America and Europe, devoting 35% of the world's crop production to animal feed (Foley et al., 2011). The agricultural intensification has drastically increased the earth's carrying capacity for human needs (Krausmann, 2016)

However, food security and hunger have not been solved: Sustainable Development Goal 2 "Zero hunger" remains unattained. Moreover, this agricultural model (called thereafter conventional agriculture) is causing dramatic damage to the environment at all scales and its sustainability is strongly questioned (Tilman, 1999; Tilman et al., 2002). The intensive use of external inputs has a strong role on water, soil and air contamination leading to the degradation of biodiversity, and to human health issues (Gomiero et al., 2011a). Intensive practices, such as tillage and irrigation, deplete soil (Montgomery, 2007) and water resources (Pfister et al., 2011), both of which are essential for life and human food supply. Industrial seeds and more recently GMOs (genetically modified organisms) are promoted as allowing high and consistent yields and limiting the need to use pesticides (in the case of GMOs). Yet, they can cause problems of access by all farmers due to corporate monopoly (Gomiero, 2018). In addition, the use of agrochemicals has not really reduced with GMOs (e.g. more herbicide is used) (Perry et al. 2016), and the reduction of genetic diversity limits the ability of plants to resist pests and diseases (Cleveland, 1995). Finally, the modernization of agriculture leads to highly non-renewable resource dependent systems, with significant impacts on climate change and greater sensitivity to energy price volatility (Pelletier et al., 2011; Pimentel et al., 1973). Moreover, the increase of animal breeding also is in itself a major cause of climate change, directly from methane emissions (enteric fermentation) and indirectly from land use change (clearance of forest to pasture).

Conventional agriculture has to maintain its productivity and reduce food loss along supply chains to provide healthy food for a growing human population. Main challenges are to improve distribution and access to food in particular for the most vulnerable, and to increase food system resilience to climate change and to market price fluctuations, while remaining in a safe operating space for humanity. Indeed, greenhouse gas emissions, biosphere integrity, cropland use, freshwater use and fertilizer use are already beyond planet boundaries (**Figure 1**). This means that agricultural systems must undergo a profound change of paradigm while the so-called energy transition seems increasingly behind schedule.

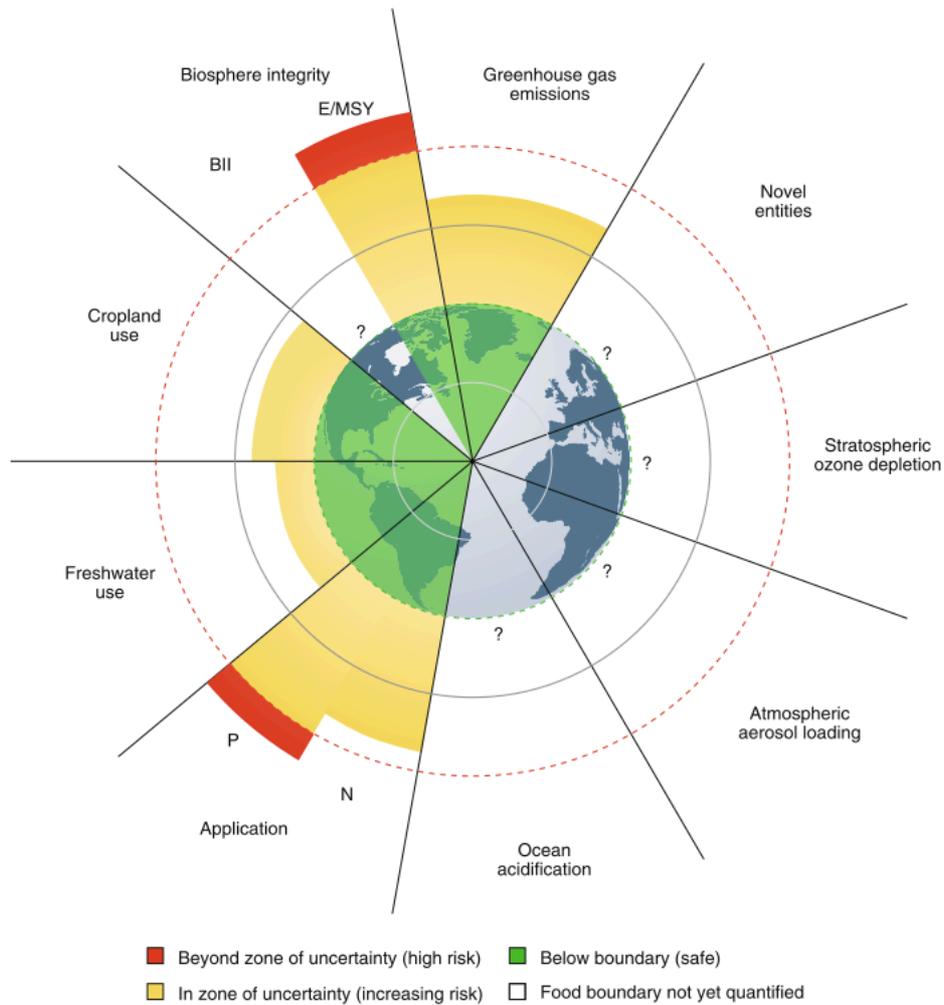


Figure 1: An estimate of the global food system’s transgression of planetary boundaries. Here, the safe operating space (green) provides an estimate of the food-related share of the planetary boundaries, that is, not the entire planetary boundary space for all sectors in the world economy. The zone of uncertainty (yellow) defines dangerous risk, whereas high-risk (red) indicates where production has exceeded the assessed uncertainty range in science. The range of uncertainty originates both from quantitative assessments and from expert judgment. Control variables have been normalized for the zone of uncertainty; the centre of the figure therefore does not represent zero values for control variables. Processes for which the food system contribution or the planetary boundary itself have not yet been quantified are highlighted with a question mark. E/MSy, extinctions per million species-years; BII, Biodiversity Intactness Index; P, phosphorus; N, nitrogen. (Rockström et al., 2020).

1.2 Potential solutions for a more sustainable agriculture

1.2.1 A more ecosystem-based agriculture

One of the main features of conventional agriculture has been to free itself from the variability and constraints of ecosystems and the environment by mobilizing technical inputs (e.g. fertilizers, pesticides, irrigation) and at the same time using mechanization. This empowerment relies heavily on non-renewable energy, creating another form of dependence with effects such as those briefly described above. In light of this reality, new agricultural models have emerged (e.g. agroecology, organic farming, ecological intensification, etc.) sharing a

common idea, i.e. using more sustainable agricultural practices implies relying more on ecosystem mechanisms to ensure a sustainable supply of resources and services.

Agriculture better connected to its ecosystem is not new (not mentioning that is its origin) and the idea of ecological agriculture gained momentum in the 1990s through agroecology (Altieri et al., 1995; Gliessman, 1990). Concepts such as agroecology, ecological intensification (Tittonell, 2014), or diversified farming systems (Kremen et al., 2012) describe practices based on the use of ecological processes and ecosystem services (Costanza et al., 2017). These are fundamental elements to the development of practices not relying on external inputs such as chemical fertilizer or agrochemical products. Regulation services influencing soil fertility, water storage and pest control appear to be the key services provided by ecosystems to farmers (Duru et al., 2015). The capacity of farming ecosystems to provide these services will depend on the natural capital available (Jordan, 2016).

In order to consider the natural capital, the farming system must be seen as an agroecosystem (Gliessman, 2016). The agroecosystem is a spatially limited, artificial, unstable system that depends on anthropic flows (i.e. external inputs) and on biotic flows to maintain its characteristics so as to obtain a quantity of agricultural products (Bulatkin, 2012). A strongly artificialized agroecosystem will depend on external inputs to function, whereas an agroecosystem closer to a natural ecosystem will depend on natural flows provided by ecosystem mechanisms (Gliessman, 1998). Crop distribution and succession, the introduction of leguminous plants in crop rotation, cover crops to reduce soil erosion and water evaporation or the diversification of plant varieties in a field to reduce the risk of disease are some of the practices attempting to reduce the use of external inputs. Inter-cropping, no tillage and direct sowing to preserve the soil properties, agroforestry and the combination of perennial and annual plants, plant complementarity via allopathic plants and biological pest control (with direct agent or pheromone), are some of the practices based on ecosystem mechanisms that are actually promoted (Wezel et al., 2014).

1.2.2 Agriculture more based on circularity

Confronted to industrial and globalized food systems with their related supply-chain risks and their strong sensitivity to market price, circular agro-food systems are gaining momentum. In opposition to linear globalized commodity-based food systems, circularity consists of developing eco-efficient closed loops working to reduce, re-use and recycle the flows of energy and material (Therond et al., 2017). A territorial and regional approach is part of this logic seeking to propose a more connected and sustainable agro-food system.

Considering the agricultural production system as an agroecosystem also implies looking at the circularity, but inside the agricultural system. It also brings us to consider thermodynamic laws to understand its evolution over time. Ecosystems are open, non-balanced, thermodynamic systems that exchange energy and matter with the environment continuously (Odum 1983). They evolve towards maximizing the rate of useful energy transformation (principle of maximum power) to reduce their entropy (Skene, 2013). For the ecologist Jorgensen (2006), the five main characteristics of an ecosystem are:

1. **Recycling:** Ecosystems recycle all matter and partly energy.
2. **Multiple uses:** All components have more than one function in an ecosystem and participate to more than one process.
3. **The function is more important than the product:** Species may change but the function is maintained in spite of changed conditions.
4. **Self-organization and self-regulation:** In order to maintain a function in the face of a change, components can be modified.

5. **Operation in a cooperative network:** Ecosystem components are linked to each other, all components are interdependent in a cooperative network (also called synergetic network).

Recycling, multiple uses and synergetic networks are characteristics of circularity and essential elements in the reproduction and development of ecosystems. Recirculating energy allows obtaining low entropy systems (Guzmán et al., 2015). Ecosystems reuse and recycle part of their biomass production to maintain their structure and functions (Guzmán et al., 2015). Improving circularity appears to be the other key element for the development of a more sustainable agricultural system.

To conclude on possible options for a more sustainable agriculture, we selected **Figure 2** from Therond et al. (2017) as a clear representation of current agriculture models through the two concepts just mentioned, i.e. ecosystem services and circularity.

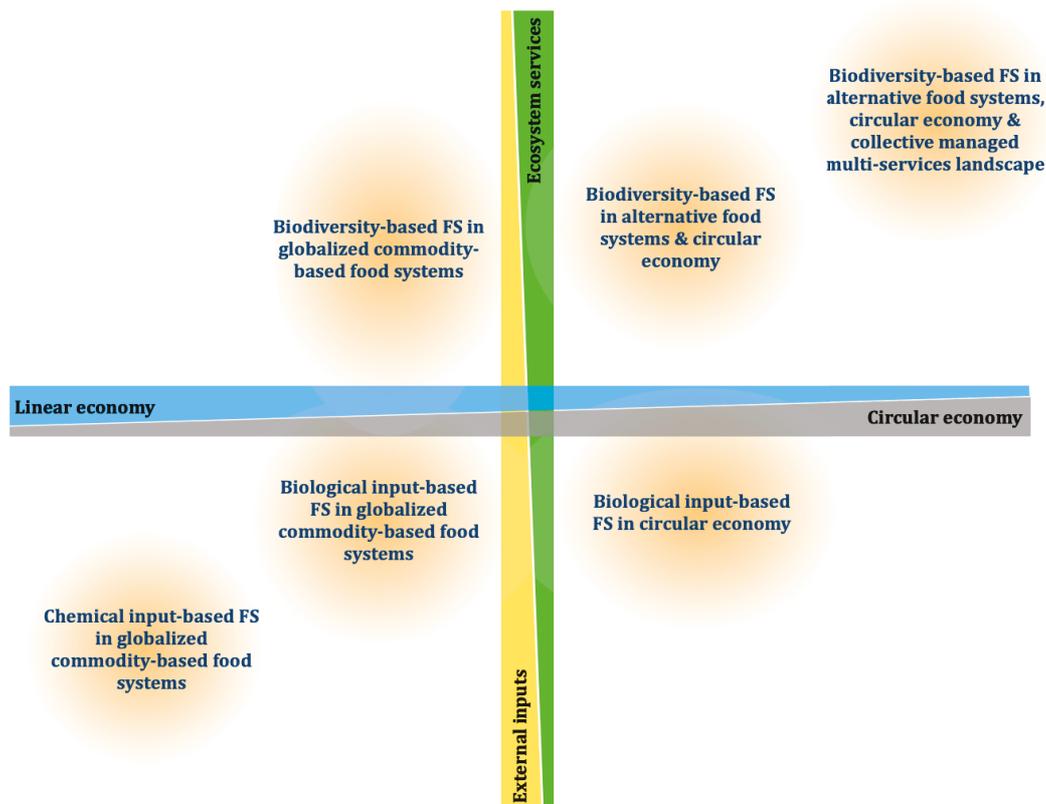


Figure 2: Six models of agriculture (FS: farming system) according to the gradient of inputs (ecosystem services vs. external inputs) and their relationship with socio-economic configurations (linear economy vs. circular economy) – adapted from Therond et al. (2017)

1.3 A need to better quantify agroecosystem flows

1.3.1 Ecosystem services and circularity of the agroecosystem weakly quantified

A good description and understanding of these flows from the ecosystems and circularity are essential elements for their adoption, application and usage. Yet, the benefits of ecosystem services are difficult to quantify (Tilman et al., 2002) and this remains one of their weaknesses. The notion of circularity for agroecosystems has been widely discussed (Guzmán Casado and González de Molina, 2017; Ho, 2013; Tello et al., 2016), but the

quantification of the agroecosystem's circularity as such, i.e. the agricultural activity within its surrounding environment, has not been directly used nor applied otherwise (Tanzer, 2020). We assume that these reasons explain in part the low adoption of agroecological practices by conventional agriculture. There is a need for indicators that compute in a single metric all the flows used and produced by agroecosystems including circular, ecosystem but also indirect flows (energy and materials used to produce external inputs). These indicators will provide an exhaustive picture of the agroecosystem functioning and allow to quantify the benefits and the impacts of circularity and ecosystem flows for different agricultural models and particularly the conventional one.

1.3.2 Energy, a holistic metric to describe the agricultural production system

Energy is a key element in the development of human societies (Smil, 2017). This has allowed them to increase the energetic power of the exosomatic instruments (which is outside the body) (Georgescu-Roegen, 1977). At the beginning, human depended on the capacity of plants to transform solar energy into chemical energy (biomass). Then, the use of wind and water to transform kinetic energy into work allowed to go further (e.g. sailing boat) and to produce more and faster (e.g. water mill). Finally, the control of combustion and the access to fossil fuels have profoundly increased human exosomatic power leading to the industrial age. The population has drastically increased in 2 decades (from 1 billion to 7.5 billion) while the agricultural population in industrialized countries has fallen (in France from 48% to 3% between 1880 and 1999) (Harchaoui and Chatzimpiros, 2019). In the end, energy consumption and its related greenhouse gas (GHG) emissions are the first indicators of economic growth (based on the gross domestic production) (Chen et al., 2016; Wang et al., 2016).

Energy is also a thermodynamic state parameter to describe an ecosystem. Through photosynthetic reaction, solar energy is converted and stocked into biomass. As we have seen previously, ecosystem development tends to compensate for the law of entropy thanks to their capacity of self-organization, of recycling and closing loops working into a cooperative network. Energy is at the core of natural mechanisms and has been widely used in ecological modelling (Odum, 1988).

Energy assessment (EA) applied to agriculture is not new as it served to demonstrate its dependency on fossil fuels during the first oil crisis (Pimentel et al., 1973). EA has subsequently been used in many works to compare the energy use efficiency of agricultural systems (Smith et al., 2015) via the indicator of Energy Return On Investment (EROI) (Hall, 2017), or to understand agricultural metabolism dynamic and evolution over time and its effects on land use, agrarian population, landscape and energetic configuration (González de Molina et al., 2020; Harchaoui and Chatzimpiros, 2019; Krausmann, 2016). It has been shown that energy use is correlated to the degree of artificialisation of an agroecosystem. As Gliessman stated (1998), the greater the natural processes of an agroecosystem are altered, the greater the amount of anthropogenic energy need will be.

Finally, energy appears to be a recognised and a wide use metric to describe the flows from the ecosphere (i.e. ecological processes) and the technosphere (i.e. processes related to human activities) (Joliet et al., 2015). However, we need to go further to better describe ecosystem flows and circularity, and in the implementation of indicators for monitoring the relationship between agricultural activity and the agroecosystem. What we are looking for in this thesis work is an approach that allows quantifying the flows provided by the ecosystem and the rate of circularity in order to communicate measurable values to stakeholders on the performances of the agricultural production system as an agroecosystem and thus facilitate the adoption of more sustainable farming practices.

1.4 Objectives of the thesis

Based on these contextual elements: (1) a non-sustainable conventional agriculture, (2) more sustainable agricultural practice alternatives based on ecosystem mechanisms and circularity, (3) the need to better quantify these notions using a proven methodological energy framework, the general research question of this thesis is formulated as follows:

"How can energy analysis be used to assess and design an efficient and sustainable agricultural production system?"

with the overall operational purpose of developing a method of characterising the farm system in terms of energy flow understandable by farmers and stakeholders. To address this question, we organized the work into 3 objectives:

- Objective 1: Review the energetic assessment approaches used to analyse agricultural production systems.
- Objective 2: Develop an exhaustive energy analysis method to compute flows of agricultural production systems as an agroecosystem.
- Objective 4: Test the method on a scale larger than a specific/single production system.

Following this general introduction, each objective will be addressed in a distinct chapter of the thesis referring to a scientific publication (either published or in preparation to be submitted) as described hereafter. **Content of chapter 2** presents an exhaustive review of the different EA approaches applied to the agricultural production system. Based on a “web of science” request, we finally selected 196 scientific papers covering the scope. A protocol is developed to perform a critical analysis of the different energetic methods. We then discuss their ability to address resource use efficiency and sustainability issues of the agricultural production system. **Content of chapter 3** describes the methodology developed for the agricultural system at farm scale. Based on the recommendations of chapter 2, we built a framework to assess resource use efficiency of the agricultural system at farm scale considering the ecosystem, circular and indirect flows. We applied the method to a real case study, a French organic mixed-farming system. Three contrasted scenarios based on the case study are proposed to test the method and discuss its ability to address sustainability issues. In accordance with objective 3, **Content of chapter 4** proposes to apply the framework to a larger scale by comparing two contrasted French departments, one oriented to crop production (i.e. Eure-et-Loir in the center of France), the other to animal production (i.e. Finistère, in western France). The adaptation of the method to a larger scale is discussed and recommendations for both regions are proposed to support their transition towards sustainability. Finally, **Content of chapter 5** draws the general conclusion of this thesis and the perspectives of the work realised, regarding strengthening and validating the method and its application to support decision-making in agriculture.

Chapter 2: Energetic assessment of the agricultural production system. A review

Jean hercher-Pasteur^{1,2}, Eleonore Loiseau^{1,2}, Carole Sinfort^{1,2}, Arnaud Hélias^{1,2}

¹ITAP, Univ Montpellier, INRAE, Institut Agro, Montpellier, France

²ELSA, Research group for Environmental Life cycle and Sustainability Assessment, Montpellier, France

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This chapter presents an overview of the energy approaches applied to the agricultural production systems. It is based on a review article accepted in Agronomy for sustainable development. The first step was to list the different existing methods, then to analyze their strengths and weaknesses through a protocol in order to identify the most suitable lines of research in assessing the sustainability and resilience of agricultural production systems.

Abstract

Energy holds a key role in farm systems. Cultivation is based on the conversion of solar energy into biomass of interest. Fossil energy allows mechanized and high-yield agricultural production system, but has a strong impact on climate change, and its supply is compromised in the next decades. Energy flows stand between two worlds: while energy is a strategic component of the economy, it is also a thermodynamic state variable for describing ecosystems. This situation reemphasizes the need for energy flow analysis in farm systems. There is a great variety in the approaches used to compute energy flows at farm scales. Yet, their main characteristics and the ways they handle farm sustainability issues need to be clarified. This review identifies ten kinds of energetic approaches, i.e., (i) conventional energy analysis, (ii) pluri-energy analysis, (iii) agroecological energy analysis, (iv) exergy analysis, (v) cumulative exergy consumption, (vi) extended exergy account, (vii) cumulative exergy extraction from the natural environment, (viii) eco-exergy, (ix) cosmic exergy analysis, and (x) energy assessment. These approaches are analyzed through key features to discuss their ability to address resources' efficiency issues and identify promising outcomes for energy assessment of farms. This analysis emphasizes the lack of clear definition of system boundaries in farm-scale studies. In addition, most of the studies mainly focus on socio-economic flows through a sectoral perspective. Yet, internal biomass flows that play a role in maintaining agroecosystem functionality can also be considered according to a circular/systemic perspective. Then, integration of soil organic matter in the energy balance leads to significant changes in energy efficiency evaluation playing a function of biotic energy storage in the farm system. Hence, some recommendations are provided to perform an exhaustive energetic assessment of farm systems as well as future lines of research to be investigated.

Keywords

Energy, Emergy, Exergy, Agricultural system, EROI (Energy Return On Energy Invest), Agroecosystem, Circularity

2.1 Introduction

Since humans became sedentary, natural ecosystems were converted into agroecosystems in order to carry out and increase specific crop and livestock production. This provided an energy output from food and raw material, which was useful for human societies (Giampietro et al., 1992). In pre-industrial societies, agriculture was the major source of energy and materials (Aguilera et al., 2015), being what we call today a bio-based economy. Since the Industrial Revolution, agriculture increased its land and human productivity by substituting its energetic requirement with fossil fuels. Agriculture becomes less reliant on the variability of natural mechanisms (Gliessman, 1998) but increasingly dependent on fossil fuels (Gupta and Hall 2011; Balogh et al. 2012; Krausmann 2016; Hall 2017). This is the turning point of our civilization from a solar economy to a mining economy (Daviron, 2016; Wrigley, 2013).

The modern agricultural system has presently reached a critical transition point in its performances (e.g. environmental impacts) (Tilman, 1999; Tilman et al., 2002) as well as its energetics pattern (e.g. the entire food system requires roughly 10 kcal of fossil energy to provide 1 kcal of food) (Bonny, 2011; Gingrich and Krausmann, 2018; IAASTD, 2009; OCDE/FAO, 2017; Pimentel et al., 2012). Energy now appears to sit at the border between two worlds (**Figure 3**), i.e., it is a strategic component of the economy (Han et al., 2019; Taghizadeh-Hesary et al., 2019) as well as a thermodynamic state variable for ecosystems (Odum, 1983).

Interest in agricultural energetic assessments began during the first oil crisis with the works of D. Pimentel (1973, 1976) and H. Odum (1973) in the 1970s. This attention declined during the 1980s when oil prices fell in 1986 (Risoud and Chopinet, 1999). Since the 2000s, energy assessment has been receiving renewed attention in part due to interest in biofuel production efficiency (Pelletier et al., 2011; Tilman et al., 2009), the impact of greenhouse gas (GHG) emissions on climate (Stocker, 2014) and the world fossil fuel peak production projected in 2025 (Mohr et al., 2015). This concern is expressed both by the amount of dedicated scientific papers (Vigne et al., 2012b) and by the variety of accounting methodologies (Pelletier et al., 2011). Energy analysis has been widely applied from farm scale to country scale (Aguilera et al., 2015). It generally attempts to determine the energy cost of agricultural production. This method, initially used for assessing fossil-fuel dependency, has applications for comparing farming practices, organic and conventional farming and recently biofuel production.

A number of existing reviews compile many energy analysis. Pelletier et al. (2011) described a general panorama of energy use in food systems with a life cycle perspective of food production. Zegada-Lizarazu et al. (2010) proposed a critical review of the energy balance of agricultural systems, highlighting the variability of the energetic value as well as the difficulty of defining a consistent system boundary. Smith et al. (2015) reviewed the energy efficiency of organic agriculture and compared it with conventional farming. They concluded that organic farming is more energy efficient than conventional farming, even though the productivity per unit of product is more variable. However, there is no exhaustive review of the energetic assessment approaches used to assess the agricultural production system.

The objectives of the present review are to identify the different energetic approaches applied to the agricultural production system, to analyze their main features and their ability to address resource efficiency issues, and to identify new lines of energy assessment promising field of investigation. It addresses farm scale by repositioning them according to other scales (i.e. crop or regional scales). First, we define a protocol to select the existing literature and provide a critical analysis of the different energetic approaches identified through five key

features. Secondly, we identify the main energetic approaches used to assess the agricultural production system. Then, we compare and analyze the different approaches through the key features. Finally, we discuss the issue of system boundaries and provide corresponding recommendations for future energetic approaches.



Figure 3: The agricultural system at the interface between the different forms of energy production (biomass, electricity) and the different land uses (crop fields, hedges, forests, facilities, wind turbines, and photovoltaic fields). (Copyright-free image)

2.2 Protocol of the review

2.2.1 Literature review method

This literature review is based on the request [TITLE: ((ener* or exer* or emer*) and (agri* or farm* or agro* or “food production” or livestock) NOT (emerging or emergency or wind or wave or tide))AND TOPIC: ((model* or balance or diagnostic or footprint or assessment or analysis))] used with “Web of Science”, 10th of August 2018. It results in a selection of 1,192 papers. From this set, a first selection was carried out through the title and the abstract. Conference papers, articles without references (no DOI address), and papers out of scope were not considered. A first categorization was made according to the scale of the study (i.e., product scale, farm scale, national scale) and by identifying articles with contextual elements. A total of 196 papers covering the scope of the review were finally selected. Even though farm scales are the main interest here, articles from other scales highlighting methodological issues were integrated. They were then organized into a comparative table in order to identify common features and to compare the different approaches. Although the present review rather focuses on energy assessments at farm scales, different scales of analysis have been covered due to the different contexts of

methodological aspects. While “Web of Science” requests revealed a general panorama, specific related articles that had not been included in the corpus were added to the review through the different references of the papers reviewed.

2.2.2 Key features to analyze energetic assessment approaches

The literature survey is analyzed through five key features, i.e., (i) goal & scope, (ii) system modeling, (iii) flow inventory, (iv) indicators, and (v) implementation. They are detailed in **Table 1** and briefly presented as follows.

(i) First, depending on the **goal & scope**, the practitioner chooses an appropriate energetic approach according to three main criteria i.e., i) system scale, ii) aim of the study and iii) type of agricultural production.

(ii) The choice of the approach has a direct influence on **System modelling**. It defines flow representation that is quantified within the system and between systems (Loiseau et al., 2012). In an energetic assessment, the agroecosystem is considered as a unique system or represented with different subsystems. According to the model and to the relevance of the analysis, focus would be put on the ecosphere or technosphere flows. The ecosphere refers to the environmental mechanisms, whereas the technosphere is related to human activities (Jolliet et al., 2015). The agroecosystem is considered here as a modified ecosystem by humans (Alhameid et al., 2017).

(iii) The type of energetic approach also determines the **flows inventoried**, i.e. (i) primary natural resources (i.e. sun, rain, wind or geothermy) referring to the environment (i.e. ecosphere), (ii) energy carrier and (iii) materials and products (fertilizers, raw materials, purchased seeds, forage, etc.) referring to the economic inputs (i.e. technosphere), (iv) human labor based on Fluck’s classification (Fluck, 1992) (i.e. muscular manpower, metabolized food energy, embodied energy of food consumed and a lifestyle measure of labour, based on gross national production), and (e) internal flows on-farm (Tello et al., 2015) corresponding to the portion of biomass from the system and reinvested in the agroecosystem (vegetal biomass reuse, manure) but also animal power used for traction.

(iv) According to the system modelling and flows inventory, **indicators** are built. An indicator is defined as an “observed variable that is used to report a non-observable reality” (Boulanger, 2004). Energetic indicators are directly related to energy assessment, such as EROI (Energy Return On Investment), energy productivity, energy intensity, net energy or energy renewability index. Other indicators express the consequence of fossil energy use (e.g. carbon footprint) or are paralleled to the economic dimension of agricultural production systems. The different energetic indicators are presented in supplementary material.

(v) Implementation refers to tools, data or existing frameworks that is mobilized to perform studies. The existence of specific software for energy assessment may suggest that the method is widely used and has a good level of methodological maturity. Likewise, even though the understandability of a method remains a qualitative criterion, it is a key element for the usability, application and adoption of the method by stakeholders.

Table 1: Key features and related criteria selected for the review

Key features	Related Criteria
i) Goal & scope	System Scale
	Aim of the study
	Type of agricultural production
ii) System modeling	Representation
	Accounting process
iii) Flow inventory	Primary natural resources
	Energy carrier
	Material and product
	Human labor
	Internal agroecosystem flow
iv) Indicators	Energetic indicators
	Other indicators
v) Implementation	Use of software
	Understandability
	Data availability

2.3 Energetic approaches used to assess the agricultural system

Energetic assessment of agricultural production system can embrace different forms of energy account that follow the first and, in some cases, the second law of thermodynamics. Ten approaches are identified and are presented according to the energy accounting: i) energy, ii) exergy and iii) energy.

2.3.1 Energy assessment

Energy assessment follows the first law of thermodynamics (i.e. the law of conservation). It has been defined as the process of determining the energy required directly and indirectly to allow a system to produce a determining product (or output) (IFIAS, 1974). The approach is commonly assimilated to process analysis (Jones, 1989) also known as bottom-up analysis (Murphy et al., 2011). Direct energy refers to the on-site energy used (e.g., fuel, electricity, gas, etc.). This corresponds to the heating value of the energy carrier consumed by the system (or process) but none of the energy requirements for prior steps (Dalgaard et al., 2001; Guintoli et al., 2014; Hülshbergen et al., 2001; IFIAS, 1978; Pratibha et al., 2015; Risoud, 1999). Murphy et al. (2011) define energy carriers as following: “It is a vector derived from a primary energy source (e.g. electricity, fuels or wood fire)”. Indirect energy (or off-site energy use) refers to the energy used to extract, transform and transport the inputs to the system. (e.g., fertilizers, pesticides, machinery, including fuels) (Aguilera et al., 2015). This corresponds to the energy embodied in the inputs, energy which is no more available as such (Hall, 2017), also called the energy

intensity of an input (Hall et al., 2011). The output represents the biomass production sold and is converted into energetic values. Energetic inputs and outputs are generally expressed in higher heating value, also known as gross calorific value (GCV), and is defined as the amount of heat released once it is combusted.

2.3.1.1 Approach #1: conventional energy analysis

Energetic analysis is the main method employed for assessing energy consumption and production (Figure 6a)). In this group, conventional energy analysis (**Figure 4**), also called net energy analysis or energy balance (Hall et al., 2011), is the most commonly applied (147 papers). Conventional energy analysis refers to works where the agricultural production system is considered as a sector of the economy (sectoral approach) (**Figure 9**), seen as a unique system, and where the socio-economic inputs and outputs are the main focus.

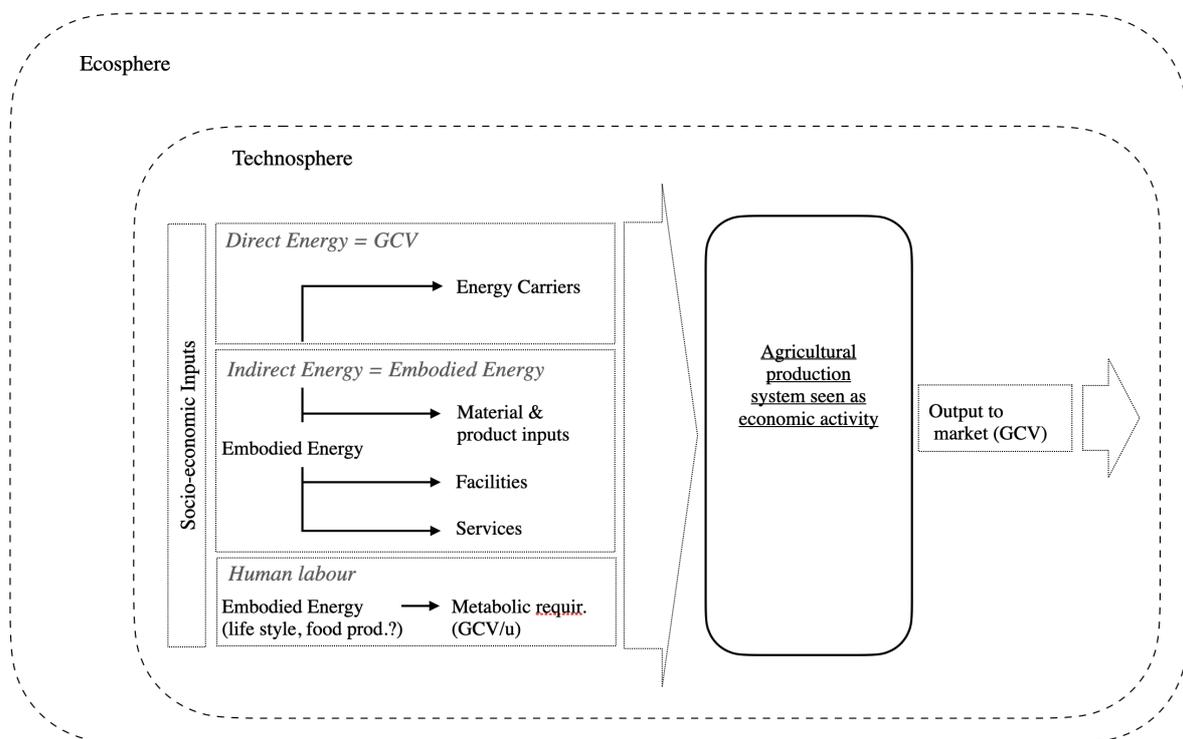


Figure 4: Conventional energy analysis diagram placed within a strong sustainability vision.

2.3.1.2 Approach #2: Pluri-energy analysis

Pluri-energy analysis framework proposed by Vigne et al. (2013b, 2014) is a first attempt to look energetic flows inside the agricultural system. This method aims at assessing the different types of energy mobilized and organized in agricultural systems, considering fossil energy, biomass (in gross energy), labour energy and solar energy. The framework proposes to focus on the energetic account of internal flows, thus picturing the contrasting subsystems of mixed farming systems. A footprint approach has also been applied to the framework (Vigne et al., 2012b). They notice that it provides a good picture of the system but does not allow for a clear identification of energy efficiency possibilities. In another work, Arrieta et al. (2018) pointed some difficulties in allocating indirect land use change to footprint.

2.3.1.3 Approach #3: Agroecological energy analysis

After the conventional approach, Agroecological energy analysis (AEA) is the most used energy assessment alternative (**Figure 5**). It is defined by the developers as an agroecological perspective of energy analysis (Guzmán et al. 2014, 2015, 2017, 2018) and a bioeconomic accountancy of the energy flows and yields of farm system (Tello et al., 2016). AEA emphasizes in the role of internal biomass reinvested in the agroecosystem, looking at the farm system as part of the socio-ecosystem (i.e. systemic approach) (**Figure 9**). It uses energy accounting for defining the socio-metabolism configuration between the agroecosystem and society (Cunfer et al., 2018; Fraňková and Cattaneo, 2018; Galán et al., 2016; Gingrich et al., 2018c; Guzmán et al., 2018; MacFadyen and Watson, 2018; Marull et al., 2016; Parcerisas and Dupras, 2018; Tello et al., 2016; Tello and González de Molina, 2017). Here, internal flow is considered as an energy flow that is produced and used by the agroecosystem through the biomass unharvested, and the biomass harvested intentionally left in the agricultural production system.

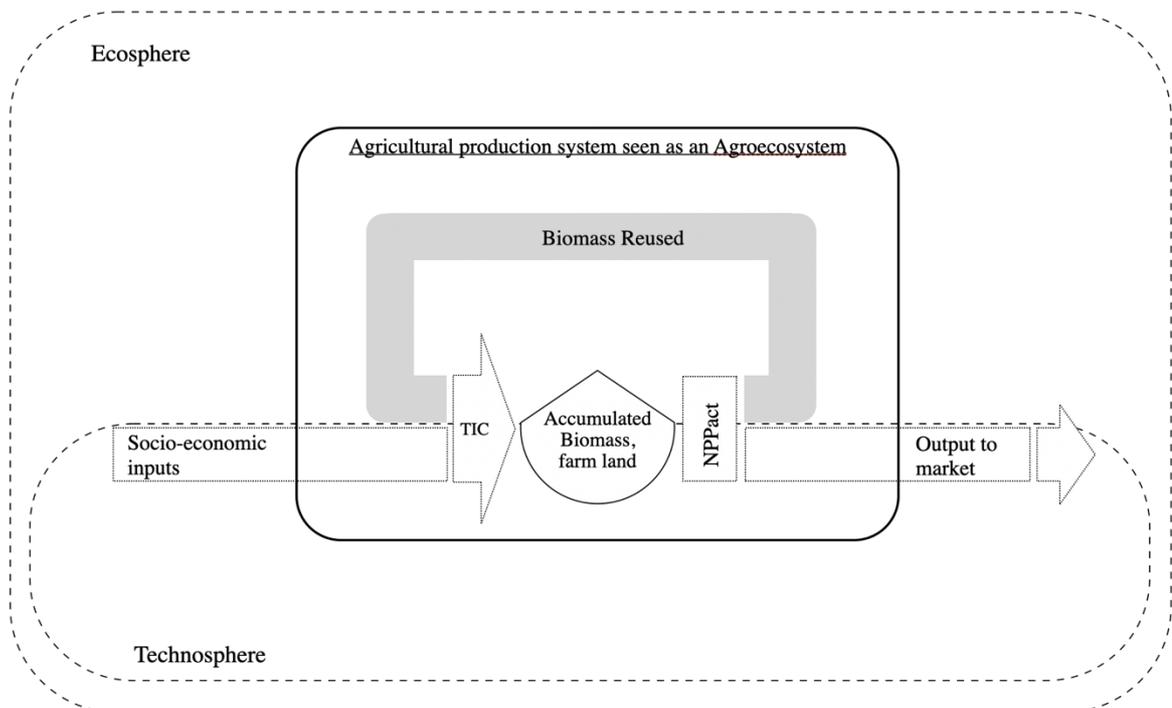


Figure 5: Agroecological energy analysis diagram placed within a strong sustainability vision.

2.3.2 Exergy assessment

Exergy follows the second law of thermodynamics. This means that all energetic processes are irreversible and produce a loss of energy called entropy (Szargut, 2005). Exergy is the maximum amount of useful work that is obtained from a particular system or resource when it has reached equilibrium (Dewulf et al., 2008). Exergy measures both the quantity and the quality of energy (Hoang and Alauddin, 2011). By quality, it means the ability of a certain energy source having certain amount of energy to cause change, i.e. the amount of energy which is extracted as useful (Dincer et al., 2005)

2.3.2.1 Approach #4 : Exergy analysis and approach #5: Cumulative exergy consumption

Exergy analysis initially focused on specific consumption related to energy carriers (e.g. Electricity for water pump or diesel consumption in tractors) to analyze the agricultural systems (Dincer et al., 2005; Utlu and Hepbasli, 2006). It is concerned with the quality of energy to cause change, degradation of energy during a process, the entropy generation and the lost opportunities to do work (**Figure 6**). Cumulative exergy consumption (CExC) extends exergy analysis beyond a single process to consider the exergy requirements of all the process and of its entire supply chain (Hoang and Alauddin, 2011; Sciubba, 2019). With the development of Life Cycle Assessment (LCA), the CExC is reinforced through the Cumulative Exergy Demand (CExD) (Hoang and Rao, 2010) present in database such as Ecoinvent. Exergy assessment and CExC share the same interest of conventional energy assessment as they are concerned by socio-economic inputs. It is expected that exergy efficiency is usually lower than the energy efficiency, because the irreversibility of the process destroys some of the input exergy (Dincer et al., 2005). For example, Huysveld et al. (2015) revealing that more than half of the resources consumed by dairy cows was irreversibly lost (through latent heating and transpiration). The remaining resources went to manure (54%), methane emission (9%), milk (32%) and animal slaughter (2%).

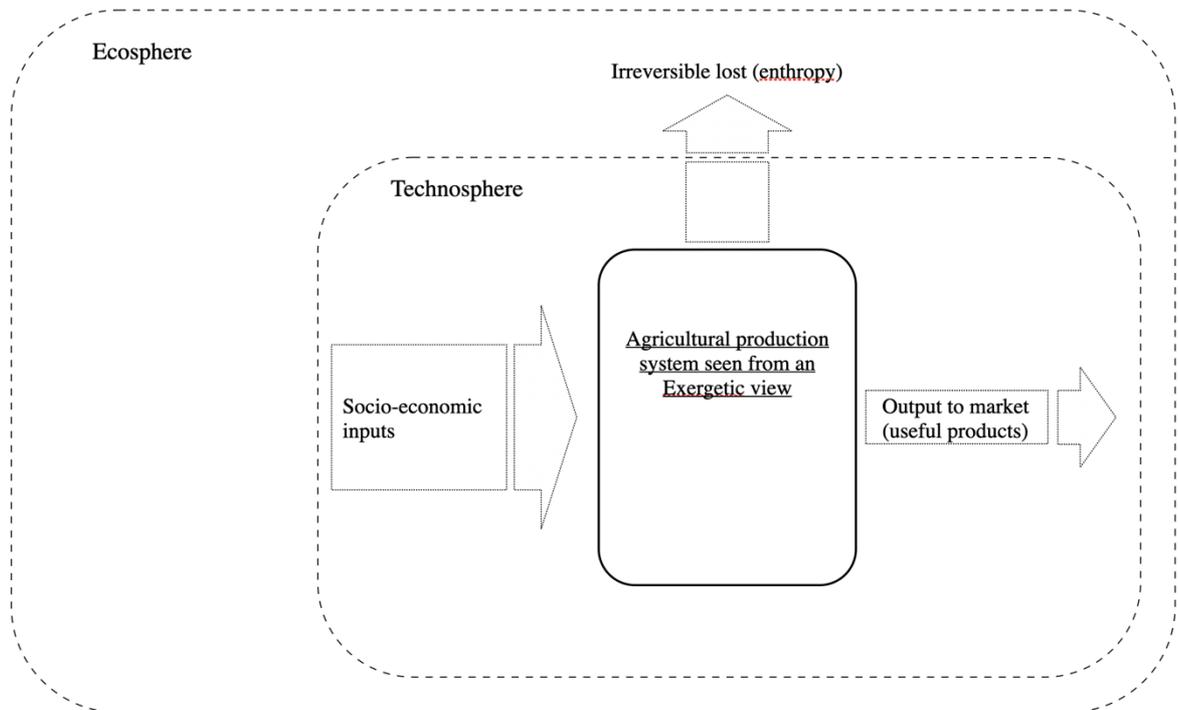


Figure 6: Exergy assessment diagram placed within a strong sustainability vision

2.3.2.2 Approach #6: Extended exergy account and approach #7: CEENE

Extended exergy accounting (EEA) involves, in addition to CExC, human labour, as well as capital and environmental impacts (Amiri et al., 2020; Sciubba, 2019, 2001). The environmental impact is assimilated to a virtual environment input cost. Manso et al. (2017) tested three exergy accounting methodologies in the Portuguese agricultural, forestry and fisheries sector, i.e., i) energy resources exergy accounting (EREA), ii) natural resources exergy accounting (NREA) and iii) EEA. The first one considers the intrinsic exergy contained in the energy

carrier, the second includes energy and matter. Manso et al. (2017) noted that the EEA results is dominated by capital and environmental impacts. Another identified approach is the Cumulative Exergy Extraction from the Natural Environment (CEENE) which was developed by Dewulf et al. (2007). This method quantifies eight categories of exergy “removed” from natural ecosystems, i.e., renewable resources, fossil fuels, nuclear energy, metal ores, minerals, water, land and atmospheric resources. In their analysis, Hoang and Alauddin (2011) concluded that when EEA and CEENE were combined, the organic content in topsoil, feed and total water withdrawal were the three main resources extracted from the environment.

2.3.2.3 Approach #8: Eco-exergy and approach #9: Cosmic exergy analysis

Another exergetic accounting method identified in this review is Eco-exergy developed by S.E. Jorgensen (2006). Eco-exergy is defined as the chemical exergy of an organism (its distance from chemical equilibrium) plus the exergy embodied in the (genetic) information. Perryman and Schramski (2015) proposed to combine EROI and Eco-exergy ratios to evaluate both the quantity and quality of energy accumulated and dissipated in the agricultural processes of nine countries. The results reveal a correlation between these food production indicators and the ecological footprint (resources being consumed) of each country while no correlation with their respective biocapacity was evidenced.

We also identify Cosmic Exergy analysis (Chen, 2006). This approach mobilized embodied exergy to define Odum’s Energy (solar energy based accounting, see **2.3.3**), resulting in a combine method placing exergy at planetary boundary scale (Chen et al., 2009, 2011). It has been applied to farm system in order to compare three agroecosystem scenarios (i.e., farmland-biogas, farmland-dairy, farmland-dairy-biogas) (Liu et al., 2017). We have not developed this method any further in the manuscript.

2.3.3 Emergy assessment

Emergy is another form of accounting energy (approach #10) (**Figure 7**). It involves a more ecocentric vision that considers in addition to the energies coming from the society, the energies from the natural flows (Giannetti et al., 2011; Smith et al., 2015; Yi and Xiang, 2016; Zhang and Long, 2010). Ecocentric vision implies that humankind is an equal part of nature and is associated with ecosystems (Abaidoo and Dickinson, 2009). Initial development of emergy analysis began in the 1980s with the works of Odum (1983, 1984). However, it is only since 2006 that emergy assessment has been applied more commonly in agricultural systems (Cavalett et al., 2006; Chen et al., 2006; Diemont et al., 2006; Martin et al., 2006). Emergy represents all the energy used during the work processes that generates a product or service according to a life cycle perspective. It is expressed with a common unit based on solar radiation (Brown and Ulgiati, 2004). Solar Joule is the unit for measuring the energy required to generate a product weighted in solar energy. Some researchers consider emergy as a sort of memory of solar energy that has been used (Pizzigallo et al., 2008). Emergy classifies inputs in four categories: i) natural renewable resources (sun, rain, wind), ii) natural non-renewable resources (e.g. soil organic matter or ground water), iii) purchased non-renewable inputs (fossil fuels, fertilizers), iv) purchased renewable inputs (e.g. seeds, organic fertilizer) (Agostinho et al., 2008; Cavalett et al., 2006; Rodríguez-Ortega et al., 2017; Zhang et al., 2013).

Emergy is often presented as a complementary accounting method offering a global vision of energy dynamics where natural flows such as the sun, wind or water are considered (Fan et al., 2018; Jafari et al., 2018; Kuczuk et al., 2017; Lu et al., 2010; Vigne et al., 2013b, 2012b). It can complement a standard socio-economic

optimization model by adding a biophysical value to an agricultural system evaluation (Kocjančič et al., 2018). In this case, energy does not reflect the usefulness of a product but rather the cumulative environmental support for its existence. Energy presents a relative homogeneity in its approach and in its accounting procedures.

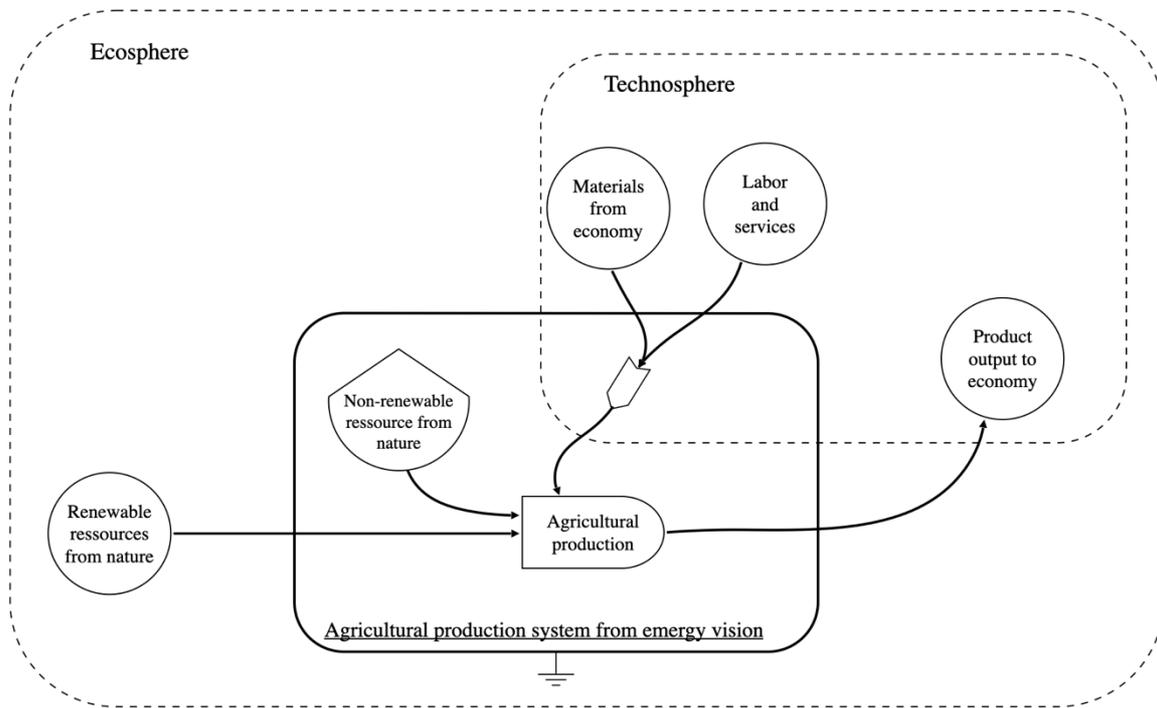


Figure 7: Energy assessment diagram placed within a strong sustainability vision

2.4 Analysis of energetic approaches through the key features

2.4.1 Goal and scope of the reviewed studies

2.4.1.1 System scale

The majority of articles from the 196 papers selected in this review concerned farm system scales (**Figure 8b**). Articles focusing on national and global scales were second most important, followed by landscape or regional scales. Finally, only a few articles focused on the crop scale. Conventional energy analysis (used for all scales) is the only used energetic approach for comparing specific crop production (Fathollahi et al., 2018), studying agronomic approaches and technologies (Arodudu et al., 2017; Budzyński et al., 2015; Diacono et al., 2017; Fathollahi et al., 2018), or specific crop growth for bioenergy (Jankowski et al., 2016). Agroecological energy analysis is applied to regional and national scales (Gingrich et al., 2018b). Indeed, one goal of this approach is to explain landscape evolution and its relation with food system pattern (Cattaneo et al., 2018; Gingrich et al., 2018a; Padró et al., 2017). Exergy approaches are also mainly focus on regional and national scale (Ahamed et al., 2011; Chen et al., 2009; Ghandoor and Jaber, 2009; Utlu and Hepbasli, 2006) with one exception addressed at farm scale (Liu et al., 2017) and another two which were out of the “web of science” request (Amiri et al., 2020; Huysveld et al., 2015). Concerning energy approach, the main scale is the farm system (24 from the 35 energy study reviewed).

2.4.1.2 Aim of the study

According to the type of study, the majority (45%) of the papers focused on the comparison of farming systems (e.g. organic vs conventional or integrated vs conventional agricultures) (Alonso and Guzmán, 2010; Bailey et al., 2003), farming practices (tillage vs non-tillage, different dairy housing system) (Alluvione et al., 2011; Uzal, 2013), or comparing agricultural product energy efficiency (for food production or biofuels) (Elsoragaby et al., 2019; Fore et al., 2011; Pimentel and Patzek, 2007). The second most important type of studies comprised specific case studies of agricultural system and production (30%) studying particularly energy consumption (Bartzas and Komnitsas, 2018; Bhatt and Bujarbaruah, 2011; Clark et al., 2016; Migliorini et al., 2012; Pérez Neira et al., 2014). Indeed, conventional energy analysis, exergy and CExC aims to analyze the direct and indirect energetic cost of agricultural production when energy assessment looks at the global resources consumption, focusing on the sustainability of the farm system. EEA and CEENE also assess global resource consumption with a more anthropocentric interest using such as land resource use. Another set of articles focused on the historical evolution of energy use (**Figure 8c**). If traditionally and presently conventional energy analysis is used to measure our increasing dependency on fossil energy, Agroecological energy analysis is particularly dynamic in assessing historical evolution (Díez et al., 2018; Guzmán et al., 2018; Harchaoui and Chatzimpiros, 2019; Infante-Amate and Picado, 2018; Marco et al., 2018; Soto et al., 2016; Tello et al., 2016). Indeed, this approach assesses socio-metabolic and landscape evolution and configuration through its energetic framework enhancing energy return into the agroecosystem understudy.

Twenty-three articles were dedicated to review and methodological aspects. Three reviews of interest have been highlighted (Pelletier et al., 2011; Smith et al., 2015; Zegada-Lizarazu et al., 2010) (see **Introduction**). A fourth review of Aguilera et al. (2015) (out of the request from “Web of Science”) must be also mentioned and presents a deep research on the historical evolution of the embodied energy in agricultural inputs. Based on methodological aspects, Jones (1989) is often cited when referring to process analysis. Here, among others, an empirical classification of system boundaries is proposed, according to the method and scale of inventory (i.e. fossil fuel accounting, process analysis, ecosystem analysis method, and thermodynamic analysis). The methodological works of Guzmán et al. (2015, 2017) and Tello et al. (2016) must also be highlighted, where a socio-metabolic (Gomiero, 2017; Krausmann, 2016, 2008) energy profile of the agroecosystem is proposed.

2.4.1.3 Type of agricultural production

Regarding the type of agricultural production assessed, crop production for food or bioenergy is the main focus (**Figure 8d**). Animal production and mixed crop livestock systems are similarly assessed.

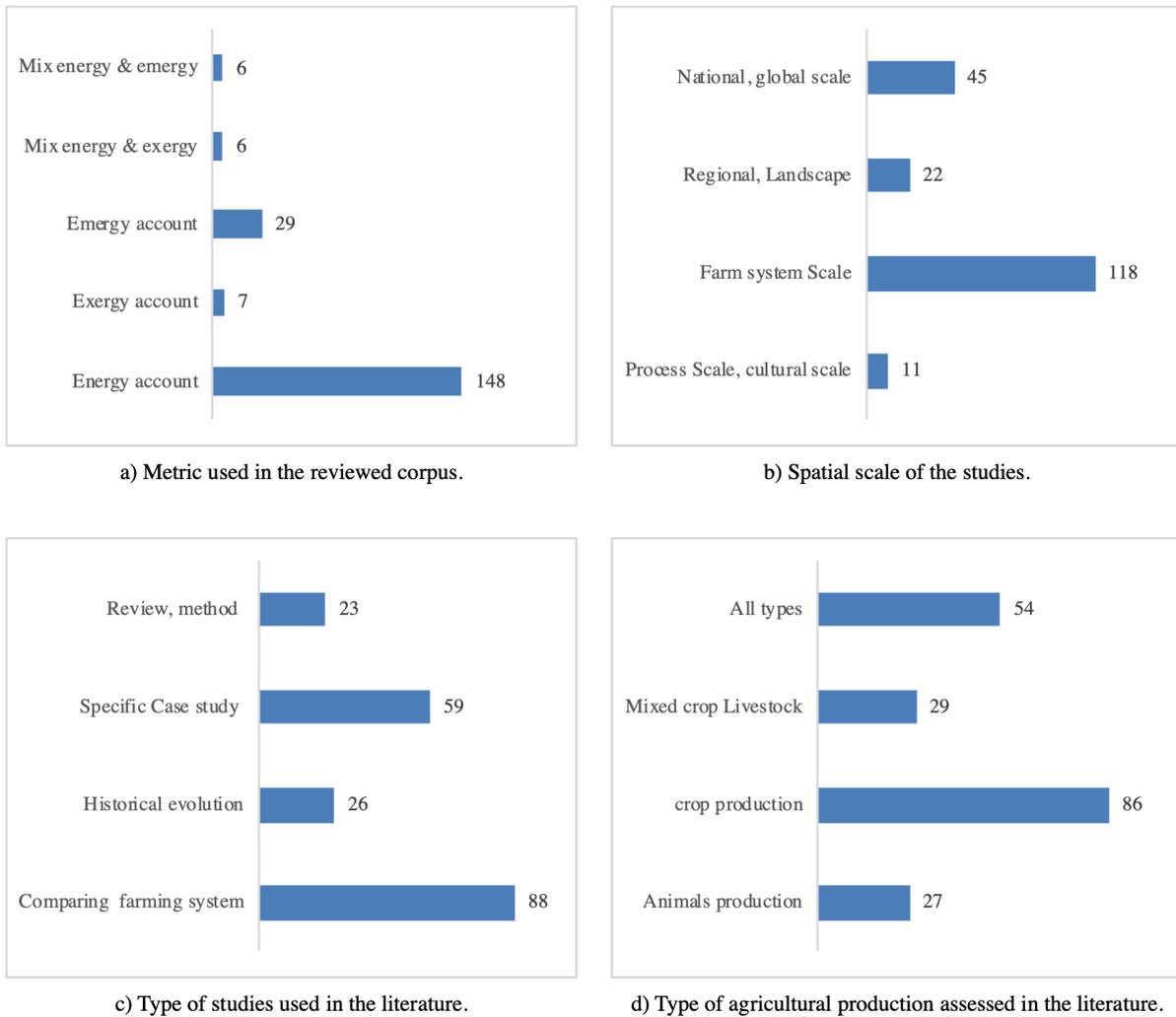


Figure 8: Distribution of the 196 scientific literature reviewed from the “Web of Science” request through different criteria: (a) the metric used, (b) the spatial scale, (c) the type of studies and (d) the type of agricultural production.

2.4.1.4 System modelling

Energy assessment generally considers the farm as a unique system (75% of the “web of science” request corpus) without any differentiation between production processes and environmental support functions (Tello et al., 2016). Subsystem representation allows for the presence of internal flows and process configuration. According to the subsystem representation, this can highlight major internal flows of biomass within the system (Tello et al., 2015). Vigne et al. (2013b) suggested the farm scale system representation should be disassembled in order to compare contrasting dairy systems. The farm was thus divided into six generic subsystems, i.e., building and material, crop, vegetal production storage, livestock, manure storage and family. Thanks to this method, significant differences in the configuration of energy flows between contrasting territories was revealed.

Tello et al. (2016) highlighted internal biomass reuse and its circularity aspects in the agroecosystem by representing three interconnected energy subsystems, i.e., livestock, farmland (composed of cropland, woodland and pasture) and associated biodiversity. The agroecosystem was split into farmland and associated biodiversity (logical distribution in a farm operator’s point of view), because each subsystem provides a different functionality

(Tello et al., 2015). Farmland produces biomass for exportation while associated biodiversity ensures the regulation and support of ecosystem services.

A large part of emergy assessment is characterized by an energy system diagram, which is more (An et al., 1998) or less (Hu et al., 2012) complex and where other approaches such as LCA are associated (Wang et al., 2015, 2014). At the difference of the other resources, natural non-renewable resources, also called local non-renewable resources (i.e. soil organic matter (SOM) and ground water consumption), is represented inside the system as a storage system (diagram representation in supplementary material) (Jafari et al., 2018; Jaklič et al., 2014; Wu et al., 2013). Fan et al. (2018) propose to reflect the dynamic of SOM storage in the agricultural production system by integrating SOM losses (i.e. already assess in an emergy assessment), but also considering SOM gain as a co-product and accounted as an input.

Exergy papers do not depict farm subsystems as they are rather focused on accounting at national scales (Ahamed et al., 2011; Dincer et al., 2005; Ghandoor and Jaber, 2009; Utlu and Hepbasli, 2006) or at process scales (Zisopoulos et al., 2017). However, the study by Huysveld et al. (2015) (although out of the request) should be mentioned in subsystem farm representation. In this case study (i.e. specialized dairy farm in Flanders), an exergy assessment is first performed at process scale (the herd), revealing that more than half of the resources consumed by the herd is irreversibly lost. In a second step, an exergy analysis at farm scale with the CEENE method was carried out. It revealed that 93% of the total CEENE, in the case of a specific intensive dairy farm, is due to feed supply.

2.4.2 Flow inventory

2.4.2.1 Primary natural resources

Energy assessment does not take natural flows into account, such as sun radiation, wind or water, as these are not produced by the socio-economic environment (technosphere) (Aguilera et al., 2015). With emergy analysis, these flows are considered through the amount of solar radiation accumulated in products and services. Nonetheless, the work of Bulatkin (2012), integrate natural resources while using Joule in its energetic accounting. The assessment is an attempt to allow for the different types of energy to be compared in terms of quality (Aguilera et al., 2015). Bulatkin (2012) proposed four categories of flows, i.e., solar radiation, organic matter and crop residue, energy of soil humus, and anthropogenic energy flows. Energy of soil humus is nicely represented through the energy lost during soil processes (i.e. soil mineralization).

Guzmán et al. (2015) propose to evaluate agroecosystem production in terms of Net Primary Production (NPP) (Guzmán et al., 2014), thus taking into account all biomass production in the system. Even if solar energy is not considered here (because it cannot be directly possessed or controlled by humans (Tello et al., 2015), NPP represents the true amount of energy incorporated into plant tissues (Guzmán et al., 2018) and, indirectly solar radiation.

2.4.2.2 Energy carrier, material and products

Few studies clearly express energy carrier (e.g. fuels) both in terms of Gross Calorific Value (GCV) and in terms of embodied energy (Felten et al., 2013; Shamshirband et al., 2015). When information was lacking, the energetic value was used for distinguishing between a cumulative value (GCV plus embodied energy) or an

enthalpy value (i.e. GCV). When diesel energetic value is close to $45,7 \text{ MJ.kg}^{-1}$ (or $38,5 \text{ MJ.L}^{-1}$) (Aguilera et al., 2015), the energy carrier is only considered in terms of GCV. Also, the use of direct and indirect terms to express inputs is a source of misunderstanding. Some consider that direct energy inputs correspond to the GCV plus the embodied energy of an energy carrier (Mendoza, 2005) when others consider that direct energy corresponds only the GCV of an energy carrier (Shamshirband et al., 2015). This can lead to forgetfulness of the embodied energy of energy carriers in study that, on the one hand, considers embodied energy of materials and products (i.e. fertilizers, pesticides, machinery, etc.) without considering the embodied energy of e.g. diesel (Lin et al., 2017; Migliorini et al., 2012; Veiga et al., 2015). Using only the GCV for energy carriers (i.e. direct energy) is justified if the main objective of the study is to measure on-farm engines consumption.

In the case of materials and product inputs, embodied energy is generally taken into account from cradle to farm-gate (Koesling et al., 2017; Pagani et al., 2016; Veysset et al., 2010). However, external biomass inputs such as seeds, manure and organic matter still not clearly described. In some cases, purchased seeds are accounted in terms of embodied energy (Bos et al., 2014; Ghorbani et al., 2011; Kuesters and Lammel, 1999), while in other cases it is the GCV of seeds that is take into account (Rahman et al., 2014; Rahman and Barmon, 2012; Rahman and Hasan, 2014). In their comparison between organic and conventional Spanish farming systems, Alonso and Guzman (2010) take into account both the cost of manufacturing and the energy content of the product (nutrient compositions) for chemical and mineral fertilizers. Pérez Neira et al. (2012) clearly presented manure inputs by only considering the energy content of the product when originating from the system itself as well as both GCV and embodied energy when purchased. In the case of materials and equipment, the energy required to produce them is depreciated according to a specific amortization method (Benoit and Laignel, 2010) or more commonly uniformly distributed over the lifetime (total energy divided by years of useful life) (Alonso and Guzmán, 2010).

2.4.2.3 Human labor

Measuring the energetics of human labor is highly controversial (Wu et al., 2011) and varies widely depending on system boundaries (Aguilera et al., 2015). The most notable works on the energy of human labor are probably the hierarchical Fluck (1992) review, the Jones (1989) thought process, the Aguilera et al. (2015) analysis, and also the work of Giampietro and Pimentel (1990). Many studies exclude human labor, particularly in industrialized systems, where it is marginal energetic value (Cleveland, 1995; Maraseni et al., 2015). Still, without human labor, we would have no production. Others argue that it is too different from fossil energy to be expressed in the same units (Hülsbergen et al., 2001; Refsgaard et al., 1998). Metabolized food energy during work is the first energetic value used to describe human effort. It used generally $2,2 \text{ MJ.h}^{-1}$, based on an 8-hour working day (Pimentel et al., 1973) in western countries and $1,96 \text{ MJ.h}^{-1}$ in Middle Eastern countries (Gündoğmuş and Gu, 2006; Mohammadi et al., 2014; Singh et al., 1988).

The last has been disapproved by Wu et al. (2011) who considered that by only accounting metabolic requirements, human labor is underestimated. The embodied energy related to production of food for laborers is mostly not accounted and can generate double counting issues (Aguilera et al., 2015). For the different manuscript based on agroecological energy analysis approach cited in this review, consumption baskets have been accounted from an embodied point of view considering site-specific data (by considering for example the energy embodied in transporting the food (Tello et al., 2015).

Sunshine Farm case study (Baum et al., 2009) also adopt an extended boundary for human labor. They applied net energy analysis for accounting human labor (Fluck, 1981), including human lifestyle through input-output analysis, which was equivalent to $75\text{MJ}\cdot\text{h}^{-1}$. Baum et al. (2009). also introduced the question of commuting energy in the farm system which could represent, following the formula of Patzek (2004), 34-54% of the $75\text{MJ}\cdot\text{h}^{-1}$ of labor. Later, Pimentel estimated the energy input for labor based on a yearly consumption of 8.000 l oil equivalent per person and 2,000 working hours, representing $167,6\text{ MJ}\cdot\text{h}^{-1}$ (Pimentel and Patzek, 2007). Since transport is a large proportion of all the energy used in agriculture, this could be a good parameter to integrate, whether it is for the characterization of the embodied energy in food production or for the embodied energy in workers' displacement.

2.4.2.4 Internal flow

Consideration of internal flows is not recent, since an old article of the review dealing with on-farm circulating flows dates back to Han et al. (1985). In this study, they consider manure reuse within the system (70% of manure is collected and used in cropland), recycled outputs from crop production (e.g. seeds, seed cakes and straw), human dejection, and reuse of biomass from non-cropland areas as green manure. Depending on the configuration between the farmers and the system, internal flows are also allocated to human nutrition. At a village community scale, Tripathi and Sah (2001) integrated the human component to the energy analysis of internal flows because humans were important consumers of the biomass production. More recently Harchaoui and Chatzimpiros (2019) emphasize in the importance to consider energy flows reinvested in food for humans and feed for draft animals (called "self-fueling") in order to measure trade-off between self-fueling and external inputs.

For Guzmán et al. (2015) internal flows refer to the flow of biomass reinvested in the system in order to keep the agroecosystem operational. The global biomass production is divided into biomass export (i.e. biomass sold), biomass reuse (i.e. harvested and reuse), unharvested biomass (i.e. roots principally) and accumulated biomass (in perennial plants). The configuration of this biomass flow characterizes and defines the capacity of the agroecosystem to generate flows of ecosystem services (Guzmán et al., 2018; Parcerisas and Dupras, 2018; Tello et al., 2016).

In emergy, representation of internal flows is not necessarily detailed (Patrizi et al., 2018), but they are generally associated with a stock called in emergy "natural non-renewable resources" (Cavalett et al., 2006; La Rosa et al., 2008) (i.e. soil organic matter, Ground water). In other emergy study, the portion of the biomass production reinvested into the system has clearly been expressed (Diemont et al., 2006; Jafari et al., 2018). However, in the case of emergy, due to the background notion of cumulative energy, the risk of double counting remains a point of awareness (Patrizi et al., 2018).

Actually, Soil organic matter is defined as the solar energy stored in the farm system (Jordan, 2016). Its renewability will depend on how we take care of this resource and is defined as a fund resource (Tello et al., 2015). At the difference of stock resource (based on the consumption of a declining resource), a fund resource is defined by a give rate of flow production (Georgescu-Roegen, 1971; Giampietro et al., 1992). This notion is a key element in understanding the interest of assessing internal flows and its role played in maintaining agroecosystem function.

2.4.3 Energetic indicators

2.4.3.1 Energy use Efficiency

Energy use efficiency, commonly called Energy return on energy Invest (EROI) is the ratio between output and input (all the indicators cited are in supplementary material) (Hall, 2017; Hall et al., 2009). Present in 75% of the 196 papers from the “web of science” request, it is the most commonly used energetic indicator and concerns principally purchased inputs (also called external inputs) and outputs sold (**Table 2**). Variability in system boundaries makes difficult comparing energy efficiency between system. In order to reinforce exhaustiveness but also to avoid confusion in the type of energy inputs, Pérez Neira et al. (2018) propose to specify energy inputs in terms of cumulative energy demand used in LCA.

In the case of agroecological energy analysis, Guzman et al. (2015) and Tello et al. (2016) consider that one EROI is not enough and suggest three different EROI (i.e. External Final EROI, Final EROI and Internal final EROI). Guzman et al. (2015) go further suggesting EROI from an agroecological point of view (**Table 3**), integrating all the biomass produce of the agroecosystem and not just the part that is sold (e.g. NPPactEROI).

In the same direction of integrating agroecosystem elements in the EROI, two energetic assessments suggest the integration of Soil Organic Matter variation (Δ SOM) into the EROI (Alluvione et al., 2011; Fan et al., 2018). If there is a loss of SOM, it is considered as an output and added to the other outputs of the system (i.e. as a nominator) (Alluvione et al., 2011; Fan et al., 2018). Fan et al. (2018) go further by considering SOM as an input (i.e. as a denominator) if there is a gain in SOM. Soil loss and decrease of SOM remain important issues in present-day agricultural practices that affect crop yield, physical soil properties, fertility and water-holding capacity (Pimentel et al., 2012). Fan et al. (2018) observations suggest that soil loss and SOM decrease produce a stronger influence on EROI than mineral fertilization. Indeed, in its study, the crop rotation (i.e. fallow-wheat-pea, with a low input strategy and no tillage) that showed the best EROI (12,9), fall to near the worst crop rotation trial (EROI: 3,7) when integrating SOM decrease.

Table 2: Energetic indicators used in the literature with an anthropic consideration of the system

Energetic indicators	Notes	References
$EROI = \frac{\text{Energy Output (sold) (MJ)}}{\text{Energy input (purchased) (MJ)}}$	<p>This EROI refers to socio-economic input output. It is equivalent to other terms: Energy (use) Efficiency, Input Output ratio, External EROI</p>	a) (See table note)
$\text{Internal EROI} = \frac{\text{Energy Output (MJ)}}{\text{Biomass reuse (MJ)}}$	<p>Refers to the efficiency of internal biomass intentionally return into the system</p>	b) (See table note)
$\text{Final EROI} = \frac{\text{Energy Output (MJ)}}{\text{External input + Biomass reuse (MJ)}}$	<p>Biomass reuse refers to harvested crop residue and reused intentionally in the system</p>	b) (See table note)
$\text{Non Renewable EROI} = \frac{\text{Energy Output (MJ)}}{\text{Non renewable external input (MJ)}}$		c) (See table note)
$\text{Fossil energy Efficiency} = \frac{\text{Energy Output (MJ)}}{\text{fossil energy direct and indirect input (MJ)}}$		(Mendoza 2005; Vigne et al. 2013b)
$\text{Gross energy efficiency} = \frac{\text{Energy Output (MJ)}}{\text{External Biomass input (MJ)}}$	<p>consider the gross calorific value of the external biomass consumed</p>	(Vigne et al. 2013b)
$\text{labor energy efficiency} = \frac{\text{Energy Output (MJ)}}{\text{Human labor (metabolic value)(MJ)}}$	<p>Adapt to local conditions and activities with a stress score value from 1 (driving) to 5 (plowing)</p>	(Vigne et al. 2013b)
$\text{Solar energy efficiency} = \frac{\text{Energy Output (MJ)}}{\text{Photosynthetic Active Radiation (MJ)}}$		(Vigne et al. 2013b)

Table note: a) (Mirini et al. 2002; Singh et al. 2002; Jianbo 2006; Baum et al. 2009; Hall et al. 2011; Alluvione et al. 2011; Ramedani et al. 2011; Rahman and Barmon 2012; Soni et al. 2013; Firrisa et al. 2014; Sefeedpari et al. 2014b; Atlason et al. 2015; Guzmán et al. 2015; Tello et al. 2016; Parcerisas and Dupras 2018; Pérez Neira et al. 2018; Bartzas and Kommitsas 2018) ; b) (Guzmán et al. 2015, 2018; Tello et al. 2016; Galán et al. 2016; Parcerisas and Dupras 2018) ; c) (Alonso and Guzmán 2010; de Muner et al. 2015; Pérez Neira 2016; Pérez Neira et al. 2018)

Table 3: Energetic indicators used in the literature with an agroecological consideration of the system

Energetic indicators	Notes	References
$\text{Agroecological Final EROI} = \frac{\text{Energy Output (MJ)}}{\text{Biomass reuse + external input + Unharvested biomass (MJ)}}$	Energy expressly invested in the system and the recycled without human intervention	(Guzmán et al. 2015, 2018)
$\text{NPPact EROI} = \frac{\text{NPPact (MJ)}}{\text{Biomass reuse + external input + Unharvested biomass (MJ)}}$	NPPact is the amount of energy actually incorporated into all plant tissues	(Guzmán et al. 2015, 2018; Galá al. 2016)
$\text{Biodiversity EROI} = \frac{\text{Unharvested biomass (MJ)}}{\text{Biomass reuse + external input + Unharvested biomass (MJ)}}$	0 means all biomass is reused. 1 means natural ecosystem without human intervention	(Guzmán et al. 2018)
$\text{Woodening EROI} = \frac{\text{Accumulated biomass (MJ)}}{\text{Biomass reuse + external input + Unharvested biomass (MJ)}}$	Informs whether the energy added to the system contributes to the storage of energy in the system	(Guzmán et al. 2018)
$\text{Environmental Efficiency of Support Energy} = \frac{\text{Energy Output} + \Delta\text{SOM (MJ)}}{\text{Energy input (MJ)}}$	this indicator aims at evaluating system efficiency by using supporting energy	(Alluvione et al. 2011)
$\text{Input Output ratio } \Delta\text{SOC} = \frac{\text{Energy Output} + \Delta\text{SOC (MJ)}}{\text{Energy input (MJ)}}, \Delta\text{SOC} > 0 ; = \frac{\text{Energy Output (MJ)}}{\text{Energy input} + \Delta\text{SOC (MJ)}}, \Delta\text{SOC} < 0$	considering variation of Soil Organic Matter	(Fan et al. 2018)
$\text{Indicator of Immediate Removal} = \frac{\text{Biomass harvested (MJ)}}{\text{EUnharvested Biomass (MJ)}}$	Determine cropping system orientation as market-focused or soil fertility focused	(Alluvione et al. 2011)
$\text{Edible Energy Efficiency} = \frac{\text{Edible Energy Output (MJ)}}{\text{EUnharvested Biomass (MJ)}}$		(Galán et al. 2016)

Table 4: Other energetic indicators used in the literature

Energetic indicators	Notes	References
$\text{Specific Energy Input} = \frac{\text{Energy Input (MJ)}}{\text{Crop yield (kg)}}$	Amount of energy used to produce one kg of product	a) (See table note)
$\text{Energy productivity} = \frac{\text{Crop yield (kg)}}{\text{Energy Input (MJ)}}$	Amount of product obtain per unit of energy input	b) (See table note)
$\text{Net Energy Gain} = \text{Energy Output} - \text{Energy Input}$		c) (See table note)
$\text{Energy intensiveness} = \frac{\text{energy input (MJ)}}{\text{Total cost (\$)}}$		(Zangeneh et al. 2010; Choudhary et al. 2017)
$\text{Energy intensity} = \frac{\text{Energy input (MJ)}}{\text{Energy output (MJ)}}$		(Koesling et al. 2017)
$\text{Energy productivity per labor unit} = \frac{\text{Energy output (MJ)}}{\text{Labor unit (h)}}$		(Choudhary et al. 2017)
$\text{Net Environmental Energy} = \text{Energy Output} + \Delta\text{SOM} - \text{Energy Input}$		(Alluvione et al. 2011)

Table note: a) (Singh et al. 2004; Ramedani et al. 2011; Rahman and Barmon 2012; Jekayinfa et al. 2012, 2013; Sefeedpari et al. 2013, 2014b; Pagani et al. 2016; Bartzas and Kommitsas 2018) ; b) (Rahman and Barmon 2012; Jekayinfa et al. 2012; Sefeedpari et al. 2012; Sefeedpari et al. 2014b; Barmon 2012; Jekayinfa et al. 2012; Sefeedpari et al. 2014b; Arodudu et al. 2016)

2.4.3.2 Other energetic indicators

Energy intensity represents the embodied energy per output. A majority of articles use the term “specific Energy input” when analyzing energetic consumption (both direct and indirect) per unit of product. Energy intensity should not be mistaken with the term “energy intensiveness” employed in other articles (Choudhary et al., 2017; Zangeneh et al., 2010) representing the cost of energy inputs consumed as a fraction of the total inputs (**Table 4**).

Energy productivity (unit.MJ⁻¹) and Net energy (Output - Input) are also common energetic indicators found in the literature. Energy productivity was more frequently used in crop production topics (Bartzas and Komnitsas, 2018; Choudhary et al., 2017; Jekayinfa et al., 2012; Sefeedpari et al., 2014a).

Concerning renewability ratio (i.e. renewable / non-renewable), even if it is principally in energy account that we met this indicator, for certain energetic analysis, particularly in Middle Eastern countries, a clear differentiation between non-renewable and renewable inputs is generally made (Beheshti Tabar et al., 2010; Choudhary et al., 2017; Mohammadi et al., 2014; Pishgar-Komleh et al., 2012).

2.4.4 Implementation

In the corpus of reviewed articles, seven articles were identified for their use of specific software to calculate energy flows in agricultural systems. Chen and Baillie (2009) assessed the use of on-farm operational energy (direct energy) for cotton production using EnergyCalc software. Another computer tool identified in 3 papers (Benoit and Laignel, 2010; Veysset et al., 2010; Vigne et al., 2014) is the Planet method developed by Risoud (1999) and Bochu (2006). Planet calculates the energy balance and performs an efficiency analysis considering essentially fossil fuels and electricity that are directly and indirectly consumed by the system (Benoit and Laignel, 2010). Kraatz (2012) also employed modelling software called REPRO (Reproduction of Soil Fertility) to analyze the farming system and to evaluate energy intensity in livestock operations. FEAT (Farm Energy Analysis Tool) is an open-source database model developed by Camargo et al. (2013) in an attempt to unify approaches, interfaces and sourcing data. It calculates energy use and GHG emissions. Finally, Fathollahi et al. (2018) performed an energy, economic and environmental analysis of forage production systems using SimaPro 8.3.0. They thus produced a complete energetic analysis combined with a LCA.

Understandability is a qualitative criteria in the present review and must be interpreted with caution as it is relatively subjective. Nevertheless, the majority of energy and exergy assessments were classified in the “difficult” category. This is partly because energy and exergy methods are based on the second law of thermodynamics.

The majority of the energetic value was obtained from the literature with a large range of variability (Vigne et al., 2012a; Zegada-Lizarazu et al., 2010). Some papers use general databases such as Ecoinvent (Barak et al., 2016; Blancard and Martin, 2014; Ghisellini et al., 2016; Koesling et al., 2017; Pishgar-Komleh et al., 2017; Pragya et al., 2017; Todde et al., 2018a; Upton et al., 2013). However, precision also requires that energetic values adapt to local conditions (Alonso and Guzmán, 2010; Vigne et al., 2013a, 2012a) (e.g. machinery production, electric matrix, fossil energy or human labor). Transport of input, such as biomass (feed, organic matter, etc.) used on-farm was usually the major adjustment made (Guzmán et al., 2018; Pérez Neira et al., 2018). Concerning energy,

a general database with transformity values (i.e. solar joule per unit of joule) is not yet available, which can lead to higher variability in energetic value (Amaral et al., 2016).

2.5 Recommendations to conduct exhaustive energetic assessments

2.5.1 Specific semantic related to energy assessment

A large part of this review concerns system boundary definition, which remains a particular point of frailty in the energy assessments. The selection of an appropriate system boundary for energy analysis and for applying indicators such as EROI is a crucial step which is often overlooked (Murphy et al., 2011). Thus, a first step for a clear and coherent system boundary will be related to the semantic mobilized. Non-homogenized semantics and the vocabulary result from the plurality of approaches. However it also reflects variability in the system boundary and limits the exhaustiveness in the flow inventory.

The distinction of inputs in “direct” and “indirect” still remains a source of misunderstanding (see **section 2.4.2.2**). We chose to define direct as the GCV of an energy carrier as it is useful for engineering purpose (i.e. the energy required in a process) (IFIAS, 1978). Embodied energy also has different definitions. Some studies characterize embodied energy as the higher heating value (gross energy) of the input, plus the energy requirements for the production and delivery of the input (Aguilera et al., 2015; Koesling et al., 2017). This would represent the equivalent of the Cumulative Energy Demand (CED) used in LCA. In this review, we chose to follow the definition of C. Hall (2017): “Embodied energy is the energy once used to make something and is no longer able to do work”. If this definition were applied to the diesel used on the farm, this would be equivalent to the energy used for its extraction, process and transport, therefore equal to 9.1 MJ.L^{-1} (Zegada-Lizarazu et al., 2010).

If the study bases its methodology in a “process analysis”, also define as a partial LCA (i.e. only energetic flow considered) (Pérez Neira et al., 2014; Todde et al., 2018b), whatever how we classify inputs in “direct and indirect”, external inputs must be accounted in terms of GCV and embodied energy, which is equivalent to the (CED) in LCA. Even though process scales and a cradle to farm gate are generally applied, differences prevail in the input inventory and subsequently in the system boundary too. Since the development of LCA (i.e. reinforcement of its application and ISO formalization), the methodology of energy accounting through a process analysis method has also been improved. An LCI (Life Cycle Inventory) protocol offers exhaustiveness in process flow inventory and is often cited as the methodological choice for energy assessment (Arodudu et al., 2016; Fathollahi et al., 2018; Fredriksson et al., 2006; Pryor et al., 2017).

2.5.2 System boundary and the different energetic approaches

The aim of the study and associated energetic approach drives the system boundary. Conventional energy analysis is focus on the socio-economic environment, i.e. how much energy has been purchased and how much has been sold. Energy assessment is frequently regarded as a benefit-cost evaluation (Jekayinfa et al., 2013; Pishgar-Komleh et al., 2017, 2011; Zangeneh et al., 2010). Emergy and some exergy approaches, by the nature of their thermodynamic accounting process, by considering sun radiation as the master flow, can argue to be at planet boundary. These latter two energy accounts have convinced a growing community of researchers, offering a global energy assessment and highlight the energy loss of a system (i.e. entropy). Their objective are generally to assess

environmental sustainability. The conventional energy assessment deserves to be more in line with our economic model and to provide more direct answers to the farming community. A better consideration of the ecosphere is a tendency that has been observed in energy assessment thanks to the development of circular approach and to the consideration of internal biomass production, thus highlighting its role in preserving agroecosystem functions (Tello et al., 2016). Nevertheless, when the energy analysis requires a better clarity in system definition, the integration of internal inputs could become an issue for the flow inventory and might open up the necessity to deal with different EROI (Guzmán et al., 2015).

Murphy et al. (2011) highlighted this issue for EROI analysis. In a production process, they organized flow inventory in increasing levels of analysis by widening the system boundary to include more inputs: i) level 1 is the internal energy consumption, ii) level 2, the external energy consumption, iii) level 3, the materials consumption, iv) level 4, the labor consumption and v) level 5, the auxiliary services consumption. Pérez Neira et al. (2012, 2014) suggested an approach similar in agricultural context. They organized the flow inventory through four categories (“level” was the word used) : 1) direct energy, 2) material and energy cost of production (embodied energy), 3) fixed capital, and 4) energy in maintaining the fixed capital.

We translate the approach of Murphy to the agricultural farming system by expansion of the system boundary to include more inputs: the first level corresponds to an internal flow of biomass reuse within the farm system. This first category of energetic flows leads to use the agroecological energy analysis approach. As farm system is at the frontier between ecosphere and technosphere, and human management mobilizing tools and machines, the next levels (2 and 3) correspond to the cumulative energy demand of external inputs, mobilizing EROI from a socio-economic interest. This category of energetic flows is assessed easily with conventional energy assessment through an energetic LCI. There is still debate on how to incorporate labor consumption. As part of the system, and, in most cases, a consumer of a part of the farm production, metabolized food energy would correspond to an internal flow when the embodied energy related to its lifestyle would be external. Human lifestyle, as well as auxiliary service consumption, is generally appreciated with an input-output economic analysis, and could correspond to Murphy’s levels 4 and 5.

2.5.3 Consideration of internal flows

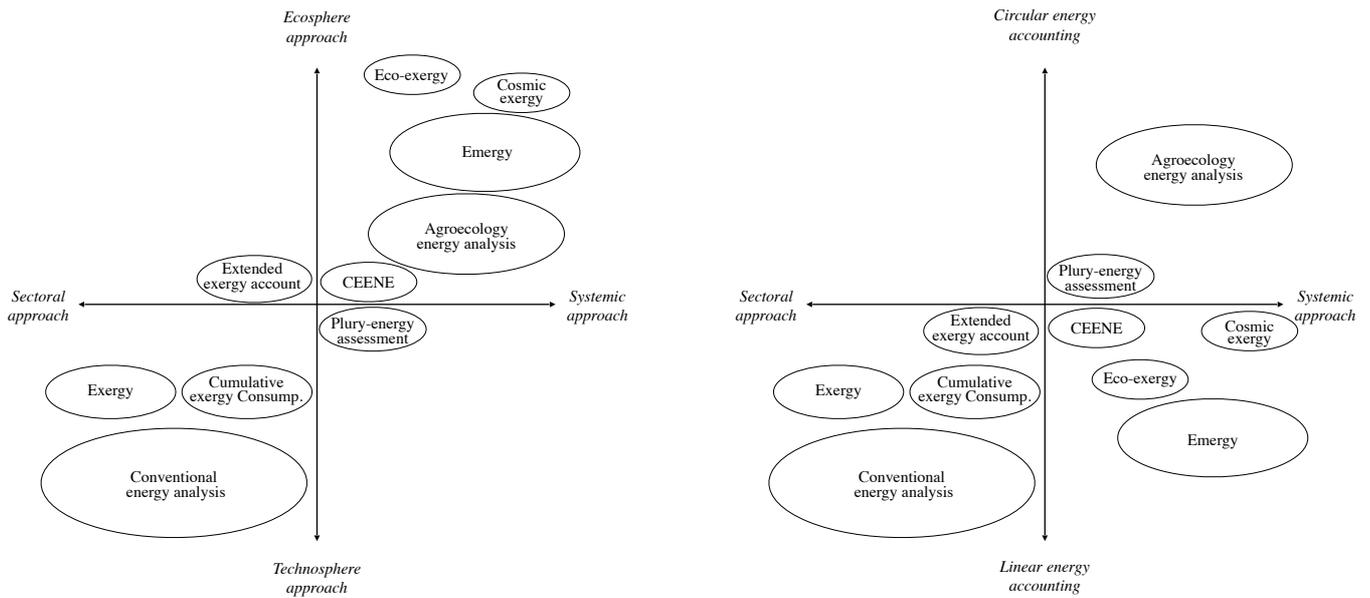
The internal flow of the system has, indeed, recently received increased attention in energy analysis, as the maintenance of the agroecosystem function is crucial (Tello et al., 2015). A recent article suggests that improvement in the efficiency in motors and in the use of fertilizers (i.e. the main drivers in energy efficiency) has already reached or is close to a plateau (Harchaoui and Chatzimpiros, 2018). The increase in energy efficiency due to technological progress for the last decades appear small (Hamilton et al., 2013). This implies that any improvement in energy efficiency of the farm system and the capacity to reduce external inputs (and trying to maintain actual output level) ought to essentially depend on operative management decisions (i.e. reduction in time use machine, economy of scale, etc.). Another solution for increasing efficiency could involve the increased use of the biomass on-farm by managing the internal circulation of flows, which is a key feature in the prospect of agroecology intensification. Ecological network analysis (Rufino et al., 2009) and indicators such as the system through flow and its relation with system resilience are noteworthy lines of research in this direction. Another useful model has recently appeared to address this problem: the Sustainable Agroecological Farm Reproductive Analysis (SAFRA). It is a linear programming model optimizing land, livestock and labor used according to

different aims (i.e. land-saving, labor-saving, commercial maximization) under a set of biophysical site-specific constraints. (Padró et al., 2019). Tools for managing on-farm flows, and building scenarios of different configuration and scale of intensification are promising field of investigation.

2.5.4 Ability of the approaches to address sustainability issues

Understanding sustainability mobilizes concepts such as agroecology, bioeconomy, circularity, systemic approaches, etc. **Figure 9** defines the approaches according to their system granularity (sectorial/systemic approaches), spheres of concern (technosphere enlarged to ecosphere) (**Figure 9a**) and circularity (**Figure 9b**). Conventional energy assessment looks at energy carriers consumption, and evaluates system energy efficiency for economic purpose as energy carriers have a strong impact on economic sustainability of the farm system. Through its generic model Pluri-energy assessment is a first interesting attempt to open the black box of farm system suggesting the circulation of internal flows. Exergy and CExC share this sectorial/linear and sectorial/technosphere approach (**Figure 9a**). Extended Exergy Assessment differs. It introduces the ecosphere by evaluating ecological sustainability in terms of “exergy of environmental remediation cost”. At the difference of the other exergy based analysis, CEENE quantifies the total exergy that is contained in the various resources that are retrieved from the natural environment. Its aim is the impact assessment of resource consumption and it offers a more systemic approach. Eco-exergy would be in contrast with technological exergy, the ecological exergy measurement. Eco-exergy suggests that the accumulated biomass in a system is the exergy content far away from its thermodynamic equilibrium (called by Jorgensen as “inorganic sup”) and related to the development, the complexity and the biodiversity of an agro-ecosystem. On the latter, Jorgensen states that eco-exergy is not enough to evaluate ecosystem sustainability and it is necessary to include biodiversity as an indicator (Dalgaard, 1995) (e.g. Shannon’s index).

Nonetheless, Agroecological Energy analysis (AEA) and Emergy offer a wider systemic approach, considering agriculture as part of a larger system. AEA addresses agroecosystem profile and patterns, looking at territorial sociometabolic exchanges. Emergy evaluates the agriculture as part of a global solar ecosystem, looking its global resource use, environmental impact, and overall sustainability. Yet, AEA and Emergy mobilize two different meanings in their accounting of resource use. Emergy is linear, based on ecological rules (e.g. self-organized and hierarchical), considering energy as a succession of transformation from large flow of low quality to smaller volume of higher quality. AEA addresses a circular approach to evaluate farm system suitability by looking at the loop in the system as the biomass reinvested in the agroecosystem in order to maintain its functionality (**Figure 9b**). In AEA, circularity is mobilized exclusively to evaluate biomass flow inside the agroecosystem, excluding the analysis of external inputs circularity (e.g. industrial ecology). Enlarging circularity on the other external inputs for AEA would reinforce assessment of the farm system integration in its territory, calling for multi-scale analysis and is a current line of research in addressing sustainability issues.



a) Technosphere/Ecosphere approach versus Sectoral/Systemic approach

b) Linear/Circular energy accounting versus Sectoral/Systemic approach

Figure 9: Classifying energetic approaches through their granularity (sectoral/systemic approach), spheres of concern (technosphere enlarged to ecosphere) and circularity (linear/circular). The pattern size represents the numbers of publications

2.6 Conclusion

Energy flows are useful in the modelling of agricultural production systems as human activity is strongly related to the use of energy, and particularly since the Industrial Revolution, of fossil energy. Energy is also a key factor for explaining ecosystem process. We identified ten energetic assessments of agricultural production systems that are performed to account energetic flows: i) conventional energy analysis, ii) pluri-energy analysis, iii) Agroecological energy analysis, iv) exergy analysis, v) Cumulative exergy consumption, vi) Extended exergy account, vii) Cumulative Exergy Extraction from the Natural Environment (CEENE), viii) Eco-exergy, ix) Cosmic exergy analysis and x) Energy assessment. CEENE, Cosmic exergy analysis and Emergy allow for a better evaluation of natural resources offering the widest boundary system, considering primary natural resources used. The main advantage of emergy and exergy is also their ability to distinguish energy types in terms of quality and to consider lost in energetic processes. However, energy analysis, in terms of heating value, has the advantage of being close to present-day economic indicators and of allowing a better understanding by the operators of the agricultural production system. This review focusses on energy analysis as it was the principal energetic assessment of the corpus. Comparison and benchmarking are difficult to carry out due to variability in the system boundary and in energetic value. However, energy assessment allows a good description of the resources consumed by the farm system.

The tendency of energy assessment to focus on socio-economic flows without considering ecosystem mechanisms becomes an issue in the case of human activities depending on the agroecosystem. Thus, recent studies have overcome these difficulties by introducing a circular perspective to energy assessment (Guzmán et al., 2015;

Tello et al., 2016). Internal flows and biomass reuse management appear as key components in the functionality and sustainability of agricultural production systems. By considering the farm energy production in terms of Net Primary Production, these internal flows are better assessed and introduce a new scale of analysis of the on-farm energy flows. Soil organic matter has proved to be a significant component in the agroecosystem energetic balance, acting as a battery of the agroecosystem, the storage being a key element in energy. Effects on biotic energy storage (e.g. SOM in soil, biomass in a perennial plant, etc.), on the stability and resilience of an agroecosystem are noteworthy questions for future studies. In addition, the energy time path, and the simultaneity between the energy output and energy requirement of the system component are issues that have not yet received sufficient attention in energy assessment.

At the end, this review reveals that each of the identified approaches has advantages and limitations for assessing resource efficiency of on-farm agricultural systems. Some of these energy-exergy-ergy approaches are more comprehensive, more capable of being applied at different scales simultaneously, or more capable to account for different energetic flows and resource consumption. To get a multidimensional understanding of agricultural systems, it would be worthwhile to combine them but that implies dilemmas and trade-offs. Those questions deserve a study in itself to identify more deeply complementarities between the energetic approaches.

Chapter 3: Identifying the resource use and circularity into the farm systems: focus on the energy analysis of agroecosystem

Jean hercher-Pasteur^{1,2}, Eleonore Loiseau^{1,2}, Carole Sinfort^{1,2}, Arnaud Hélias^{1,2}

¹ITAP, Univ Montpellier, INRAE, Institut Agro, Montpellier, France

²ELSA, Research group for Environmental Life cycle and Sustainability Assessment, Montpellier, France

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This chapter presents the energy analysis method developed in the thesis. Given the different energy approaches mentioned in the previous chapter and the need for a method accessible to all stakeholders that takes into account all the flows present in the agroecosystem, the proposed methodology is based on the agroecological energy analysis and the emergy framework. The agroecological energy analysis offers an accessible unit of measurement and a circular vision of the flows present in the agricultural production system. The emergy framework uses a systemic approach that takes into account natural resources and offers a well-proven graphical representation based on ecological modelling. Once the methodological framework was set up, it was applied to a case study around which 3 scenarios were proposed to test the method and its indicators. This chapter is taken from a scientific paper presented in "Resources, Conservation & Recycling".

Abstract

A generic method is described for assessing energy flows in an agricultural production system, which represents both a socio-economic activity and an agroecosystem. Based on the efficiency and sustainability of resource exploitation, it focuses on the circularity of the biomass reinvested in the system. A generic mixed-farming system has been modelled using a systemic approach, where the process sub-system and energy storage sub-systems are distinguished. Biotic energy storage identified as Associated Ecosystem (AE) was defined. Soil mineralization was selected as accessible operational data reflecting soil activity. It is also useful for assessing the AE energetic flow. The present approach was tested in a real French mixed farm case study. Contrasting scenarios were proposed to test the model and selected indicators (EROIs and Circularity). The main energetic flows regulating the system were represented by the biomass reinvested in the system as well as the AE energetic services. EROIs demonstrate similar behaviours with varying intensities except when biomass is imported in the system. In the case of intensive breeding, contrasting results for the Circularity ratios were observed, while homogenous results were found in the case of extensive scenarios. This tendency might serve as a useful indicator for assessing the resilience of the resource management of a system. The proposed method allows for a better comprehension of agricultural production systems and can be a useful tool when developing more sustainable agriculture.

Keywords

Agricultural production system, energy stocks, energy flows, associated ecosystem, circularity, soil mineralization.

3.1 Introduction

Modern agriculture is facing crucial challenges (Foley et al., 2011). Farm systems need to adapt their production level and productivity to provide a balanced diet for a growing population while ecosystems must be preserved and the use of non-renewable resource inputs should be restrained (see Sustainable Development Goals target 2.4). These resources are not only limiting but also have a strong impact on the climate, which in turn threatens the resilience of biomass production (Altieri et al., 2015). In response to these challenges, new production modes, such as agroecology or organic farming, are emerging. However, tools are still required for assessing their potential benefits and trade-offs. Farm systems can be defined as both (i) agroecosystems (i.e. a modified ecosystem submitted to agricultural activity) interacting with the ecosphere (i.e. the environmental and natural mechanisms), and (ii) socio-economic activities interacting with the technosphere (i.e. related to human activities). The sustainability of a farm system involves both dimensions, i.e. natural resources (i.e. sun, water, organic matter) and socio-economic inputs,

The energy analysis is particularly relevant when assessing the efficiency of resource exploitation and the sustainability of the farm system. On one hand, for an ecosystem, energy represents a thermodynamic state variable (Jørgensen, 2010) that explains the biotic trophic chain, self-organization and ecosystem development (Odum, 1988). On the other hand, energy is a key driver for increasing agriculture productivity. Since the beginning of fossil fuel energy exploitation, the world population has grown from 1 to 8 billion humans, while areas cultivated for agricultural purposes have only increased by 67% (Smil, 2000). Technological advances have revolutionized human productivity, comfort and increased Gross Domestic Production, although it has been at a severe cost. Our present model is based on the use of non-renewable fossil resources, that is changing our global climate, and leading the world into the Anthropocene (Steffen et al., 2018).

Initially, the energy analysis of an agricultural production system builds its framework by assessing the direct (e.g. fuels) and indirect (i.e. the embodied energy of the production and transport of an input) energy requirements, with focus on socio-economic inputs and outputs (Dalgaard et al., 2001; IFIAS, 1974; Pimentel, 1976; Risoud and Chopinet, 1999). See Hercher-Pasteur et al., (2020) for a review. The efficiency of the system is investigated in terms of heating values, which are generally represented by the Energy Return On Investment (EROI) ratio. This approach has the advantage of being comparable to present-day economic concerns, such as energy prices (Pimentel et al., 1973), and is used as a proxy for environmental performance (Green House Gas, GHG, emissions) (Gomiero et al., 2011b). However “externalities” such as natural and biotic flows and associated environmental impacts are not taken into account. Other energetic approaches offer a more ecological point of view (e.g. energy) by considering natural renewable and non-renewable resources (Martin et al., 2006). Recent studies involve a circular perspective on energy assessment, where the biotic flow dynamics of a farm system considered as an agroecosystem are better assessed (Guzmán et al., 2015). Soil organic matter, acting as biotic energy storage, has proved to be a significant component in the energetic balance (Fan et al., 2018; Jordan, 2016). Following these new features in energy assessment, the present work offers a generic and operational method for assessing the energy profile of agricultural production systems. It combines external input-output flows, internal flows, circularity and internal energy stocks. The objectives focus on understanding the organization and structure of the energetic flows that regulate and drive an agricultural production system. Hence, a circular and a systemic approach to the farm system has been adopted, by modelling internal energy exchanges. The different dimensions

of the sustainability of an agricultural system, i.e. resource use efficiency and resilience (Therond et al., 2017) can thus be considered in order to support decision-making, reduce the dependence on fuel and chemical-based inputs and promote ecosystem services.

Section 2 describes the initial energy assessment method, which is illustrated by a case study on a mixed-farming system. In addition, three contrasting scenarios are compared. Section 3 presents the results with flow diagrams and an input/output table. Finally, the ability to assess the potential sustainability of the farming system, the relevance of the method and its limits are discussed in section 4.

3.2 Material and method

3.2.1 Theoretical construction of the method

This work shares common methodological principles with agroecological energy analysis (AEA) (Guzmán Casado and González de Molina, 2017; Tello et al., 2016), emergy (Cavalett et al., 2006; Odum, 1984) and Life Cycle Assessment (LCA) (Hauschild and Huijbregts, 2015).

As for AEA, the present energy assessment model resembles a bio-economic concept (Georgescu-Roegen, 1977; Mayumi, 2001) where two types of natural resources are considered: fund resources (implying circularity to maintain productivity, i.e. a biological resource) and stock resources (finished resource according to its extraction benefit / cost ratio, i.e. a fossil resource). In accordance with AEA, the farm system is comparable to an agroecosystem, requiring circular energy flows (in the form of biomass) to maintain its structure and functions. The present method therefore assesses the whole amount of biomass produced by the agricultural system in terms of Net Primary Production (NPP).

Emergy analysis is carried out by applying a systemic approach to the farm system model, according to an energy flow diagram (Ferraro and Benzi, 2015) where two main sub-system typologies are distinguished, i.e. producer and storage sub-systems. A sub-system can be defined as a "producer" when, at the end of the transformation process, it aims at obtaining material or energy products (e.g. the cultivated biomass or livestock that provide food, the biomass plant or the photovoltaic plant producing an energy vector). A sub-system can be qualified as "storage" when, during its process, it aims at providing energetic services (e.g. the tractor and its associated tools that prepare the field, the biodegradation of biomass by soil living organisms to provide available nutrients to plants) (Jordan, 2016). Energetic services is the sum of useful work, plus the energy dissipation.

Moreover, as for LCA, system modelling is based on a life cycle perspective where all the direct and indirect energy flows required by the farm system to operate from cradle to farm gate are considered. For this reason, the Cumulative Energy Demand (CED) from the Ecoinvent 3 database was used for expressing all the external inputs.

3.2.2 System modelling

The model represents the farm system at a steady state via four interconnected sub-systems that reflect the different components of the agricultural production system at the intersection between the ecosphere and technosphere: i) Cultivated biomass, ii) Domestic animals, iii) Facilities and tools, iv) Associated ecosystem.

Figure 10 illustrates all the potential flows.

The Cultivated Biomass (CB) sub-system refers to the vegetal biomass intentionally produced and managed by the farmer. This corresponds to all agricultural land and cultivated meadows. The biomass produced can be mobilized by other production processes (e.g. animal feed, anaerobic digestion plants etc.) or exported to the market (biomass sold). The other major use of produced biomass will be to supply organic matter to the agroecosystem (i.e. the unharvested biomass).

The Domestic Animals (DA) sub-system involves animals raised within a farm system. Presently, the main function of animal breeding is to produce milk or meat, with a sustainable livestock turnover rate (i.e. fund resource). However, before the Industrial Revolution and today in certain traditional farm systems, its main function consists in providing energetic services (i.e. field labour or transport).

The Facilities and Tools sub-system (FT) refers to all the machines, tools and facilities employed by Man for increasing power, ability, performance and comfort. This sub-system involves the “exosomatic” instruments of the farm, i.e. based on power that is external to the agroecosystem (Georgescu-Roegen, 1977; Jordan, 2016). FT mainly provides support for cultivating biomass and animal breeding. However, it can also be a source of material and energy products by transforming biomass or direct natural resources into other products of interest (e.g. sun radiation can be converted into electricity using photovoltaic panels, biomass into methane using a biogas plant, and grain into flour using a mill).

Finally, “Associated Ecosystem” (AE) represents the portion of the ecosystem associated to the agricultural production system. This concurs with Tello et al. (2016) who modelled an interconnected sub-system called Associated Biodiversity. AE refers to ecosystem mechanisms and to the natural biomass that provide regulating and supporting services to agroecosystems. These include nutrient recycling by microbial soil communities, water recycling, or pollination. In contrast with FT, AE involves the “endosomatic” instruments of an agroecosystem.

Figure 10 depicts an aggregated energy system diagram, based on the Odum's (1971) scheme convention, and on the input-output table (**Table 5**). Each sub-system merges storage and production, according to how they predominantly define the type of sub-system. Agroecosystem farms interact with an external market that provides and receives four types of external inputs described in the section below. The green lines represent the material and energy flows and the yellow line the support and services energetic flows. Stock variations are represented for storage sub-systems, i.e. FT and AE (green arrows indicate an increase in stock, while red arrows indicate a decrease in stock). Arrow numbering refers to the input output table energy flows presented below with the same colour code.

Table 5: Generic Input Output table of material and energy flows and energetic service flows (*in italic*), discriminating external from internal flows.

		1	2	3	4	5	6	7	8
		INTERNAL INPUT				EXTERNAL INPUT			
		Cultivated biomass	Domestic animal	Facilities & tools	Associated Ecosystem	Energy Carrier	Products	Materials & equipment	Services
INTERNAL OUTPUT	1 Cultivated biomass	Seeds and accumulated biomass	Animal feed	Biomass for processing	Unharvested biomass	Biomass for heating	Biomass without process	-	(Farming class)
	2 Domestic animals	(Animal labour)	Animal birth (Herding)	Biomass for processing	Animal dejection	Animal dejection	Meat, milk	-	(Animal labour)
	3 Facilities & tools	(Cultural practices support)	Animal feed (Animal production support)	On-farm energy carrier (Support to farm process)	Compost, digestate	Biofuels, electricity	Biomass processed	Wood lumber & tools	(Housing, rental of tools)
	4 Associated Ecosystem	(Nutrient & water recycle)	Natural pasture	-	Unharvested, accumulated biomass	-	Foraging medical and food plants	-	(Ecotourism)
EXTERNAL OUTPUT	5 Energy carriers	-	-	Energy carrier (Fuel, electricity)	-	-	-	-	-
	7 Products	Purchased seeds, fertilizer, pesticide	Purchased animal feed	Paint, grass, replacement	-	-	-	-	-
	6 Materials & equipment	-	-	Purchased material (Amortization)	-	-	-	-	-
	8 Services	(Plant assessment)	(Veterinary)	(Repair)	(Ecological assessment)	-	-	-	-

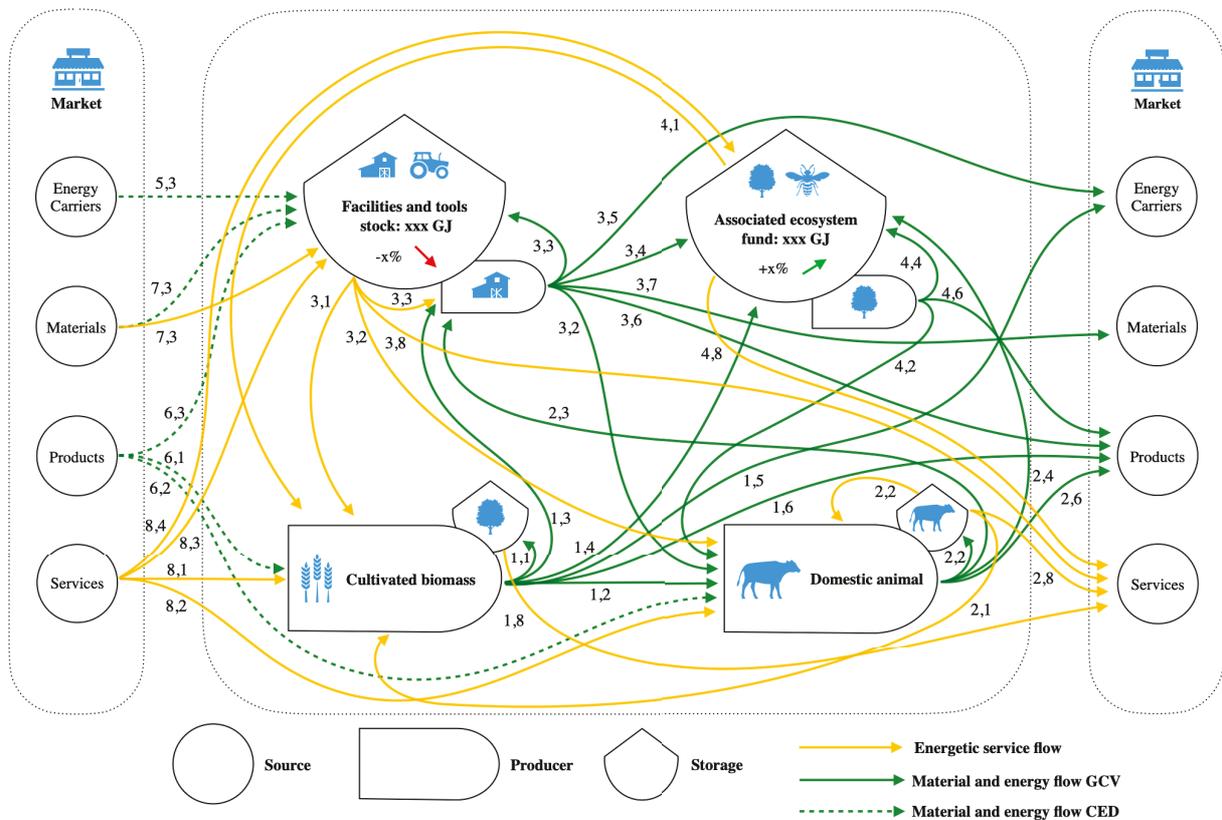


Figure 10: Generic energy flow diagram of the farm system. Arrow indices refer to the input-output table (line, column)

3.2.3 Flow inventory

The market produces the external flows. These are organized into four categories: i) energy carriers, ii) materials and equipment, iii) products and iv) services.

Energy carriers comprise all inputs necessary for operating tools and machines (see **Table 5**, flow 5,3). Material and equipment involves a fixed capital acquired for constituting the FT sub-system stock. Products comprise consumable inputs that ensure machine maintenance or productive processes (e.g. fertilizer, agrochemical products, animal feed, medication, paint, spare parts). Services include diverse external activities required by a farm system (e.g. agronomic advice, veterinary, mechanic, etc.). To compute the energetic value of this external input, the embodied energy mobilized by the operator (e.g. energetic cost of transport) to provide the service is evaluated. In order to evaluate the state of health and depreciation rate of the fixed capital, amortization is classified as an energetic service.

On-farm energy flows are produced by the agroecosystem and are expressed in gross calorific values (GCV). These flows are mobilized in a production process in order to obtain a new product (e.g. animal feed biomass for producing milk, biomass to obtain an energy carrier). They can also be employed as energy carriers to fuel a process (e.g. electric power from photovoltaic panels) or invested within a storage sub-system (e.g. biomass used in FT such as timber). The inputs invested from producer sub-systems into the AE stock associate unharvested biomass, animal excretions, and co-products such as digestate from a biogas plant, with flows (1,4), (2,4) and (3,4) respectively (**Table 5**).

Direct solar energy was not taken into account as it can mask the remaining flows. Here the amount of solar energy appropriated by the plant was investigated, considering the entire biomass production of the system (i.e. Net Primary production of the system) (Guzmán et al., 2018; Haberl et al., 2013).

On-farm energetic service flows generated by the agroecosystem were more difficult to measure since they involve both complex and intangible processes, particularly for the AE. Farm services essentially provide support for the farm producer sub-system (e.g. CB and DA) but can also be used as external outputs such as housing, ecotourism, or rental of tools and animal labour. This should, partly, depend upon the capital stock of the sub-systems (e.g. richness in biodiversity and landscape of the agroecosystem, bedroom equipment, etc.) Indeed, these types of services can be assessed through an input-output analysis of the system.

For FT, all consumed energy carriers are transformed into mechanical work and entropy. Depending on how a machine is utilised, the consumed energy is allocated to support cultivating practices (mainly fuel consumption), animal production or process production, corresponding to flows (3,1), (3,2) and (3,3) respectively (**Table 5**). The depreciation of materials is integrated within these flows. According to a similar logic, the service provided by animal labour is equivalent to the total amount of energy consumed by the latter. To avoid double counting, energy exported by animals is deducted (i.e. the manure invested into the AE and the product exported to the market).

In addition to photosynthetic energy from sunlight, the ability of the AE to provide energetic services (and in extent to produce entropy) partly depends on the amount of energy stored within the system that supports natural services, i.e. the accumulated carbon biomass in the system. According to the Soil Organic Matter (SOM), soil appears to represent the main source of carbon stock (Minasny et al., 2017), with a role in the biotic energy storage of the AE. Soil provides essential ecosystem services (Vidal Legaz et al., 2017) including nutrients and water regulation, food and fibre production, and climate change mitigation with the carbon stock (Minasny et al., 2017).

It plays a central role in agriculture productivity and sustainability (Amin et al., 2020; Dornbush and von Haden, 2017; Pimentel et al., 2012). However, soil still remains a complex opaque matrix (Geisen et al., 2019) which is yet under investigation in order to better understand the soil biota and interactions involving SOM, nutrient availability, water-holding capacity, etc.... (Barrios, 2007; Dominati et al., 2010; Oldfield et al., 2019; Vogel et al., 2018). Nonetheless, soil mineralization is the result of soil activity and is a measurable and available type of data. Thus, the energetic services provided by the AE are characterized using soil mineralization processes (see flow (4,1) in **Table 5**). It is considered as a proxy for services provided by the associated ecosystem.

Soil mineralization depends on the structure and composition of the soil, on the local climate, and on the local biota. For practical reasons, agronomic science uses a mineralization coefficient (k_2) corresponding to a specific pedoclimate condition applied to SOM. It can be defined according to a formula based on soil samples (Boiffin et al., 1986; Girard et al., 2011) or through a model such as AMG (Saffih-Hdadi and Mary, 2008). Finally, the energetic services $f_{4,1}$ (GJ) provided by AE for CB are defined as:

$$(1) \quad f_{4,1} = \sum SOM_i \cdot k_{2i} \cdot GCV_{SOM} \cdot area_i$$

where:

GCV_{SOM} corresponds to the heating value of soil organic matter (MJ/kg), SOM_i (kg/ha) (see supplementary material **A1**.) is the SOM according to the land use i in the system and $area$ (ha) is the surface i in the system.

3.2.4 Taking energy stock into consideration

The first mandatory step in understanding and describing the services provided by a farm system is to define its present stock. In the case of the AE, SOM was considered to be the master driver of the energetic stock, acting as a “bio-battery” for the agroecosystem. As AE is a fund system, its dynamic depends on the energy flows invested in it (in terms of biomass) and on the energy loss (in terms of mineralized SOM). The other form of biotic energy storage is the biomass accumulated on a perennial plant that can offer specific services and support (e.g. Soil erosion control, shelter for animals, biodiversity habitats). Compared to SOM, their potential for energy storage remains low (Pellerin et al., 2013). Nevertheless, they hold a key role in the reinforcement of SOM (Pimentel et al., 2012). The AE stock is defined as the average SOM of the different land use typologies and the accumulated biomass present on perennial plant.

For FT, the energy used to build the different infrastructures and equipment in terms of CED was taken into account and weighted according to the time already spent (see eq. in supplementary material **A1**.). The longer the lifespan, the less is the stock depreciation. The larger the capital in FT, the greater is its capacity to provide services. However, unlike AE, FT is an exosomatic instrument, i.e. a stock system in constant depreciation. Its renewal ought to depend on inputs provided by the technosphere, which is presently essentially derived from non-renewable resources (i.e. minerals and fossil resources).

3.2.5 Indicators used in the assessment

A large variety of energetic indicators has been used to assess the farm system (Hercher-Pasteur et al., 2020). To evaluate its efficiency, we focus on the Energy Return On Investment ratio (EROI) (Hall, 2017).

$$(2) \quad EROI = \frac{F_{f \rightarrow m}}{F_{m \rightarrow f}}$$

with $F_{f \rightarrow m}$ (MJ) the sum of the outputs from the farm to the market and $F_{m \rightarrow f}$ (MJ) the sum of the inputs from the market to the farm. EROI is not sufficient for describing farm system dimensions (Tello et al., 2016). Therefore, in addition to conventional EROI, an Agroecosystem EROI has been presented as follows:

$$(3) \quad EROI_{Ag} = \frac{F_{f \rightarrow m} + F_{f \rightarrow a}}{F_{m \rightarrow f} + F_{a \rightarrow f}}$$

where $F_{f \rightarrow a}$ (MJ) is the sum of the outputs from the farm to the associate ecosystem and $F_{a \rightarrow f}$ (MJ) the sum of the inputs from the associated ecosystem to the farm. Considering the farm system as a socio-economic activity, EROI represents the energy efficiency between the cumulative energy consumed from the market and the energy produced for the market. Agroecosystem EROI combines socio-economic flows with associated ecosystem dynamics. This essentially represents SOM stock dynamics, thus highlighting both the amount of biomass invested in the associated ecosystem and the service provided in the opposite direction (see supplementary material **A2.** for a system boundaries representation and main energetic flows).

In order to better assess the circularity in the system, circularity indicators proposed by Tanzer, (2020) have been selected. The present framework is based on the ratio between the portion of flows from/to the associated system and the total flows from/to the market, as follows:

$$(4) \quad Circ_{in} = \frac{F_{a \rightarrow f}}{F_{m \rightarrow f} + F_{a \rightarrow f}}$$

$$(5) \quad Circ_{out} = \frac{F_{f \rightarrow a}}{F_{f \rightarrow m} + F_{f \rightarrow a}}$$

3.2.6 Case study

The case study concerns a real 49 hectare (ha) mixed organic farm located in western France (Maine-et-Loire). Its main products are milk and cereal. The farm owns 30 livestock unit (LU) equivalents grazing over 10 ha of permanent pastures. There are 18.5 ha of temporal pastures and 10.5 ha dedicated to crops (wheat, rapeseed, sunflower, rye, maize and fodder beet). Part of the crop production is consumed on the farm (as animal feed) while the rest is transformed (i.e. into flour and oil) and sold directly to the local market. The farm possesses a traditional barn and a new barnstable.

Crop rotation is organized according to an eight-year cycle corresponding to five years of temporal pasture and three years of commercial culture. In a similar way, 9 ha have been dedicated to agroforestry, i.e. introducing trees in field crops.

SOM values are obtained from the average of soil samples collected by the farmer on the different land types (i.e. permanent pasture (4.5% of SOM), temporal pasture (2.90%) and crop (2.30%)). The selected mineralization coefficient (k_2) is 3,8% (Saffih-Hdadi and Mary, 2008), corresponding to similar local pedoclimatic conditions. In order to assess the volume of biomass stock accumulated on hedges, 2 types of hedges (i.e. implemented hedges and young hedges) were classified according to the Bouvier typology (Simon et al., 2018). Isolated trees and trees implemented for agroforestry have also been included in the total stock of biomass (see supplementary material for the case study specific data **A3.** , and the general data used **A4.**).

3.2.7 Scenarios to test the method

In order to exemplify the use of the model and the energetic indicators identified for assessing the farm system, 3 contrasting scenarios were investigated. These have been named: i) Intensive breeding scenario, ii) Intensive vegetal production scenario and iii) Extensive mixed-farming scenario (see supplementary material for a comparative description of the scenarios and case study **A5.**).

For the intensive breeding scenario, the herd based on the maximum nitrogen unit per hectare allowed (i.e. 170kg of N unit/ha) and based on the farmers recommendation was increased, resulting in a 90 LU herd. In this scenario, the installation of new facilities has also been considered to support milk production (1000 m²).

The second scenario suggests animal production is halted, to be replaced by an exclusively vegetal biomass production. In this scenario, crops were focused on 20 ha of wheat, 9 ha of rapeseed, 5.5 of barley and 4.5 ha of sunflower. Transformation activities were maintained on the farm (flour and oil).

In the extensive mixed-farming scenario, a seven-year cycle is proposed, based on four years of temporal pasture working as fallows (i.e. 22.5 ha) and three years of commercial culture (i.e. 5.5ha of wheat, 5.5ha of rapeseed and 5.5ha of barley). The livestock was reduced so it might keep a role as a storage sub-system rather than a producer sub-system. Indeed, to replace mowing practices, domestic animals have a role in maintaining meadow productivity by grazing over an extensive pasture (6000 kg.ha⁻¹ of grass dry matter). The livestock intake ratio (MJ/LU), the electric consumption ratio (kWh/LU) and the veterinary expenses (\$/LU) were all maintained as before. This results in a 10 LU for the extensive scenario. Milk productivity per LU fell by 22% (Clark et al., 2006) as milking was chosen to be performed only once a day in order to trade-off loss with other non-milking activities.

3.3 Results

3.3.1 Energetic flows of the farm system and studied scenarios

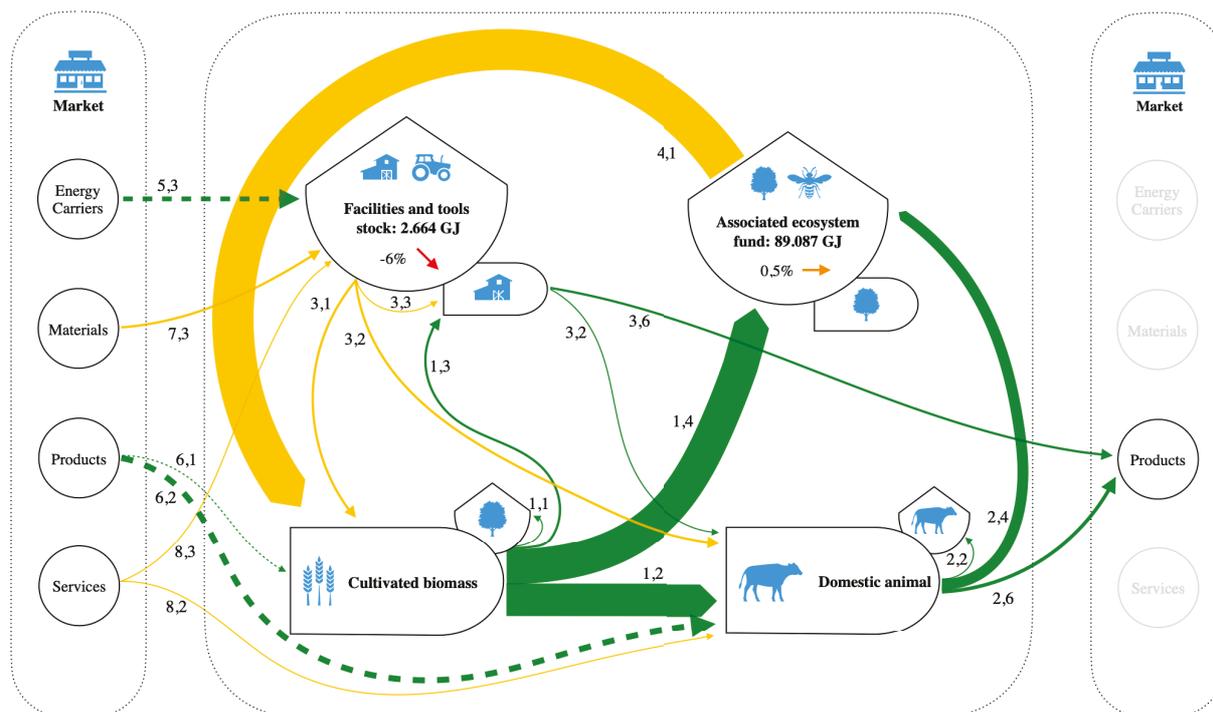


Figure 11: Energy flows diagram of the case study (see diagram flows of the scenario in supplementary material A6.)

Figure 11 represents the energy flow diagram of the farm. The largest arrows are proportional to the quantity of energy. This reveals that the largest flow of energy and material is issued from cultivated biomass, domestic animal feeding (1,2) and AE stock fueling (1,4). The AE stock level remains stable, thus pointing out that the biomass invested in the system allows for its functions to be maintained and for the provision of energetic service flows (4,1). The latter is generated by SOM mineralization and represents the most important flow of energy. More than 50% of the biomass invested in domestic animal feed is irreversibly lost (mainly through metabolic heating). From the remaining material flows, manure represents the largest DA output, i.e. invested in the AE. Finally, the main external input flow is purchased feed (7,2), even if this flow only represents 15% of the total animal intake. Similarly to the value of purchased feed, the second most important external input concerns energy carriers (fuel 56% and electricity 44%). The main difference between purchased feed and energy carriers is that the first originates from 94% of renewable biomass, while fuel is a 100% non-renewable resource and 95 % of electricity derives from non-renewable resources (see supplementary material A4.). Another noteworthy flow is the amortization of the material and equipment that constitute the fixed capital (7,3), mainly due to the energy embodied in facilities.

The farm system diagrams of the different scenarios (see supplementary material A6.) indicate that on one hand purchased feed is the major external input for intensive breeding. On another hand, in the case of an intensive vegetal production scenario, fuel for the tractor and electricity for processing are the main flows. Unlike the case study and extensive scenario, both intensive scenarios reveal unbalanced flows between what is invested in the AE and what is provided by the latter for cultivated biomass. Both present lower energetic service flows provided by the AE due to changes in land use (more crop fields with lower SOM and less mineralization). Simultaneously, more inputs are invested in the AE (scenario 1 due to animal feed import, scenario 2 due to an increase in yield with the use of fertilizers).

Table 6: Input Output table of the case study in GJ (energetic service flows are *in italic*)

		1	2	3	4	5	6	7	8	
		INTERNAL INPUT				EXTERNAL OUTPUT				
		Cultivated biomass	Domestic animal	Facilities & tools	Associated Ecosystem	Energy Carrier	Products	Materials & equipment	Services	Flows provided
INTERNAL OUTPUT	1 Cultivated biomass	20,9	2741,7	201,4	2943,8	0,0	0,0	-	(0,0)	5908 (0)
	2 Domestic animals	(0,0)	26,6 (0,0)	0,0	902,9	-	327,0	-	(0,0)	1257 (0)
	3 Facilities & tools	(211,7)	55,4 (45,1)	0,0 (25,6)	0,0	0,0	145,9	0,0	(0,0)	201 (282)
	4 Associated Ecosystem	(3385,3)	0,0	-	0,0	-	0,0	-	(0,0)	0 (3385)
EXTERNAL INPUT	5 Energy carriers	-	-	416,9	-	-	-	-	-	417
	7 Products	4,9	482,0	0,0	-	-	-	-	-	487
	6 Materials & equipment	-	-	0,0 (135)	-	-	-	-	-	0 (135)
	8 Services	(0,0)	(13,2)	(44,9)	(0,0)	-	-	-	-	(58)
Flows received		26 (3597)	3306 (58)	618 (224)	3847 0	0	473 0	0	0	-

Input Output table of the different scenarios are in supplementary material A6.

3.3.2 Resource use efficiency and circularity

In the case study, the *EROI* is low, (0,42), (**Table 7**) when compared for example with other organic dairy farm studies (1,7) (Smith et al., 2015). This is due to the amount of forage purchased, but also to the choice of model and to the use of CED (i.e. in addition to the embodied energy of the purchased forage, the GCV of the biomass is considered). This farm is presently going through a transition period, reducing its animal activities and reinforcing vegetal production. These might account for certain yield values observed during the case study that forced the farmer to purchase feed. $EROI_{ag}$ is close to one (0,96) and can be explained by important flows reinvested within the farm (3,462 GJ) (Tab.2). $Circ_{out}$ results (89%) indicate that the main part of the output is invested in the system. $Circ_{in}$ results are lower, with 75% of the input coming from the system.

The intensive breeding scenario presents a similar *EROI* to that of the case study (0,47) and a higher $EROI_{ag}$ (1,64). A higher $EROI_{ag}$ is due to an important increase in manure transferred to the AE. At the same time, changes in land use (fewer pastures and more crops) lead to a reduction in the mineralization rate and consequently in the energetic service provided by the AE. As the flow of manure to the AE is in the numerator (output) while the energetic service is in the denominator (input), the resulting $EROI_{ag}$ rises. $Circ_{in}$ and $Circ_{out}$, respectively 41% and 83%, show contrasting results that suggest an unbalanced situation. The Intensive breeding scenario increased its facilities to support new livestock (90LU), and increase FT stock (7,6 GJ). Even though the use of machines and engines is larger, a strong increase in facilities leads to a lower depreciation rate.

For the intensive vegetal production scenario, the *EROI* (4,3) and the $EROI_{ag}$ (3,57) are both higher. Firstly, this is because there are no more cows with their associated metabolic loss. Secondly the use of fertilizer, and particularly nitrogen, has boosted the yields. In this scenario, the $Circ_{out}$ was observed to be the lowest value

(52%) relatively to the $Circ_{in}$ (60%). Here, the stock of cultivated biomass was highest (129 GJ) as it requires a larger amount of seeds to be sowed. The depreciation rate of FT is most significant due to a higher use of engines without modification of FT stock (2,664 GJ).

The Extensive mixed-farming scenario presents an $EROI$ of (2,11) and an $EROI_{ag}$ of (1,78). The reduction in the presence of animals leads to a higher amount of biomass invested in the system and exported from the system. This is also the result of a lower consumption of external inputs. Fertilizers were not used and engines were only dedicated to the reaping of crops and not for any mowing of pasture. In this scenario, $Circ_{out}$ and $Circ_{in}$ present most similar results, respectively 83% and 86%.

Table 7: Indicators and Stock of the Case study and the 3 scenarios

		Mixed-farming case study			Scenario 1: intensive breeding			Scenario 2: intensive vegetal production			Scenario 3: extensive mixed-farming		
EROI	EROI	0,42			0,47 112 %			4,30 1015 %			2,11 476 %		
	Agroecosystem EROI	0,96			1,64 171 %			3,57 372 %			1,78 184 %		
	Output circularity	89 %			83 %			52 %			83 %		
	Input circularity	75 %			41 %			60 %			86 %		
		GJ	Δ Stock	%	GJ	Δ Stock	%	GJ	Δ Stock	%	GJ	Δ Stock	%
Stock relative variation	Associated Ecosystem	89087	461	0,5 %	69050	6000	8,7 %	65129	5162	7,9 %	74931	2075	2,8 %
	Facilities & tools	2664	-154	-5,8 %	7678	-278	-3,6 %	2664	-197	-7,4 %	2664	-158	-5,9 %
	Domestic animals	133	-1	-0,9 %	394	-3	-0,8 %	0	0	0,0 %	42	36	0,0 %
	Cultivated biomass	73	4	5,7 %	80	4	5,2 %	129	4	3,2 %	84	4	4,9 %

3.4 Discussion

3.4.1 Capacity of indicators to support decision making in favour of sustainability

Sustainable farming implies that present needs should be met without compromising the ability of future generations to deal with their own requirements (Brundtland, 1987). Two temporal dimensions constitute this definition: one is related to the present performance of a system while the other concerns the ability to ensure long-term production, i.e. the resilience of the system (Duru et al., 2015).

With the $EROI$ ratio, the performance of the system is described through resource use efficiency, focusing on the ability of the system to produce an output according to the amount of inputs consumed. $EROI$ and $EROI_{ag}$ show equivalent tendencies. The introduction of soil organic matter in the $EROI_{ag}$ flattens $EROI$ variations between scenarios. The scenario with a complete vegetal production logically demonstrates higher $EROI$ since it has one process stage less than before (i.e. livestock transforming vegetal biomass into milk and meat). In the case of the intensive breeding, the $EROI$ was similar to the case study with a higher $EROI_{ag}$. The land use changes increased biomass production (corn silage) and at the same time decreased energetic services provided by the AE (pastured land to crop land). This resulted in an higher $EROI_{ag}$ compare to the case study. However, the unbalanced situation in the circularity ratio of the intensive scenario calls for a closer investigation into the degree of sustainability of the systems.

With less stored energy to provide internal energetic services, intensive breeding becomes more dependent upon external inputs, and more sensitive to resource availability and price variations. In addition, Circularity ratios of scenario 1 indicate an important provision in organic matter associated with a lower rate of mineralization. A first assumption suggests that the “bio-battery” of the system charges when the *AE Δ stock* is high (Tab. 3). A second assumption suggests this unbalanced situation (i.e., Contrasted Circularity) could damage the “bio-battery” when the level of charge is too high. The persistent issue related to nitrate leaching in intensive breeding systems seems to confirm this second assumption. In contrast, extensive mixed-farming (scenario 3) demonstrates the most balanced In/Out Circularity. In terms of resource uses, Circularity and the AE state of charge are significant indicators when assessing the resilience of a system. Further studies are still required to confirm this tendency.

The results of the case study need to be weighted. Considering a normal yield for permanent grassland, the farm might be self-sufficient in terms of animal feed, thus significantly increasing its resource use efficiency. The extensive mixed-farming system appears to be the most sustainable one, with an *EROI* reaching 2 and a high and balanced Circularity. By increasing the complexity of the farm system, the different functions of a process and in particular the services provided by one process to another are enhanced. However, economic viability has not been assessed. Currently, the farmer’s first source of income represents the milking activity. By dividing the livestock by three, the economy would be clearly impacted. Therefore, it is assumed that by rather reducing the time devoted to animal husbandry (e.g. only one milking per day, free pasture, etc.), the farmer would gain more time for other types of income.

3.4.2 Significance and suitability of the framework

A picture is worth more than a thousand words (Brown, 2004): Indeed, an energy flow diagram provides a better assessment of the different energy flows present in the farm system as well as a first mandatory step for the farmer and the stakeholders to comprehend the agricultural production system. The introduction of a sub-system called Associated Ecosystem should reveal the master internal flow that maintains farm system functions (Guzmán et al., 2015).

The conversion of a conventional industrial farming system towards agroecology practices can be a difficult challenge. However, by mobilizing the concept of energy efficiency, which is already present in farm management schemes, and by using the present energetic approach, which is based on thermodynamic laws, a conventional farming system can be encouraged to take up more sustainable practices.

Indeed, the capacity to mobilize endosomatic energy relies on the energy stored in the farm agroecosystem (Jordan, 2016). The more the latter provides energetic services, less is the need for exosomatic energy to produce a significant output. This statement represents another opportunity for decision-makers to propose policies, where incentives aim at agricultural production systems that promote energy storage in the agroecosystem. The significance of these measures could be doubled, if energetic services were provided and if climate mitigation could be implemented (through biotic carbon storage and reduction in the use of exosomatic energy).

3.4.3 Limits and perspectives of the method

The use of soil mineralization is a primary attempt in expressing the services provided by an ecosystem. This requires precise data, since the mineralization coefficient has an incidence on the results. Nevertheless, recent advances in the modelling of mineralization (Clivot et al., 2019) and satellite imagery (Vaudour et al., 2019) ought to improve the data and its accessibility. In addition, a better description of the different components that contribute to mineralization (e.g. soil biota) should help characterize specific services provided by the AE. Indeed, a service provided by the ecosystem includes the self-organization of the trophic chain biota, which is associated to biodiversity (corresponding to flow (4,4) in **Table 5**). The internal regulation of functions in agroecosystems largely depends on the existing biodiversity (Altieri, 1999), which contributes to the enhancement of nutrient availability and to the reduction in crop diseases (Roese et al., 2020; Zhang et al., 2020). The notion of services raises the question of related knowledge and information. The Energetic representation of this information still represents a flaw in this kind of energy assessment. A promising line of research was proposed by Jorgensen who suggested using Eco-exergy (Jørgensen, 2015) in order to express the information embodied in the Ecosystem.

Traditionally, energy efficiency focuses on the ability of a process to provide an output, and aims at minimizing energetic losses with a negative view on entropy generation. In the case where the ecosystem is able to provide natural services, this point of view can be reversed, since the maintenance of a complex internal organization (i.e. the provider of services) relies on the generation of entropy (Skene, 2013). This ecological modelling statement highlights the capacity of agroecosystems to provide internal natural services through its degree of complexity and its capacity to generate entropy. Resource use efficiency on external inputs can be increased partly by improving the capacity of the system to use endosomatic energy. This depends on the energy stores and on the system's level of complexity.

The different energetic flows have been measured in terms of heating values. Material and energy were distinguished from services: the first is based on quantified physical flows, the second relies on proxies. However, the use of heating values to measure energy can represent a limit when expressing the different qualities of energetic vectors. One Megajoule of diesel is not equivalent to 1 MJ of hot water, and 1 MJ of milk is not equivalent to 1 MJ of straw. The choice of an accessible metric for the different stakeholders thus induces trade-off.

A site specific approach was selected, since an agroecosystem depends on local conditions. Although the farm system has been the scope of the study in order to test the method, the framework could be used at other scales (e.g. regional scales), which are the object of current lines of research. In addition, a site specific approach does not highlight the market integration effort performed by the farmer by transforming vegetal biomass on the farm. In this approach on-farm and upstream flows can be taken into account. However, in future studies, it would be worthwhile to take into account downstream flows and to consider the output from the farm gate to its consumption site, and eventually its return towards the agroecosystem through a recycling process chain. Finally, this would entail an assessment of the circularity between the market and the agroecosystem.

The framework does not involve human labour. In the present case study and in systems containing significant exosomatic instrumentation, the energetic value is low compared to other flows mobilized by machines. However, for certain agricultural systems, human labour appears to be an important consumer of resources. In this case, it would be possible and worthwhile to integrate human labour as an additional energetic storage sub-system provider of energetic services. Another reason why human labour has not been included is because the manner of considering human labour is still in debate (Wu et al., 2011) (i.e. should only metabolic requirements or also

lifestyles be taken into account; should a level of knowledge with an impact on different farming practices be considered?).

3.5 Conclusions

A method has been presented, aiming at assessing the energy flows within an agricultural production system in order to evaluate the resource use efficiency and sustainability through circularity. This method is based on the latest line of research in energy assessment, where the agricultural production system is considered as a socio-economic activity and as an agroecosystem. This assumption entails the mobilization of different energetic ratios in order to reflect the different dimensions of an agricultural production system.

According to a systemic approach, the framework was based on a diagram representation of a farm system. A sub-system called the Associated Ecosystem was introduced and the production processes from storage sub-systems were differentiated. This also involves the distinction between energy and material flows and energetic service flows. In order to characterize the energetic service flows provided by the AE, soil mineralization was selected as an accessible expression of soil activity which holds a key role in the production of biomass. The model revealed that the main energetic flow occurring in the agricultural production system is a circulating flow towards the AE and returning to the production processes through energetic services.

Energy storage is a critical issue in our present-day society. This is also true for agricultural systems, since the provision of ecosystem services depends on the biotic energy storage, avoiding extensive use of external inputs. This approach could represent a suitable tool for conceiving better agricultural farm management and public policies through the monitoring of the relationship between the agricultural activity and its associated ecosystem. The trends revealed by the circularity indicators are promising and could act as a foundation in the assessment of the system resilience in its management of resources. Unbalanced internal energy flows should affect the energy stock equilibrium. In addition, low Circularity results would point to systems based on external inputs. In such a case, the analysis of the renewability of these flows becomes even more necessary.

While potential improvement remains possible, the framework may allow for better in depth understanding of agricultural systems through the different energetic flows that occur and could represent a useful source of knowledge when designing a more sustainable future agriculture.

*Chapter 4: Agroecosystem energy assessment of
two contrasting territories*

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Chapter 4 applies the developed energy analysis method at the territorial level. For this purpose, the agricultural systems of two contrasting French departments, one specializing in animal production and the other in cereal production, are compared. The aim of this chapter is to test the adaptability of the method on a larger scale and to see whether it is capable of providing information on the sustainability of a territory.

Abstract

This paper proposes to assess agricultural production resource use efficiency and resilience of two contrasting departments of France using a new framework of energy assessment. The method, initially design at farm scale, is applied at territorial scale. The aim is to test the method at a larger scale and to evaluate its ability to assess resource use efficiency and sustainability of agricultural regions. For that, agricultural production is placed at the agroecosystem dimension by integrating a subsystem representing the natural ecosystem capital called associated ecosystem (AE). The last is defined through its Soil Organic Matter stock. The energetic flow provided by the last is captured using soil mineralization as a proxy. EROI (Energy Return On Investment) and circularity are the indicators family's used.

The method established an energy profile faithful to the specificity of each region while showing the characteristics of the internal flow. For being crop specific producer, Eure-et-Loir shows the better EROI but with an agroecosystem EROI reduced because of a reduce energy services provided by the AE. Finistère department shows a low EROI because of its specialized animal breeding system with a higher agroecosystem EROI due to the important flow provided by the AE. Both scenarios present unbalanced Input/Output Circularity, particularly the animal breeding region due to its imported animal feed and because a large part of its vegetal biomass production is lost in the animal production process. By widening the agricultural activity to the agroecosystem, the method is useful in assessing the overall needs of natural and technical resources and proposes relevant indicators to measure its efficiency and resilience.

Keywords

Regional Agricultural production, energy stocks and flows, associated ecosystems, energy assessment, soil mineralization, circularity, EROI.

4.1 Introduction

The orientations of agricultural activities are linked to the local social and pedoclimatic characteristics. However, the industrialization of agriculture, supported by intensive practices and standardized processes, has favored the specialization of agricultural areas on a reduced number of production types. Industrial agriculture depends on the world commodity market to buy its inputs and sell its output, which increases its sensitivity to price changes. Focusing on price competitiveness, this approach also favors the long-distance supply chain, which increases the overall energy consumption of the agricultural production system (e.g. soybean meal for animal feed from South America to Europe)(Pelletier et al., 2011).

In this context, the circular economy is increasingly being used to improve the economic and environmental performance of agricultural systems. Expectations are a reduced supply chain, closing material and energy loops and bringing production closer to consumers. The scale of the territory and the region are then the focus of reflection, offering opportunities to reduce the use of non-renewable resources, to reuse material and energy flows in a synergistic and collaborative way and to recycle these wastes.

Energy assessment is particularly relevant for assessing the resource use efficiency and the sustainability of the system. Initially (Pimentel et al., 1973), the energy assessment of agricultural production system has been used to determine the direct (mainly determined from fossil fuel combustion) and indirect (embodied energy in upstream process) energy requirements in order to produce a given output (e.g. the biomass produce and exported to the market)(IFIAS, 1974). Indicators of efficiency, such as EROI (Energy return On Invested) are often used (Hall, 2017). Recent development of energy analysis extends energy flow assessment with the consideration of the agricultural production system as an agroecosystem. The purpose is to emphasize the flow exchanges between technosphere (human-drive processes) and ecosphere (environmental mechanism) (Guzmán Casado and González de Molina, 2017). Additionally, the distinction of fund- versus stock-resources (Georgescu-Roegen, 1971; Giampietro et al., 1992) reveals the presence of circular flows that maintain agroecosystem natural mechanisms (Guzmán et al., 2015; Tello et al., 2016). Recently, a new method applied at farm scale has been proposed (Hercher-Pasteur et al, submitted). The farm sustainability is viewed through a systemic approach encompassing the agroecosystem and proposing efficiency and circular indicators. This approach considers external input-output flows, internal flows, circularity and internal energy stocks.

This work presents a use of this methodology on a regional scale by comparing two contrasting French departments (intermediate administrative division): Finistère where agricultural activities are specialized in animal husbandry and Eure-et-Loir, mainly oriented towards the production of annual crops. The objectives are to exemplify the method at another scale (the department) and to discuss its ability to describe and assess the performance and sustainability of agricultural area. Section 2 presents the data used for each department and gives a brief overview of the method. Section 3 brings together the results and discussions, first presenting the diagram of the energy flows of the two regions and then discussing the level of efficiency and sustainability of each region through the different energy indicators.

4.2 Materials and methods

4.2.1 Studied territories

Finistère and Eure-et-Loir have been selected to assess contrasting productions. The first is an important animal breeding region of France with pig, cattle and poultry farming, when the other is an important produce of annual crops such as wheat or rapeseed. Both are in a pattern of intensive production seeking to maximize production and present, according to their production, high yields compared to the French average.

The Eure-et-Loir is located south-west of Paris. Soils of silty formation are the most abundant, with a high water retention capacity. Due to its intensive practices, soil erosion is significant (mainly between 2 and 5 T.ha⁻¹) (Thorette, 2015) with a low soil organic carbon (SOM) of 86 T/ha (Gis Sol, 2010). The rainfall (Chartres city references) is estimated at 637 mm and the average temperature at 10.4 C° (Climate-Data). Production corresponds to the year 2015 (**Table 8**) and comes from the French agricultural statistic database (Agreste).

Table 8: Agricultural productions in L'Eure-et-Loir region

Eure-et-Loir		
Vegetal product	Area (ha)	Production (T)
Triticale	174835	1501749
Wheat durum	27355	204041
Barley	62350	518316
Maize (grain)	21095	222130
Rapeseed	86210	344840
Sun flower	155	372
Protein peas	9240	34040
Forage maize	5000	117500
Meadows	25500	494700
Sugar beet	9805	902060
Potatoes	7351	352495
Animal product	LU^a	Production (T)
Milk cow	10842	
<i>Milk</i>		53249
<i>Cull cow bright weight</i>		1 293
Meat cow	25981	
<i>Meat cow bright weight</i>		3 508
Poultry	74885	
<i>Poultry bright weight</i>		11050
<i>Eggs</i>		236

^aLU: livestock unit, the grazing equivalent of one adult dairy cow producing 3 000 kg of milk annually

Finistère is in the extreme north-west of France. The nature of the soils is rather silty, with rather heterogeneous variations ranging from medium sandy silt to sandy silt. The main characteristic is its rich SOM with an average estimated at 155 T/ha (Gis Sol, 2010). Due to the important presence of animal breeding the region

suffer water pollution through nitrate and phosphorus leaching (Morel et al., 2004). The average rainfall (Quimper city references) is estimated at 1037 mm with an average temperature of 11.5 C° (Climate-Data). Production corresponds to the year 2015 (Agreste) and are listed in **Table 9**. Detailed information for both regions on the estimated share of production exported, imported and locally consumed can be found in supplementary material **131**).

Table 9: Agricultural production in Finistère

Finistère		
Vegetal product	Area (ha)	production (T)
Triticale	56385	410901
Wheat durum	0	0
Barley	27470	203525
Maize (grain)	45502	386858
Rapeseed	6360	20937
Sun flower	5	12
Protein peas	940	3573
Forage maize	60770	3439582
Meadows	157359	8906519
Sugar beet	87	6524
Potatoes	5850	194507
Animal product	LU	Production (T)
Milk cow	236054	
<i>Milk</i>		<i>1 189 708</i>
<i>Cull cow bright weight</i>		<i>14 131</i>
Meat cow	177147	
<i>Meat cow bright weight</i>		<i>3 508</i>
Pig	1792241	
<i>Pig bright weight</i>		<i>431 302</i>
Poultry	1198626	
<i>Poultry bright weight</i>		<i>159 823</i>
<i>Eggs</i>		<i>36 331</i>

4.2.2 Agroecosystem Energy assessment method

The proposed framework considers the agricultural system both as an agroecosystem and a socio-economic activity. Agricultural systems require circular energy flows of biomass to maintain its natural structure and ecosystem functions (Guzmán et al., 2015) and flows from the technosphere to supply facilities and energy for engines. The agricultural system is organized in four subsystems, reflecting the different components at the crossroad between ecosphere and technosphere: i) Cultivated biomass (CB), ii) Domestic animals (DA), iii) Facilities and tools (FT), iv) Associated ecosystem (AE).

CB subsystem refers to the vegetal biomass intentionally produced. It concerns crop fields and non-natural pastures. DA subsystem corresponds to animals breeding. FT refers to all machines, tools and facilities that humans use. Finally, AE refers to the portion of the ecosystem associated with the agricultural production system without intentional human intervention for management (soil, hedges, non-planted forest). AE corresponds to the natural capital of biomass providing regulating and supporting services (e.g. nutrient recycling by the microbial soil communities or water recycling).

AE and FT are named storage subsystems. Their main function is the provision of- support services with associated dissipation of energy (e.g. the tractor and its associated tools preparing the field, the biodegradation of biomass providing nutrients to the plants). CB and DA are transformation subsystems, with processes leading to another material or energy products of interest (e.g. the cultivated biomass providing grain or the livestock providing milk). An energy system diagram with specific nomenclature (Odum, 1971) is used to frame the system.

4.2.3 Flow and stock inventory

4.2.3.1 External flows

All incoming external energy flows are addressed from cradle to farm gate. Cumulative Energy Demand (CED) from Ecoinvent 3 database (see supplementary material **B2.**, p. 132) is used. Outputs exported to the market are expressed in gross calorific value (GCV). Incoming or outgoing external flows are split in four categories: i) energy carrier, ii) material and equipment, iii) product and iv) service.

For both regions, energy carrier corresponds to fuel engine consumption in cultural practices, electricity in milkmaid and propane plus electric consumption in grain drying. Fuel consumption is estimated using standard cultural practices (i.e. cultivating, plowing, rolling, seeding, fertilizing spraying and harvest) (Aguilera et al., 2015) and associated average fuel consumptions. For each culture, fertilization, spraying and plowing has been adjusted (i.e. number of passes and percentage of fields plowed) according to French statistics (Agreste) (see supplementary **B3.**, p.133). Milkmaid consumption is calculated according to the average of electric consumption per milk production (61 kWh/1000 L of milk) (ADEME, Institut de l'élevage, 2009). The energetic consumption of the maize grain drying results from the use of 34 L of propane and 5 kWh of electricity for 1 T of Maize at 85% of dry matter (Dyck, 2017).

Material and equipment correspond to the fixed capital amortization. Here only animal facilities are considered, based on facilities dimension ratio per Livestock Unit (LU) for cow milk, cow meat, pig and poultry, respectively 15, 10, 1.7, 7.1 m²/LU (DRAAF, 2010).

Products concerns purchased inputs. In the present work, they are represented by the fertilizers (Nitrogen, phosphate and potassium) and the animal feed. The used quantities come from French statistics (Agreste) (see supplementary data).

Among the various services provided by external flows (technical advice, veterinary), it is estimated that repairs in the building over a 50-year lifetime (Nemeček and Kāgi, 2007), represent 10% of the total energy use to build it.

4.2.3.2 Internal flows

Biomass production is considered in terms of Net Primary Production (NPP) and expressed in GCV. This allows revealed the biomass that is harvested or pastured (i.e. the biomass exported or reuse in another process) and the unharvested biomass (roots and crop residue left in the field and reinvested in the associated ecosystem). NPP is calculated according to yield data and using conversion factors (Guzmán et al., 2014) to determine the proportion of vegetal biomass reinvested in the AE (i.e. roots and unharvested aerial biomass) (see supplementary material **B4.**, p. 134). “Planet method ratio” (ADEME, 2011) are used to define the quantity of manure produce for each type of animal production according to LU values.

Internal services flows are provided by FT and AE. The services provided by FT correspond to the energy carriers used in the different production processes (fuel and/or electricity for field work, grain drying, milking). The quantification of services provided by the AE is more challenging. Support services are shaped by complex, interconnected, multifunctional and self-organized components that define the ecosystems. As soil is the main source of carbon stock (Minasny et al., 2017) and the place of important ecosystem services (Vidal Legaz et al., 2017), the approach is focused on this compartment. Soil mineralization can be determined with accessible data and is used to represents the soil activity. This can be seen as a proxy of provided services by the associated ecosystem.

Soil mineralization depends on the soil organic matter (SOM) present and on the pedoclimatic conditions. SOM for Eure-et-Loir and Finistère regions has been evaluated based on carbon stock in the first 30 cm of soil (see section 2.1.), respectively 86 T/ha and 155 T/ha of SOM. Based on regional climatic conditions (temperature and pluviometry), on soil typologies average (clay content and limestone) and on the referent coefficient of mineralization (K2) (Saffih-Hdadi and Mary, 2008) of similar regions, 3% and 5% has been attributed, respectively for Eure-et-Loir and Finistère.

4.2.3.3 Energy stock

The energy stock assessment concerns essentially FT and AE. We evaluate the stock of FT through animal breeding facilities. The other facilities and agriculture machinery are not taken into account due to the lack of access to data at the regional level.

Energy stock of the AE is calculated through SOM. Accumulated biomass on a perennial plant is not considered here as compared to SOM, their potential of energy storage can be neglected (Pellerin et al., 2013).

4.2.4 Indicators used in the assessment

To assess farm system efficiency, we focus on the Energy Return On Invested ratio (EROI) (Hall, 2017). We proposed to mobilize in addition to conventional EROI (1), an Agroecosystem EROI (2) presented as follows:

$$(1) \quad EROI = \frac{F_{f \rightarrow m}}{F_{m \rightarrow f}}$$

with $F_{f \rightarrow m}$ (MJ) the sum of the outputs from the farm to the market and $F_{m \rightarrow f}$ (MJ) the sum of the inputs from the market to the farm, and:

$$(2) \quad EROI_{Ag} = \frac{(F_{f \rightarrow m} + F_{f \rightarrow a})}{(F_{m \rightarrow f} + F_{a \rightarrow f})}$$

with $F_{f \rightarrow a}$ (MJ) the sum of the outputs from the farm to the associate ecosystem and $F_{a \rightarrow f}$ (MJ) the sum of the inputs from the associated ecosystem to the farm. EROI represents the energy efficiency between the cumulative energy consumed from the market and the produced energy to market, looking at the farm system as socio-economic activity. Agroecosystem EROI merges with socio-economic flows, the agroecosystem dimension, which corresponds to the biomass invested in the AE and the SOM mineralization.

The description of the circularity of the system analyzes the relationship between the flows issued or invested from/to the AE with the total consumed or produced. Two indicators are used. Inflow circularity (eq. 3) describes the portion of energy provided by the Associated ecosystem (i.e. soil mineralization) of the total energy consumed by the agroecosystem. Outflows circularity (eq. 4) describes the portion of vegetal biomass left to the associated ecosystem on the total biomass produce (i.e. the NPP).

$$(3) \quad Circ_{in} = \frac{F_{a \rightarrow f}}{(F_{m \rightarrow f} + F_{a \rightarrow f})}$$

$$(4) \quad Circ_{out} = \frac{F_{f \rightarrow a}}{(F_{f \rightarrow m} + F_{f \rightarrow a})}$$

The proposed effect factors do not quantify damage to natural resources comparable to existing endpoints. The units proposed by EF#1 and EF#2 are specific to freshwater resources degradation problems, and could not be consistently applied to other resource depletion problems (like fossil depletion). The characterization factors afterwards developed are therefore midpoint CFs since they indicate a potential resource problem.

4.3 Results and discussion

4.3.1 Overview of energy flows for two contrasting regions

Figure 12 and **Figure 13** show the energy flow diagram for the two regions. Their configuration confirms the contrasting nature of the production model.

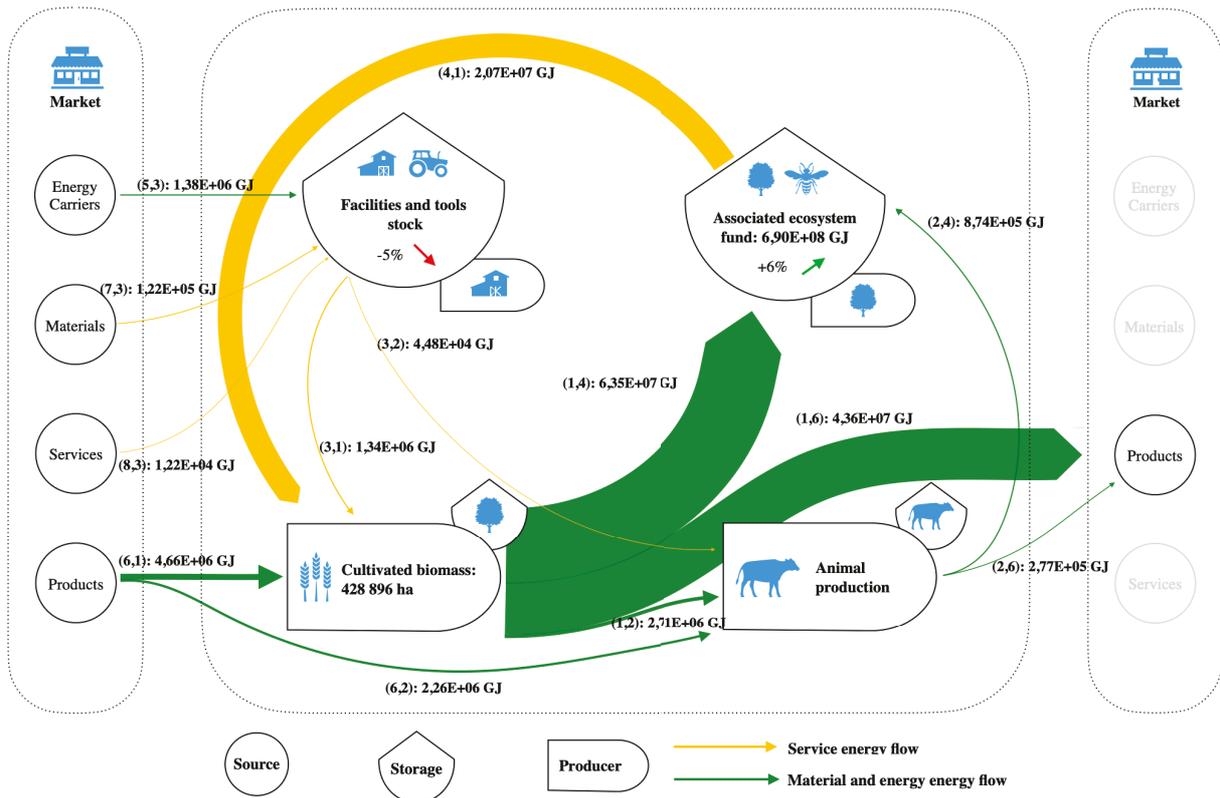


Figure 12: Energy flows diagram of the Eure-et-Loir department. The width of the arrows is proportional to the amount of energy. The number (x,x) is the flow description and refers to the input/output table in supplementary material B5., p. 137

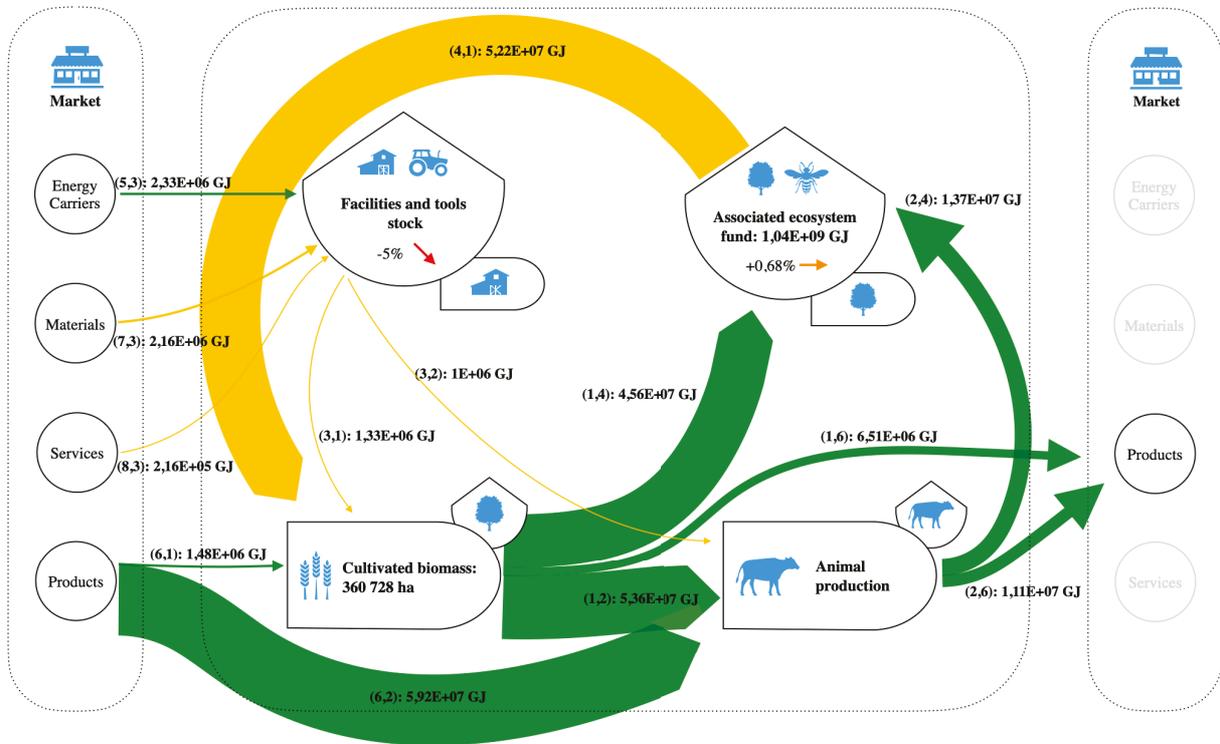


Figure 13: Energy flows diagram of the Finistère department. The width of the arrows is proportional to the amount of energy

The Eure-et-Loir is oriented towards the production of plant biomass, which represents its main source of export. Only a small part of the plant biomass is used to feed animals, which corresponds to the pastured area and forage maize. The main production flows from CB to AE are the roots of cultivated biomass and crop residues (except for triticale, wheat and barley, where above-ground biomass is also exported). This high level of plant biomass production is explained by a significant use of fertilizers, being the main external energy consumption. The energy services provided by soil mineralization are lower than in Finistère and could be explained by the lower stock in SOM (**Figure 12**) and by the local pedoclimatic conditions (i.e. less rain and more cold). This results in a positive relative change in the Eure-et-Loir AE stock (6%). Intensive agriculture has declined soil biodiversity and soil organism (Blakemore, 2018; Tsiafouli et al., 2015) reducing the capacity to process crop residue in stable humus, thus favoring soil erosion (Piccolo, 1996). The relative positive increase in the AE stock through the biomass invested must be pondered with the rate of erosion present in the region which can be accentuated if there is periods without plant cover. Integration of the erosion in the model would be helpful to be more precise on stock dynamic. Also, the modelling of the mineralization process, which remains simple in this approach, should be investigated in more detail. The scale of the study may mask differences between localities in the region. Mineralization may also be influenced by agricultural practices. Low rates of mineralization may result from soil compaction and loss of soil living organisms. On the contrary, irrigation practices can stimulate soil mineralization by increasing soil moisture.

On the other hand, intensive livestock farming is carried out in Finistère. This specialization leads the region to be highly dependent on purchased animal feed (half of the energy equivalent of animal feed is imported), representing the main external inputs. The consumption of energy carriers and the use of fertilizers are low compared to imported feed. The significant difference is partly due to the use of CED, which takes into account the energy value of the feed and not only the energy cost of production and distribution. Livestock production leads to significant energy loss in the milk and meat production process (metabolic losses). Of the total plant biomass production ((1,2) and (1,6) flows, see **Figure 13**), only 29% is exported ((1,6) and (2,6) flows). A large part of the animal feed is pasture. This can be justified on condition that the grazing land is on land of low interest for other productions. Half of the plant biomass production is invested in AE. In addition, animal dejection accounts for half of the DA output. Despite this, the AE stock is relatively balanced thanks to the level of soil mineralization taking advantage of the high SOM stock and the favorable pedoclimatic conditions of the region. This result does not directly highlight the local environmental problems of eutrophication present in the region due to intensive livestock farming, although the large flows to and from AE suggest that this sub-system is under great stress. As for the Eure-et-Loir, the scale of the study may mask environmental problems that may be linked to a specific locality.

4.3.2 Assessing the performance and the resilience of both regions

For the sustainability assessment of the resource use, both static and dynamic dimensions have to be taken into account (Therond et al., 2017). The first dimension considers the present performance of the system in providing outputs, the second concerns the ability of the system to ensure long-term production, which is related to the resilience of the system.

The Eure-et-Loir has an *EROI* of 5.2 (**Table 10**), reflecting high performance in food production. This is partly due to its specialization in crop production which avoids losses in the conversion process as observed for

animal production. The $EROI_{ag}$ follows the same trend, but with a reduced value (3.7) due to the low provision of energy services by AE. High productivity is achieved through extensive use of fertilizer inputs, which is largely dependent on non-renewable resources for its production. Nitrogen supply from renewable resources is a major concern. The introduction of more leguminous crops, as well as the complementarity of livestock production could be factors in reducing the region's dependence on mineral fertilization. But this will have an impact on $EROI$ and land use.

In comparison, the Finistère has a low $EROI$ (0.3) for two main reasons. The first is due to its specialization in livestock farming, which logically introduces metabolic losses. The second reason is that this specialization has reinforced livestock farming beyond the region's capacity to provide feed, resulting in a high import. Unlike the Eure-et-Loir, the $EROI_{ag}$ of the Finistère has more than doubled (0.7). This is explained by the fact that AE is an important provider of energy services (**Figure 13**). It should be noted that with about three times less fertilizer used and less land under cultivation, Finistère has a NPP close to that of Eure-et-Loir. This result is partly explained by the important energy services provided by AE through mineralization.

Circularity indicators characterize the agroecosystem through the relationship between the associated ecosystem and agricultural production activities. The higher the $Circ_{out}$, the greater the development of the ecosystem. The higher the $Circ_{in}$, the greater the autonomy of the farm.

The Eure-et-Loir region has a greater $Circ_{in}$ than $Circ_{out}$, 71% and 59% respectively. A low exit circularity means that the biomass invested in AE is low compared to the biomass exported. A low rate of biomass yield could lead to a reduction in the functionality of the agro-ecosystem. At the same time, higher input circularity suggests that the farm is to some extent dependent on agro-ecosystem functions. This relatively unbalanced situation may eventually alter the functions of AE and needs to be taken into account.

In the case of Finistère, $Circ_{in}$ and $Circ_{out}$ show opposite and contrasted results, respectively 44% and 77% (Tab. 3). Even though the energy service of AE is significantly higher in this region, the large imported biomass generates the low $Circ_{in}$. Indeed, the region is very dependent on the flows arriving on the market. At the same time, Finistère has a high $Circ_{out}$, revealing that the majority of the biomass produced is left in the AE. One of the reasons for this situation is that almost 50% of the biomass invested in animal production as food is lost at the metabolic level, which reduces the energy exported. The unbalanced situation between input and output circularity is more in line with the environmental problems present in the region and could explain the environmental problems that the region is actually facing. If feed purchases were reduced, $Circ_{in}$ would increase due to the high level of mineralization in the region. At the same time, a reduction in feed will lead to a reduction in livestock numbers, reducing losses and bringing the two indicators of circularity closer together.

Table 10: Indicators and Stock of Eure-et-Loir and Finistère

		Eure-et-Loir			Finistère		
EROI	EROI	5.2			0;3		
	Agroecosystem EROI	3.7			0.7		
	Output Circularity	59 %			77 %		
	Input Circularity	71 %			44 %		
		GJ	Δ Stock	Relative variation	GJ	Δ Stock	Relative variation
Stock variation	Associated Ecosystem	6;90E+08	4;36E+07	6;33 %	1.04E+09	7.10E+06	0.68 %
	Facilities & tools	2;44E+06	-1;22E+05	-5.00 %	4.31E+07	-2.16E+06	-5.00 %

4.3.3 Interest, usefulness and limits of the framework

The introduction in energy assessment of the "associated ecosystem" highlights the link between agricultural production and the agro-ecosystem. The energy assessment of the latter was approached through the SOM, a first attempt to characterize it, using mineralization as a proxy for representing the energy services provided by the ecosystem. Our approach proposes to reverse the traditional energy aspect, focusing on energy dissipation more than on physical and material flow to describe natural services. Like engines that consume energy carriers and release CO₂, soil activity mobilizes organic matter and releases CO₂ through mineralization. The same logic is followed to express the energy consumed by the FT and EA subsystems. If the FT will need fuel, requiring a few million years to transform the biomass and be usable, the soil will need SOM, requiring several years to transform the biomass and be usable. This means that the investment in biomass and the mineralization of the OM are spread over several years. The energy stock indicates more of a trend than an annual variation and must be seen in the long term..

The services provided by the associated ecosystem are therefore only considered via mineralization. Further research is needed to represent more services rendered by the associated ecosystem. For example, in the present study the presence of hedgerows and accumulated biomass in perennial plants was not taken into account, because it represents a small amount of biogenic carbon stock in the agro-ecosystem. However, the services it can provide are substantial and directly related to soil erosion mitigation and pest control. It would be interesting to combine research carried out in landscape assessment with an energy perspective such as the integrated energy-landscape analysis (Marull et al., 2016), to assess more precisely the energy services provided by perennial plants and the landscape.

On the other hand, measuring energy flows only in terms of calorific value can be limiting because the services provided by the ecosystem depend in part on biodiversity and the interconnected and cooperative network of the living world. To some extent, the level of AE storage is linked to the level of biodiversity present in the system. To take this into account, Jorgensen (2006) proposed to introduce the information contained in living organisms into the energy account using eco-exergy. For him, the information helps to increase the distance from the thermodynamic equilibrium and to expand to increase its energy value and stock. These are potential development to better measure and define AE even if they are less operational and consensual.

In this initial work, we do not take into account all the flows in the technosphere (damping of engines, pesticides, pumping for irrigation, etc.), which would have required an excessive data collection effort. However, the purpose of this work was to test the evaluation framework developed for the farm scale, on a larger scale, i.e. the department. With regard to the objective of testing the method and its related indicators, the work shows valuable results and confirms the usefulness of the framework for assessing the agro-ecosystem, providing guidance for decision-making. More specifically, circularities are indicators that help to assess the resilience of the agroecosystem and the farm. High $Circ_{in/out}$ suggests farming systems based on natural services and biomass suppliers to the AE and close to natural systems. On the contrary, Low $Circ_{in}$ suggests farming systems based on technosphere services without biomass supply to the AE and close to the landless production system. High $Circ_{in}$ with low $Circ_{out}$ indicates systems based on energy services provided by the AE but with a low return of the produced biomass to it with the risk of loss of functionality of the agroecosystem. An $Circ_{in}$ lower than a $Circ_{out}$ indicates that we are potentially "overloading" the AE stock. Unbalanced circularity indicates potential problems on the resilience of a system.

4.4 Conclusion

This framework, designed at the farm level, has been applied at the regional level to compare two contrasting French agricultural production systems (i.e. Eure-et-Loir and Finistère). The method aims to assess, through energy flows, the efficiency and sustainability of resources. It examines the two dimensions of the agricultural system by considering it as a socio-economic activity and as an agro-ecosystem. For this purpose, the method is built through a systemic approach and considers a subsystem called associated ecosystem which represents the natural capital of agricultural production. It represents the supporting resources of the agro-ecosystem providing services to production processes. These resources depend on a circular flow of biomass to maintain its energy stock, the SOM being seen as the "bio-battery" of the agroecosystem. The mineralization of SOM was chosen to represent the energy flow provided by AE because it is a main function on the plant's production support (linked to the availability of nutrients and water), for its behavior (carbon stock and dissipation) and for the representativeness of soil mechanisms.

The method reflects the energy configuration of the two regions. It allows a good description of the flows that take place in the regions, also revealing the importance of the internal circular flow. The Eure-et-Loir region presents the best efficiency in the use of resources, mainly due to its low level of livestock production. However, its high yields are due to a high consumption of fertilizers which depends on non-renewable resources. The low $Circ_{out}$ suggests a reduced return of biomass to the agroecosystem which needs to be monitored to avoid accentuating the low level of energy stock in the AE. The Finistère region has a low efficiency in the use of resources due to its specialization in livestock farming and high volumes of imported feed. However, the important energy services provided by AE allow for better energy efficiency at the agro-ecosystem level. The circularity indices is highly unbalanced. This is due to a high dependency on food and the fact that a large part of the plant biomass production is lost in the animal production process. The resilience of the Finistère region is compromised. The specificities of the territory must be balanced with its production capacity.

Circularity indices are promising indicators in the assessment of system dependency. The previous farm-scale study (Hercher-Pasteur et al., submitted) showed high and balanced indicators (up to 80%) for the extensive

systems that were intended to be the most sustainable. The next step would be to apply the method and its indicators to groups of homogeneous systems in order to confirm the trend and possibly deduce circularity targets to be achieved.

Chapter 5: General discussion and conclusion

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The objective of this thesis was to provide an energetic view of agricultural production systems and to see how this allows evaluating and defining more sustainable practices. The first objective was to review the different energy assessment approaches used to analyze agricultural production systems. The second objective was to develop a method that takes into consideration both natural and technological mechanisms included in agricultural production. The hypothesis of this thesis was that the low consideration of ecosystems processes in quantitative assessment of agricultural systems partly explains the low adoption of agroecological practices by conventional agriculture. Thus, through a systemic energetic approach of agricultural production systems, by integrating the natural capital (called the associated ecosystem) as much as the technical capital, we have been able to measure the ecosystems processes contributions to the agricultural production. We also established indicators of circularity of the agroecosystem. Finally, the third objective was to test the method on a scale larger than a specific production system.

In this chapter, the main outcomes of the thesis are summarized, to point out the limits and perspectives of the framework developed and, finally, to conclude this research work.

5.1 Main outcomes of the thesis

5.1.1 A general panorama of energy assessment of the agricultural system

First of all, this thesis identifies the different energetic approaches of the agricultural production system (Chapter 2). An extensive review of the energetic approaches has been realized with a focus on farm scale (196 papers covering were finally selected). A protocol has been established to provide a critical analysis of the corpus through five key features: (i) goal and scope, (ii) system modeling, (iii) flow inventory, (iv) indicators, and (v) implementation. Ten kinds of energetic assessment approaches have been identified among three main families of energetic accounting methods: “Energy analysis”, based on the quantification of the calorific power of a product, “Exergy analysis”, based on the measure of the maximum reusable work provided by products and services, and “Emergy analysis”, based on the computation of all the succession of energy transformations required to provide products and service, starting from sun radiation.

The differentiation of the quality of the different energy vectors remains a problem that has been solved with exergy and more particularly with emergy accounting. However, energy analysis presents the advantage of being closer to present-day economic indicators and allow a better understanding by the operators and stakeholders of the agricultural system. Nevertheless, variability in system boundaries still an issue and focusing only on fossil energy consumption can miss the account of biomass consumption by, for example, animal production systems. An exhaustive assessment implies to consider all the different flows consumed by the system and for that it has been recommended to used data set such as cumulative energy demand (CED proposed in Ecoinvent data base).

More generally, we have noticed a new tendency on the perception agricultural production system seen as an agroecosystem requiring flows from technosphere and flows from ecosphere to be maintained. More recently, studies start considering the production of all the biomass produce (i.e. In terms of NPP) and introduce a circular dimension to the energy assessment (i.e. agroecology energy assessment, see **Figure 5**, p. 17). Here, the agroecosystem is considered as a fund resource that needs a constant rate of investment, in this case of biomass, to provide a given rate of products, at the difference of a stock resource based on the consumption of a declining

resource. Also, soil organic matter has been regularly pointed to be another key component in the energetic balance of an agroecosystem, getting more attention in energy assessment and in the agronomic field in general. The indicators used to assess the agricultural system must reflect this dual dimension of the farm, in order to take into account the sustainability of the farm, both in socio-economic and ecological terms.

According to the objectives of this work, agroecological energy analysis offers a usable metric (it stays on calorific value) and a circular vision of the flows present in the agricultural production system. On the other hand, emergy proposes a powerful systemic approach based on a graphical representation proven by ecological modeling.

5.1.2 Looking at farm as an agroecosystem: methodologic outcomes

The second outcome was the development of an accessible method that illustrates the two dimensions of the farm, i.e. the socio-economic activity and the agroecosystem. Through a systemic representation of agricultural systems, two types of capital, characterized as storage processes, are identified. Facilities and Tools (FT) represents the fixed capital or the exosomatic instrument coming from the technosphere. The associated ecosystem (AE) represents the natural capital or the endosomatic instrument coming from the ecosphere. Their function is to come in support to production processes providing services to the cultivated biomass (CB) and the domesticated animals (DA), which main function is to transform a product into another product of higher quality (e.g. solar radiation in edible food, grass in milk and meat).

In doing so, the energy mobilized by storage processes is transformed (into useful work) and dissipated (e.g. the tractor burning diesel). If a tractor is stationary, it does not dissipate energy yet it does not provide services as well. It is this change in perspective, taking energetic services as a all, that allows us to characterize the services provided by the AE. The soil being the main contributor of the agroecosystem to carbon storage, through the soil organic matter (SOM), and the place of many ecosystem services, soil mineralization is proposed as a proxy to measure the services provided by the AE. Indeed, soil mineralization is the result of the biomass energy conversion realized by the activity of soil organisms, which participate in nutrient cycling, humus formation and soil aggregates . It also presents the advantage of being an accessible data through the coefficient of mineralization (K2).

At the end, the model considers external inputs (in terms of cumulative energy demand, CED) and circular and ecosystem flows (in terms of Gross Calorific Value, GCV) quantified with the same metric, i.e. energy. The resulting indicators provide information on resource use efficiency and the resilience of the farm system. The method is applied to a real case study (a farm) and three contrasting scenarios are proposed to test the interest of the developed indicators and framework.

To assess the resource use efficiency of the farm, we compute *EROI indicators* when the agricultural system is seen as a socio-economic activity, taking into account external inputs outputs, and an agroecosystem EROI ($EROI_{Ag}$) when it is appreciated as an agroecosystem, by integrating flows from/to the AE. Then, we used circularity to measure the relationship between agricultural activity and its associated ecosystem through 2 indicators, respectively inflow circularity ($Circ_{in}$) and outflow circularity ($Circ_{out}$). Inflow circularity assesses the energy provided by the associated ecosystem in relation to the total energy consumed when outflow circularity is a ratio between the energy invested into the associated ecosystem and the total energy produced. The state of stocks of storage processes are also taken into account in the evaluation.

It appeared that for systems that do not import biomass (i.e. 100% vegetal production and animal breeding without imported feed) $EROI$ is higher than $EROI_{Ag}$. Indeed, internal flows, through their importance in the flow inventory, flatten resource use efficiency rates. On the contrary, in systems where biomass is imported, $EROI_{Ag}$ is higher than $EROI$. Indeed, the importation of biomass into the farm system particularly affects the $EROI$ and less the $EROI_{Ag}$ due to the internal flows.

Concerning the indicators of circularity, they show that the greater the intensity of a farm system is with high imported biomass (intensive animal breeding), the greater contrasted the circularity will be, with a low $Circ_{in}$ and a high $Circ_{out}$. This is explained by a strong reliance on external inputs and by the artificial increase of biomass invested in the AE. On the other hand, intensive plant production practices would present less contrasted but lower circularity with a higher $Circ_{in}$ to $Circ_{out}$. This reflects agricultural practices with a weak return to the agroecosystem while remaining dependent on the fundamental services provided by the soil. Finally, in the case of a farm system with extensive practices (i.e. mixed-farming system with no importation of animal feed), it would present high and balance $Circ_{in}$ and $Circ_{out}$. This result seems to confirm the trend that farm systems with sustainable farming practices should present high and balance circularity indicators.

5.1.3 Testing the method to a larger scale

We tested the method on a larger scale than a farming system, i.e. an agricultural region as a whole. Two contrasted territories (French departments) in their agricultural production have been selected to compare their resource efficiency. Eure-et-Loir is oriented to intensive crop production when Finistère is oriented to intensive animal breeding.

The results obtained at the level of a territory show the same trend and behavior as in the case study. Finistère shows contrasted circularity while the Eure-et-Loir shows less contrasted circularity with in $Circ_{in}$ higher than $Circ_{out}$. The inversion of the circularity indices for the Eure-et-Loir may indicate a stress on the functionalities of its associated ecosystem, which may affect the natural capital in the long term. This is also the case for the resource use efficiency indicators with Finistère lower and inverted $EROIs$ ($EROI : 0.3 ; EROI_{Ag} : 0.7$) and the Eure-et-Loir has a higher energy return rate ($EROI : 5.2 ; EROI_{Ag} : 3 .7$).

This application of the method on a larger scale shows its capacity to provide a general view of the energy profile of agricultural production at territorial scale. Moreover, resource use efficiency and circularity indicators are valuable to easily present trends and rates of agricultural regions regarding the use of different types of resources and assess their efficiency and sustainability.

5.2 Limits and perspectives

5.2.1 Limits of energetic assessment approach developed

Even if energy analysis allows computing all the flow presents in the agroecosystem into a single metric, it may still be difficult for stakeholders such as farmers to grasp the direct links between their agricultural practices and the energy consumption. For example, energy analysis does not directly address the question of fertilizers flow management, which is another major issue for agriculture. Also, energy analysis does not take the environmental

that certain practices may have into account. However, through the consumption of fossil fuels it is possible to have a first idea of direct greenhouse gas (GHG) emissions and its related impact on climate change (even if there are other emission factors such as manure spreading).

In addition, if the price of energy is a parameter taken into account by farmers on certain choices, the economic realities and the market price remain the principal elements in decision-making. The adoption of certain practices that are more environmentally friendly requires a new organization in the whole food supply chain, a better recognition of externalities and the support of government institutions.

Soil erosion was not considered in the flow inventory. However, it could be seen as a consumption of natural resources. The integration of erosion could be, among other things, a way of relativizing the high EROI of certain intensive crop systems that presents, in general, erosion issues.

Finally, the use of mineralization as a proxy of soil activity apply strengthen it measure. In the present work, we used a simple coefficient, while mineralization implies complex reactions and processes, with variation in time. Even if the principle of a model is to offer a simplified representation of a complex system, it would be worthwhile to improve the mineralization measurement. This also implies better characterization of the service of mineralization. As previously mentioned, mineralization has been used to express the service provided by the AE, which is the result of the soil organisms' activity. A deeper look to microbial biomass population would be useful to evaluate the quality of SOM mineralization. Indeed, both are often closely correlated even if stress factors reduce microbial biomass more rapidly than SOM (Dilly, 2005).

5.2.2 Considering others energetic services

In the proposed energetic EA approach, provision of services are represented by the use and the dissipation of energy. However, it is important to see that there is different logic depending is the service is provided exosomatic or endosomatic instruments. In the case of services provided by FT, the focus is placed on reducing energy consumption and therefore our energy losses. In the case of the AE, we look to increase the services provided. This can be implemented by increasing the amount of biomass present in the agroecosystem. It can also be achieved by increasing the multifunctionality of a component in the system that produces and provides a service.

This principle, which we have partly mobilized in our method (in the case of the extensive scenario and the multiple-use of the cows), could be the basis to better characterize energetically other services present in the agroecosystem. This would concern endosomatic components that have multiple use with more than one function. This means that if a functionality is identified that is provided to a production process, it would seem fair to consider it as a service performed.

(i) *service provided by crop to other crop* (corresponding to the cell (1,1) in the input/output **Table 5**, p. 43) : It is the case of a plant being used as a support for another plant. An example of this is the cultivation of wine on high ground in the Minho region of Portugal, where the vine relies on the tree to grow. Here the trees provide a service supporting the wine and it is also a producer of biomass output (fruits). Another example would be the Milpa technique that combines squash with corn and beans. In this case, the bean leans on the corn to grow. The corn is a producer of output and a support to beans growth.

(ii) *Service provided by plants grown on the ground* (cell (1,4)): Plant cover is now often recommended, for example between rows of vines to combat erosion. Its function here is to protect the soil against erosion. This

could concern agroforestry as well. The function of the cultivated biomass is not only to provide biomass to the AE, but rather a service of soil erosion mitigation.

iii) *Service provided by trees (from CB or AE) to animals* (cell (4,2)). The shelter provided by the canopy of a tree for animals in the field can be a precious asset in summer.

In these three examples, considering the energy dissipated by the plant support to measure the energetic services provided (E_{serv}) would be the amount of solar radiation energy absorbed by the plant (E_{int}), minus the energy stock (E_{stock}) in the biomass produced

$$E_{serv}(GJ) = \sum E_{int}(GJ) - E_{stock}(GJ)$$

5.2.3 Going deeper in energetic exchanges

The present energetic method proposed to represent the farm in four sub-systems: two production processes (animal and vegetal production) and two processes of storage (fixed capital and the associated ecosystem). However, if we go deeper in the energetic analysis, we could imagine a representation of all the different crops and livestock components. Concerning the cultivated biomass, this would lead us to be at the plot scale. Thus, the soil might no longer be associated with a global subsystem representing the AE but would be placed more specifically at the level of each plot and associated with a type of crop. This would allow, among other things, to take into account the crop rotations and the phases of uploading and downloading of the energy stored in the soil (**Figure 14**) and to introduce a temporal dimension to the energy analysis. In order to better address the stock dynamics at plot scale, a complete crop cycle would seem to be the most relevant time period to be taken into account. This logic is already present in the farmer management through its organization of crop rotations.

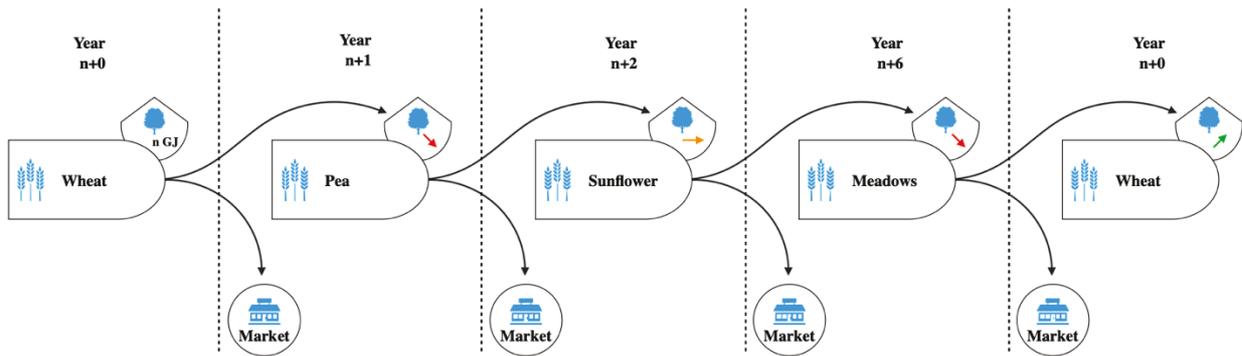


Figure 14: Example of a crop sequence at the plot scale looking and considering energy stock variation

Integrating the temporal dimension in the energetic assessment becomes even more important if the agricultural production system is based on natural mechanisms presenting different dynamics to be conciliated with short-term productive imperatives (i.e., the agricultural activity must be profitable to maintain the investment made in the agro-ecosystem). For this, the agricultural activity must clearly identify the different time scales that exist in the supply of services provided by the agroecosystem. For example, in the short term, the roots of a crop can have a direct impact on the crop that follows it through the soil structure or the nitrogen supply in the case of

legumes. In the medium term, depending on the climate, the mechanisms for decomposing plant biomass into organic matter can take several years. In the longer term, the presence of living organisms and a rich biodiversity participating to biocontrol and to soil mineralization, implies the existence of a stable habitat depending in part on the presence of perennial plants.

This is also true in regards to renewable energies whose production is intermittent. One of the keys to a successful integration of renewable energy on the farm will depend on the ability of agricultural production processes to align with the energy production cycle. Energy storage is still one of the weak points of electrical energy. Limiting storage means making consumption periods to coincide with production periods. This will require a certain degree of adaptability from the agricultural production processes. This will be even more necessary if a process is directly linked to a renewable resource without a storage step. Having a solar grain dryer means drying the grain when there is sunlight. Having a windmill means grinding its grain when it is windy. In the same way, if agricultural machinery becomes partly electric, energy optimization could involve loading the machines when energy is available, having them parked properly during that time. This could imply deep changes in farm work organization, going in some respects in the opposite direction of the continuous industrial flow logic.

Given the diversity of time scales of energy processes, the introduction of the temporal dimension in the method would be an additional asset in the optimization and complementarity of energy processes present on the farm. It is to be expected that there is a need for tools to monitor the different temporality of the processes in order to make the energy supply and demand match.

5.2.4 The role of Information and Communication technologies in monitoring energetic flows

Communication and information technologies (ICTs) should play an important role in this sense and could be an important tool in the distribution of energy resources available at a given time.

Real-time knowledge of a vehicle's fuel consumption or geolocation of the tractor path within a field are tools that already exist and may lead to reductions in fuel consumption. In the same way, real-time knowledge of energy production from renewable energy and the state of load of the various batteries in the system would allow to maximize the use of energy from intermittent renewable resources. The integration of weather forecasts, already present today, remains an essential element to be able to anticipate and organize agricultural tasks.

If ICTs have until now mainly positioned themselves in the optimization and reduction of external inputs through precision agriculture, the illustration of the importance of internal flows from the agroecosystem invites also a change of logic. Indeed, the ICTs could also guide the knowledge of the environment for responses aimed at optimizing and mobilizing internal flows in the agroecosystem. This concern, for example, the management of the allocation of biomass reinvested in the system. Depending on the specific needs of the soil and the plot, the amendment would be considered according to its composition or degree of composting and better distributed within the farm. This could also involve insects and living organisms of the agroecosystem and their distribution in the system. Areas of poor insect populations could thus indicate a lack of habitat or the need to introduce biocontrol agents with the displacement of populations from a rich area to a poor area.

5.2.5 Consider the other dimension of circularity

Being focus on the relationship between the agricultural activity and its associated ecosystem, the method proposed a site-specific approach which is linked to a specific agroecosystem. The circularity inside the agroecosystem appears an element essential to the maintenance of its functionality. Also, increasing complexity and diversification in the production allow maximize the valorization of co-products from the production process with another and minimizing energetic lost. The circularity inside the system appears to strengthen the resilience of the system.

However, this search for looping flows must not be done to the detriment of the integration of the system on its territory. Indeed, the links between agricultural systems can be an asset and contribute to the resilience of systems in the face of external shocks affecting one system more than another. This also concerns the question of the complementarity of productions within a territory and the resulting diversity of productions and the impact that this can have on the environment and landscapes. As shown in Finistère department, too much specialization can weaken the complementarity between animal and plant production systems, making the territory dependent on animal feed, on the one hand, and, on the other hand, making animal excrement a problem rather than an asset in the cycle. The diversity of productions within a territory is an asset to be strengthened.

The circularity also concerns the relationship of the farm with the market. There is actually a growing interest for local products, short food supply chains and the reconnexion between agriculture and food consumption. This implies to change from a site-specific approach to a product approach looking at the life cycle of the product. The developed model allowed to see at the upstream energy consumption of the agricultural system. The next step would be to look at the downstream of the farming system. It would allow to see in its globality the resource use until the final stage of the farm outputs exported. By doing this, it would also allow looking at the loop between the agricultural system and the market. However, it must be noted that industrial societies are on a linear model and where the recycling of biomass to be reinvested in the agroecosystem is in most cases inexistent.. Yet, concerning food residues, there are some projects of valorization through anaerobic digestion, but few are the farmers using the digestate co-product.

Thus, relocation could be an opportunity to rebuild a circularity between agriculture and food consumption. The construction of a relationship between the farm and the consumer will be needed in order to recover part the biomass exported out of the system. This kind of partnership would be eventually easier for small structure practicing direct farm sales. But the configuration of these direct sales and return must be assessed with caution and will depend on consumer-retailer distance, the quantity purchased and the transport. A recent study suggests that direct on-farm sales can be highly impactful compared to an organized long national food supply chain, mainly due to the transport of the consumer (Loiseau et al., 2020). However, emerging short supply chain has a wide margin for progress and could build a useful strategy of circularity with consumers.

5.3 Conclusion

In the end, this PhD thesis allowed to go further in the characterization of the farm as an agroecosystem. With a first exploratory work of the different energetic approaches applied to farm systems, we were able to identify the strengths and weaknesses of the different energy analysis methods and their ability to address sustainability issues. This allowed us to build a framework that highlights the relationship between agricultural activity and its agroecosystem, to quantify this relationship in order to produce monitoring indicators while remaining on simple metrics to ensure its accessibility to the various stakeholders.

In response to the research question:

"How can energy analysis be used to assess and design an efficient and sustainable agricultural production system?"

The energy analysis can be used to assess and design an efficient and sustainable agricultural production system:

- i) Identify the system requirements in renewable and non-renewable resources. This concern external inputs but also internal resources of the agroecosystem.
- ii) Describe the relationship between the agricultural activity and its agroecosystem. This is possible thanks to a systemic approach that considers, like technical capital, the natural capital as an integrated component of the agricultural system and called in the method the “associated ecosystem”.
- iii) Define the nature of the component and its function. All the machines, facilities and tools are the technical stock of a farm system that provides services. The SOM and the accumulated biomass in perennial plant are the biotic stock that also deliver services to the farm activity. The farm is composed of its production processes which aim is to provide, at the end of the transformation process, a product from vegetal or animal origins.
- iv) Consider the energy stored in the system. The capacity to provide a service is directly related to level and state of energy stock, the soil being seen as the bio-battery of the system.
- v) Provide indicators that measure the resource use efficiency of the farm and indicators monitoring the relationship between the agricultural activity and the agroecosystem. The circularity describes this link through the biomass invested and the service perceived from/to the associated ecosystem.

The circularity seems to be an important parameter in the sustainability of the agricultural system. Efficiency in the use of resources is also an important element in the optimization of the production system, but it must be handled with caution because it responds to different logics depending on whether it is addressed to the agricultural activity or to the agroecosystem. The first aims to optimize output flows while the second looks to optimize internal flows to minimize its losses and increase its capital through, among other things, the complementarity of its components.

This observation, which the implementation indicators seem to confirm, is one of the important points of this thesis and shows that the implementation and design of a more sustainable agriculture requires more diversified systems (at specific and at territorial level) in the production of biomass. This diversification would allow, among other things, to increase the services rendered by one production process to another and to increase the functionalities of its components.

To go further, diversification is addressed to the agroecosystem but also to the farm's activity. Thus, it would allow offering in addition to agricultural products other services demanded by society (e.g. recreation, formation, cultural events, socialization, ...). The development of this link between the farm, its territory and the market would be as much an asset in strengthening the resilience of agricultural activity as in its attractiveness.

This method, through an energetic vision of the farms as an agroecosystem, opens doors in the implementation of more sustainable agricultural systems. This energetic approach could be the basis for the development of a tool for advice and support for agricultural production systems in their transition to new agricultural practices such as agroecology, in the widest sense of the term.

Résumé étendu en français

Chapitre 1

Contexte et objectifs généraux

> Les défis de l'agriculture moderne

L'agriculture issue de "la révolution verte" a permis une forte augmentation de la production et de la productivité grâce à l'utilisation d'intrants (fertilisation et produits sanitaires), à l'amélioration des semences, à la mécanisation et à l'irrigation. Il fallait répondre à une augmentation de la demande alimentaire mondiale.

Mais ce modèle agricole (que l'on appellera par la suite agriculture conventionnelle) entraîne des impacts sur l'environnement, à tous les niveaux, et sa durabilité est fortement questionnée (Tilman et al. 2002). Nous assistons à une chute de la biodiversité sans précédent. L'usage intensif des intrants a un impact néfaste sur les écosystèmes, l'eau et la santé humaine. Les pratiques agricoles intensives telles que le travail intensif des sols et l'irrigation (70% de l'eau douce est consommé par l'agriculture) épuisent les ressources hydriques et pédologiques. L'homogénéisation des semences à haut rendement tout comme des paysages a appauvri la diversité génétique des cultures, réduisant leurs capacités de résistance. A cela s'ajoute le fait que l'agriculture conventionnelle est devenue très dépendante des ressources fossiles, qui ont un fort impact sur le changement climatique. Elle est particulièrement sensible à la volatilité des prix de l'énergie. (Foley et al. 2011).

L'agriculture est confrontée à un énorme défi. Elle doit continuer d'être productive pour répondre à la croissance de la population humaine, tout en étant moins dépendante des énergies fossiles et en réduisant son impact sur le changement climatique, sur les ressources et sur la biodiversité. A cela s'ajoute la nécessité d'accroître sa résilience face au changement climatique, au variation des marchés et à la pénurie de ressources à venir.

> Des solutions pour une agriculture plus durable

○ Une agriculture s'appuyant sur les mécanismes des écosystèmes

L'une des principales caractéristiques de l'agriculture conventionnelle a été de s'affranchir de la variabilité et des contraintes de l'environnement, en mobilisant des intrants (e.g., engrais, pesticides, irrigation) issus de la technosphère (liée à l'activité humaine). Cependant, on assiste à un retour des pratiques agricoles, comme l'agroécologie (Altieri et al., 1995; Gliessman, 1990), qui proposent de s'appuyer davantage sur des mécanismes naturels pour assurer un approvisionnement durable en ressources et en services (de l'écosphère). La fertilité des sols et sa capacité de stockage en eau, le contrôle des maladies et des ravageurs sont les services écosystémiques clés pour l'activité agricole (Duru et al., 2015). Mais la capacité à fournir ces services dépend du capital naturel du système agricole (Jordan, 2016).

Pour considérer ce capital naturel, il importe de voir le système de production agricole comme un agroécosystème (Gliessman 2016). L'agroécosystème est un système artificiel qui dépend de flux anthropiques (i.e., issus de l'homme) et de flux biotiques (issus de l'environnement) nécessaires pour conserver ses

caractéristiques et sa capacité à produire. La distribution et la succession des cultures, l'introduction de légumineuses dans la rotation, les cultures de couverture et l'agroforesterie pour réduire l'érosion des sols et l'évaporation de l'eau, la diversification des variétés de plantes dans les champs pour réduire le risque de maladie ou la lutte biologique contre les parasites sont quelques-unes des pratiques s'appuyant sur les mécanismes des écosystèmes et qui tentent de réduire l'utilisation d'intrants.

- Une agriculture s'appuyant sur la circularité des flux

Face à un système alimentaire industriel mondialisé, face au risque d'approvisionnement qui en découle et à la sensibilité au prix du marché, la circularité du système agroalimentaire est une thématique qui prend de l'ampleur. La circularité cherche à boucler les flux en travaillant sur la réduction, la réutilisation et le recyclage des flux d'énergie et de matériaux (Therond et al. 2017). L'approche territoriale et régionale s'inscrit dans cette logique, en cherchant à proposer un système agroalimentaire plus connecté et durable.

Considérer le système de production agricole comme un agroécosystème implique de s'intéresser à la circularité, mais cette fois à l'intérieur du système agricole, c'est-à-dire entre l'activité agricole et l'écosystème où elle prend place. Maintenir les fonctionnalités d'un agroécosystème demande de réinvestir en interne une partie de sa production de biomasse afin d'alimenter les mécanismes de l'écosystème (Guzmán et al., 2015). La construction de complémentarités au travers de la circularité des flux entre les différentes productions d'un système agricole d'une part et entre l'activité agricole et son environnement naturel d'autre part, sont un autre élément majeur pour le développement d'un système agricole plus durable et résilient.

- > Un besoin de quantifier les flux des agroécosystèmes

- Des mécanismes naturels et de la circularité faiblement quantifiés

Une bonne description des flux issus des écosystèmes et de leur circularité dans le système de production agricole est essentielle. Cependant, les bénéfices offerts par les mécanismes naturels restent difficiles à quantifier. La notion de circularité dans les agroécosystèmes a été développée, mais une quantification des échanges entre l'activité agricole et son environnement direct n'a pas été véritablement traitée. Nous supposons ici que la faible adoption de pratiques agroécologiques par l'agriculture conventionnelle s'explique en partie par ce manque d'information. Il est donc nécessaire de disposer d'une unité de mesure permettant d'exprimer la circularité et les flux fournis par les écosystèmes afin de quantifier les bénéfices et leurs effets sur la durabilité des systèmes de production agricole.

- L'énergie, une unité de mesure universelle bien connue

L'énergie est un élément clé dans le développement des sociétés humaines (Smil, 2017). Cela nous a permis d'aller plus vite, plus loin, de produire plus et ainsi d'augmenter notre puissance énergétique au travers de nos instruments exosomatiques (qui est à l'extérieur du corps). Si au départ nous dépendions de la capacité des plantes à transformer l'énergie solaire en énergie chimique (la biomasse), l'accès aux énergies fossiles a profondément modifié le monde. La population a fortement augmenté en 2 siècles (de 1 milliard à 7,5 milliards), la population agricole dans les pays industrialisés a chuté (en France de 48% en 1880 à 3% en 1999). Au final, la croissance

économique est intimement liée à la consommation énergétique et aux émissions de CO₂ (Chen et al., 2016; Wang et al., 2016).

L'énergie est également la variable d'état thermodynamique utilisée pour décrire les écosystèmes. Tous les processus de transformation énergétique génèrent des pertes, une variation d'entropie (2^{ème} principe de la thermodynamie). Or les écosystèmes se caractérisent par leurs capacités à maximiser la quantité d'énergie utile (la biomasse) grâce à leurs capacités d'auto-organisation, de recyclage et de bouclage des flux dans un réseau coopératif. L'énergie est au cœur du mécanisme naturel et a été largement utilisée dans la modélisation écologique (Odum, 1988).

L'analyse énergétique a également vite été mobilisée pour étudier la relation entre consommation énergétique et production agricole notamment au moment de la première crise pétrolière (Pimentel et al., 1973). Elle a été utilisée pour comparer l'efficacité énergétique des pratiques agricoles (Smith et al., 2015), pour comprendre la dynamique et l'évolution du système agricole au fil du temps (Soto et al. 2008 ; Krausmann 2016 ; Harchaoui et Chatzimpiros 2019), et a également permis d'illustrer la circularité du flux de biomasse dans l'agroécosystème (Guzmán et al. 2015).

L'énergie est donc une unité de mesure bien connue pour décrire l'écosphère (c'est-à-dire les milieux et les mécanismes environnementaux associés) et la technosphère (c'est-à-dire les activités humaines) (Jolliet et al. 2015). Il est cependant nécessaire d'aller plus loin dans la description des flux issus des écosystèmes et de la circularité.

> Objectif de la thèse

Sur la base de ces éléments de contexte, la question générale de recherche a été formulée comme suit :

« Comment l'analyse énergétique permet-elle d'évaluer et de concevoir un système de production agricole performant et durable ? » Avec la finalité opérationnelle de développer une méthode d'analyse des systèmes agricoles en termes de flux d'énergie, qui soit compréhensible par les agriculteurs et les parties prenantes. Pour répondre à cela, trois objectifs ont été définis :

- Objectif 1 : Identifier les différentes approches d'évaluations énergétiques des systèmes de production agricole.
- Objectif 2 : Représenter les flux énergétiques présents dans le système de production agricole vu comme un agroécosystème.
- Objectif 3 : Tester la méthode en la mettant à l'épreuve à une autre échelle d'analyse, plus large que l'exploitation agricole.

Chaque objectif sera abordé par un chapitre de la thèse. Le chapitre 1 est l'introduction générale de ce manuscrit. Le chapitre 2 présente un panorama exhaustif des différentes approches énergétiques appliquées au système de production agricole. Le chapitre 3 décrit la méthodologie d'analyse énergétique développée pour évaluer l'efficacité de l'utilisation des ressources et la résilience du système agricole à l'échelle de la ferme, vue comme une activité socio-économique et comme un agroécosystème. Le chapitre 4 applique le cadre méthodologique proposé à une plus grande échelle, en comparant deux régions agricoles contrastées, l'une orientée

vers la production végétale, l'autre vers la production animale, respectivement l'Eure-et-Loir et le Finistère. Enfin, le chapitre 5 regroupe la conclusion générale de la thèse et ses perspectives de travail.

Chapitre 2

L'analyse énergétique des systèmes de production agricole

> Contexte et objectifs

L'étude menée dans ce chapitre a pour but de répertorier l'ensemble des approches énergétiques, d'analyser leurs forces et leurs faiblesses et d'identifier les pistes à privilégier pour l'évaluation de la durabilité et de la résilience des systèmes de production agricole.

> Méthode

Cette analyse bibliographique est basée sur la requête [TITLE: ((ener* or exer* or emer*) and (agri* or farm* or agro* or "food production" or livestock) NOT (emerging or emergency or wind or wave or tide))AND TOPIC: ((model* or balance or diagnostic or footprint or assessment or analysis))] réalisée dans la base de données « Web of Science ». Parmi les 1,192 résultats de la requête, un total de 196 articles scientifiques a été sélectionné à la lecture du résumé.

Un protocole a été défini pour fournir une analyse des différentes approches énergétiques au travers de 5 caractéristiques : (i) objectif de l'étude, (ii) modélisation du système, (iii) inventaire des flux, (iv) indicateurs, et (v) mise en œuvre. En effet, selon l'objectif de l'étude, l'utilisateur sélectionnera la méthode qui lui semble la plus appropriée. Par ailleurs, le choix du modèle va définir la représentation des flux énergétiques, ce qui détermine par la suite l'inventaire des flux et la sélection des indicateurs appropriés pour observer les variables. Enfin, la mise en œuvre et le degré d'applicabilité des approches énergétiques seront évalués.

> Résultats et discussion

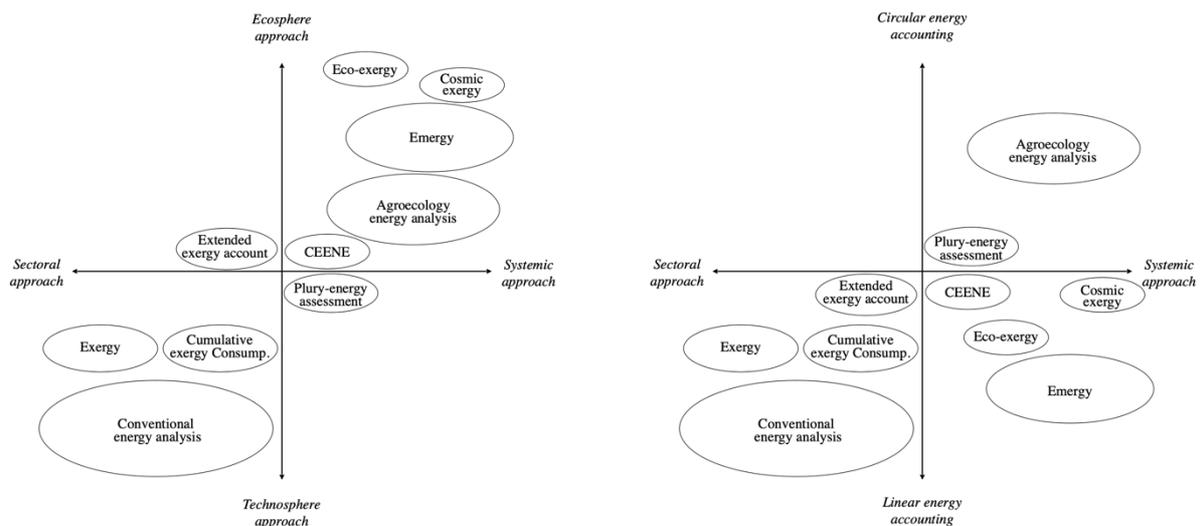
L'étude a permis d'identifier 10 approches énergétiques qui se base sur 3 unités de mesure différentes (l'énergie, l'exergie et l'émergie : i) l'analyse énergétique conventionnelle, ii) l'analyse pluri-énergétique, iii) l'analyse énergétique agroécologique, iv) l'exergie, v) l'analyse cumulative exergétique, vi) l'analyse étendue exergétique, vii) l'extraction cumulative d'exergie du milieu naturel (CEENE), viii) éco-exergie, ix) l'exergie cosmique, x) l'émergie.

L'approche énergétique s'appuie sur le pouvoir calorifique d'un produit pour mesurer son contenu énergétique. Elle considère les flux d'énergie directement consommés par le système et les flux indirects qui prennent en considération l'énergie utilisée en amont du système dans l'extraction, la transformation et le transport de l'intrant, en fonction de sa production en biomasse (Dalgaard et al., 2001; Risoud, 1999). Les **approches exergétiques** s'appuient sur la deuxième loi de la thermodynamique (irréversibilité des processus énergétiques et la production d'entropie). Elle mesure le travail utile d'un processus énergétique nécessaire pour revenir à son point d'équilibre. **L'émergie** propose de prendre en compte la somme des transformations énergétiques nécessaires

pour obtenir un certain produit en considérant l'énergie solaire comme point de départ des transformations (Odum, 1988). Appelée également énergie mémoire, son unité est le joule solaire.

Malgré sa capacité de différencier les flux énergétiques en termes de qualité, l'éxergie est une unité de mesure difficile à appréhender pour l'ensemble des parties prenantes. Aussi nous ne l'approfondirons pas. L'émergie considère l'ensemble des flux énergétiques (issu de l'environnement naturel et technique) et les distingue en termes de qualité. Elle implique la réalisation d'un diagramme énergétique indiquant la nature des différents composants du système agricole, offrant une vue globale des fonctions de l'agroécosystème (Martin et al., 2006). Sa logique énergétique reste tout de même éloignée des approches économiques actuelles.

L'analyse énergétique conventionnelle est la plus appliquée de par son unité de mesure et son focus sur les flux socio-économiques, mobilisant des indicateurs connus, comme l'EROI (taux de retour énergétique). Mais la non-prise en compte des ressources biotiques est une faiblesse dans le cas de l'agriculture qui dépend des processus naturels. L'approche circulaire (figure 1) de l'analyse énergétique agroécologique (Guzmán et al., 2015; Tello et al., 2016) sont des réponses à ce manquement. En effet, cette dernière considère l'ensemble de la biomasse produite en termes de Production Primaire Nette (PPN) lui permettant d'intégrer les flux biomasse réinvestit dans le système participant au maintien des fonctionnalités de l'agroécosystème. Essentiellement appliquée à des échelles territoriales, cette approche propose l'utilisation de plusieurs EROI, considérant notamment la biomasse réinvestie comme un flux d'entrée consommé par l'agroécosystème.



a) Technosphere/Ecosphere approach versus Sectoral/Systemic approach.

b) Linear/Circular energy accounting versus Sectoral/Systemic approach.

Figure 1: Classification des approches énergétiques en fonction de leur granulométrie (approche sectorielle vs systémique), de leur sphère d'intérêt (technosphère vs écosphère), et de leur circularité (linéaire vs circulaire).

> Conclusion

L'analyse énergétique présente de nombreuses approches avec des forces et des faiblesses à concilier selon l'objectif de l'étude et permet d'apprécier la durabilité des systèmes de production agricole. Cependant, aux vues des objectifs de ce travail, l'analyse énergétique agroécologique offre une unité de mesure accessible et une vision circulaire des flux présents dans le système de production agricole. L'émergie propose une approche systémique puissante s'appuyant sur une représentation graphique éprouvée par la modélisation écologique. La combinaison des deux pourrait être judicieuse, mais impliquerait également des compromis.

Chapitre 3

Identification de l'utilisation des ressources et de la circularité dans les exploitations agricoles: prise en compte de l'agroécosystème dans l'analyse énergétique

> Contexte et objectifs

Ces dernières avancées dans l'analyse énergétique nous amènent à considérer le système de production agricole en tant qu'agroécosystème au travers d'une vision circulaire des flux énergétiques et de porter un regard systémique sur les différentes composantes de la ferme. Le Chapitre 3 présente une méthode générique pour évaluer le profil énergétique des systèmes de production agricole. L'objectif est de développer une méthode accessible qui offre un inventaire exhaustif des flux, s'appuyant sur une vision systémique afin de mettre en lumière les flux issus de l'agroécosystème, d'y intégrer la circularité qui caractérise ce dernier et de fournir des indicateurs de suivi nous informant sur la performance et la résilience de la ferme. La méthode est appliquée à un cas d'étude réel (une exploitation agricole en polyculture élevage). Trois scénarios contrastés sont proposés pour tester les indicateurs.

> Matériel et méthode

La ferme est caractérisée par des processus de stockage et des processus de production. Les processus de stockage concernent le capital fixe (matériel, outils et bâtiments) et le capital naturel (composante de l'écosystème non maîtrisé par l'homme) appelé « écosystème associé ». Leur fonction est de fournir des services au processus de production. Cette action est associée à la dissipation d'énergie (par exemple le tracteur qui brûle du gasoil). Concernant les services fournis par l'écosystème associé, le sol étant le principal réservoir de carbone de l'agroécosystème et le siège de nombreux services écosystémiques, nous proposons d'utiliser la minéralisation du sol comme proxy. En effet, celle-ci est le résultat de l'énergie dissipée sous l'effet de l'activité des organismes du sol et présente l'avantage d'être une donnée accessible. Selon la typologie de la ferme, celle-ci aura un ou plusieurs processus de production classés en deux groupes, la biomasse cultivée et les animaux domestiqués. La fonction d'un processus de production est d'avoir en sortie un autre produit (par exemple le rayonnement solaire en aliments comestibles, l'herbe en lait et viande). Cependant, chaque sous-système pouvant avoir des fonctionnalités subjacentes est associé à un processus de stockage (comme les semences pour l'année suivante) ou à un processus de production (comme des panneaux photovoltaïques produisant de l'électricité) (voir figure 2 et le tableau d'entrée/sortie associé Tab.1)).

Les flux d'entrée externe au système sont mesurés en énergie cumulée, c'est-à-dire la somme des énergies consommées du « berceau » aux portes de la ferme, ainsi que sa valeur énergétique. Les flux de biomasse produits en interne sont exprimés en pouvoir calorifique supérieur. La production totale en biomasse du système est considérée afin d'identifier la part de biomasse qui reste dans l'agroécosystème (racines et résidus de culture).

Nous proposons d'analyser la durabilité à travers 2 indicateurs d'efficacité d'utilisation des ressources EROI et agroécosystème EROI ($EROI_{Ag}$) et 2 indicateurs de circularité : la circularité des flux entrants ($Circ_{in}$) et la circularité de flux sortant ($Circ_{out}$).

- 1) $EROI = \frac{F_{f \rightarrow m}}{F_{m \rightarrow f}}$
- 2) $EROI_{Ag} = \frac{F_{f \rightarrow m} + F_{f \rightarrow a}}{F_{m \rightarrow f} + F_{a \rightarrow f}}$
- 3) $Circ_{in} = \frac{F_{a \rightarrow f}}{F_{m \rightarrow f} + F_{a \rightarrow f}}$
- 4) $Circ_{out} = \frac{F_{f \rightarrow a}}{F_{f \rightarrow m} + F_{f \rightarrow a}}$

Avec:

$F_{f \rightarrow m}$ (MJ) la somme des sorties de la ferme au marché,

$F_{m \rightarrow f}$ (MJ) la somme des entrées du marché à la ferme,

$F_{f \rightarrow a}$ (MJ) la somme des sorties de la ferme à l'écosystème associé,

$F_{a \rightarrow f}$ (MJ) la somme des entrées de l'écosystème associé à la ferme.

Le cas d'étude est une ferme de polyculture élevage de 49 ha produisant du lait et des céréales. Les 3 scénarios contrastés d'évolution des productions sont : i) élevage intensif, ii) culture céréalière intensive et iii) polyculture élevage extensif.

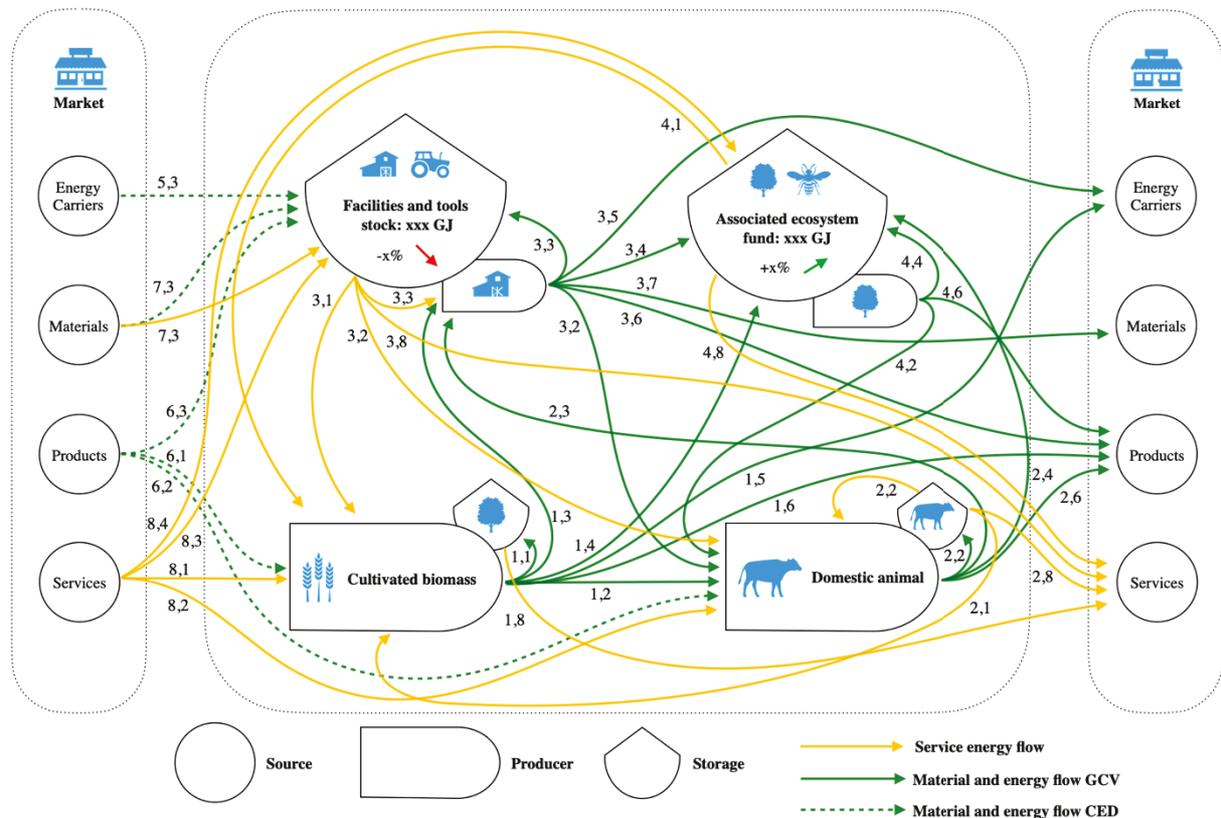


Figure 2: Diagramme générique de flux d'énergie (en vert) et de services énergétiques (en jaune). Les indices des flèches font référence au tableau d'entrée/sortie.

Table 1: Tableau générique d'entrée/sortie des flux d'énergies et des flux de service énergétique (*en italique*), différencié entre flux externe et interne au système.

		1	2	3	4	5	6	7	8	
		INTERNAL INPUT				EXTERNAL INPUT				
		Cultivated biomass	Domestic animal	Facilities & tools	Associated Ecosystem	Energy Carrier	Products	Materials & equipment	Services	
INTERNAL OUTPUT	1	Cultivated biomass	Seeds and accumulated biomass	Animal feed	Biomass for processing	Unharvested biomass	Biomass for heating	Biomass without process	-	(Farming class)
	2	Domestic animals	(Animal labour)	Animal birth (Herding)	Biomass for processing	Animal dejection	Animal dejection	Meat, milk	-	(Animal labour)
	3	Facilities & tools	(Cultural practices support)	Animal feed (Animal production support)	On-farm energy carrier (Support to farm process)	Compost, digestate	Biofuels, electricity	Biomass processed	Wood lumber & tools	(Housing, rental of tools)
	4	Associated Ecosystem	(Nutrient & water recycle)	Natural pasture	-	Unharvested, accumulated biomass	-	Foraging (medical and food plant)	-	(Ecotourism)
EXTERNAL OUTPUT	5	Energy carriers	-	-	Energy carrier (Fuel, electricity)	-	-	-	-	-
	7	Products	Purchased seeds, fertilizer, pesticide	Purchased animal feed	Paint, grass, replacement	-	-	-	-	-
	6	Materials & equipment	-	-	Purchased material (Amortization)	-	-	-	-	-
	8	Services	(Plant assessment)	(Veterinary)	(Repair)	(Ecological assessment)	-	-	-	-

> Résultat et discussion

Le cas d'étude (Figure 3) présente un $EROI$ (0.42) faible dû à l'achat d'aliment animal et dû à la perte énergétique métabolique de l'animal. À l'échelle de l'agroécosystème l' $EROI_{Ag}$ est proche de 1 (0.96) dû aux interactions de l'activité agricole avec son écosystème associé ($Circ_{out}$: 89% ; $Circ_{in}$: 75%). Concernant les scénarios, l'élevage intensif montre des indices contrastés au niveau des taux de retour énergétique ($EROI$: 0.47 ; $EROI_{Ag}$: 1.64) et de la circularité ($Circ_{out}$: 83% ; $Circ_{in}$: 41%). Ces résultats s'expliquent par l'augmentation d'achat d'alimentation animale qui entraîne une augmentation « artificielle » des flux investis (le fumier) dans l'écosystème associé, et par le changement d'usage des sols (conversion de pâturage en culture de fourrage) qui réduit le taux de minéralisation. Cela reflète les problématiques que peuvent avoir les élevages intensifs, à savoir une forte dépendance au prix d'achat d'alimentation animale et aux problèmes environnementaux liés à la gestion des effluents. À l'inverse, la culture céréalière intensive montre une circularité en sortie inférieure ($Circ_{out}$: 52%) à la circularité en entrée ($Circ_{in}$: 60%) avec un taux de retour énergétique élevé ($EROI$: 4.3 et $EROI_{Ag}$: 3.6). Les faibles taux de circularité et un $Circ_{out}$ inférieur au $Circ_{in}$ semblent être en accord avec les problématiques des grandes cultures, à savoir la forte dépendance aux intrants et l'appauvrissement des sols. Au final, le scénario extensif, se présentant comme le plus durable, présente des taux de circularité homogènes ($Circ_{out}$: 83% ; $Circ_{in}$: 86%) et des taux de retour énergétique proche de 2 ($EROI$: 2.1 et $EROI_{Ag}$: 1.8).

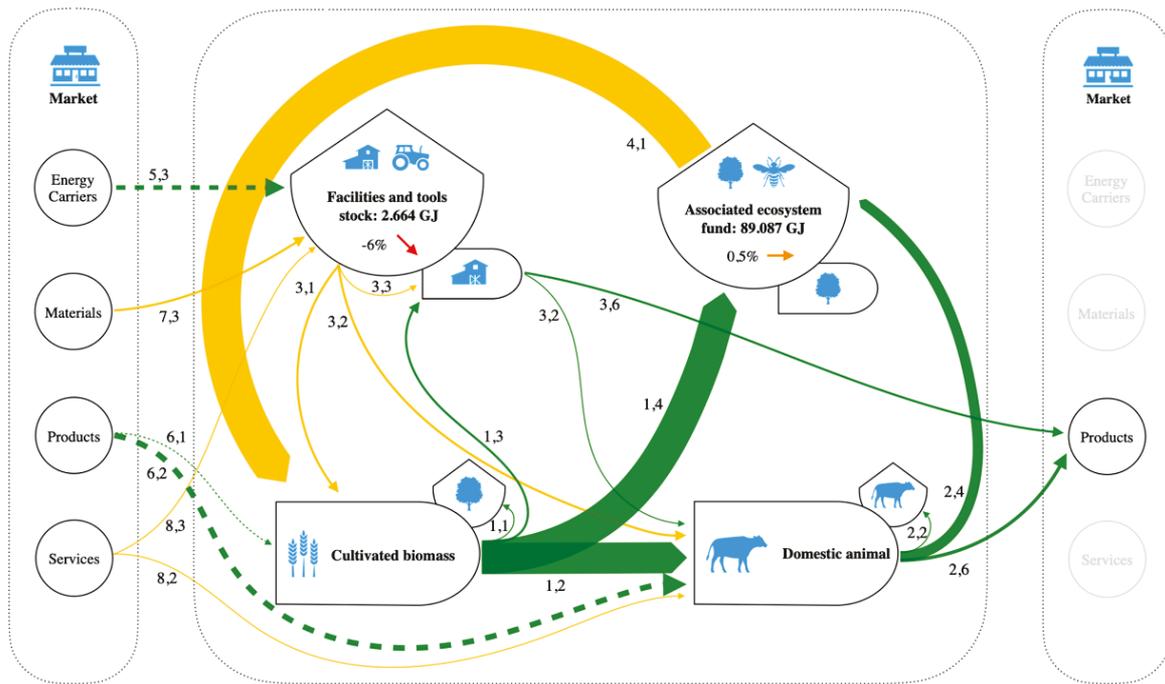


Figure 3: Diagramme des flux d'énergie du cas d'étude. L'épaisseur des flèches est proportionnelle à la valeur.

> Conclusion

La méthode permet de dresser une bonne image des flux présents dans la ferme et permet, au travers de la minéralisation, d'exprimer les services fournis par l'écosystème associé. Les indicateurs fournissent des résultats permettant d'évaluer la performance à travers l'efficacité d'utilisation des ressources et la résilience de la ferme au travers de la circularité entre l'activité agricole et son écosystème associé. Ainsi des taux de circularité élevés et homogènes seraient garants d'un agroécosystème résilient. Par ailleurs, $EROI_{Ag}$ doit être pondéré en fonction du stock énergétique présent dans la ferme.

Chapitre 4

Application de la méthode à l'échelle territoriale : comparaison de deux régions agricoles contrastées

> Contexte et objectifs

De par les spécificités locales, pédoclimatiques et sociales, les régions possèdent des productions agricoles qui leur sont propres. Cependant, les logiques industrielles d'intensification, de standardisation et d'efficacité économique de la production ont entraîné dans certains cas de nouvelles spécificités et la concentration d'un type de production sur un territoire donné. Or l'économie circulaire et la territorialisation sont de nouveaux critères pour avoir une production agricole plus durable. L'objectif de ce chapitre est de tester la méthode développée à

une autre échelle et de comparer la durabilité de deux régions contrastées, l'Eure-et-Loir spécialisé dans la grande culture et le Finistère spécialisé dans la production animale.

> Matériel et méthode

La production agricole des deux régions se base sur les données statistiques d'Agreste 2015. Les entrées énergétiques concernent le carburant des machines agricoles, l'électricité des bâtiments d'élevage, le séchage des céréales (maïs), la consommation en fertilisants et l'achat d'alimentation animale. Le capital fixe concerne les bâtiments d'élevage. Le capital naturel est égal au taux de matière organique dans le sol, 86T/ha pour l'Eure-et-Loir et 155 T/ha pour le Finistère, moyenne définie à partir de données cartographiques de Gis Sol (2010). Le taux de minéralisation a été défini en fonction des conditions pédoclimatiques et ajusté selon des coefficients de minéralisation de référence (Saffih-Hdadi and Mary, 2008) donnant 3% pour l'Eure-et-Loir et 5% pour le Finistère. La méthode développée précédemment ainsi que ses indicateurs sont appliqués aux deux régions.

> Résultat et discussion

L'Eure-et-Loir présente un taux de retour énergétique ($EROI : 5.2 ; EROI_{Ag} : 3.7$) plus élevé que le Finistère ($EROI : 0.3 ; EROI_{Ag} : 0.7$) car sa production animale est réduite. Elle n'achète quasiment pas d'alimentation animale et s'est spécialisée dans la production de céréale à haut rendement. La forte spécialisation dans l'élevage du Finistère se confirme par un indice de circularité contrasté ($Circ_{out} : 77\% ; Circ_{in} : 44\%$) comparé à la circularité de l'Eure-et-Loir ($Circ_{out} : 59\% ; Circ_{in} : 71\%$), avec une forte importation en alimentation animale induisant un $Circ_{in}$ faible. Cependant l'inversion des indices de circularité pour l'Eure-et-Loir peut indiquer un stress sur les fonctionnalités de l'écosystème associé pouvant entamer le capital naturel.

> Conclusion

La méthode, appliquée à l'échelle territoriale, reflète bien les caractéristiques des 2 régions. Le faible taux de retour énergétique et la circularité contrastée indique une faible durabilité du modèle agricole du Finistère et confirme les problématiques environnementales qu'elle connaît. L'Eure-et-Loir est très efficace dans l'usage des ressources grâce à la forte utilisation d'engrais, mais dont la production dépend d'énergie non renouvelable.

Chapitre 5

Conclusion et perspectives

> Conclusion

En conclusion, cette thèse a permis le développement d'une méthode d'analyse énergétique qui met en avant l'apport des services fournis par le capital naturel à l'activité agricole, de le quantifier et d'établir des indicateurs de suivi nous informant sur le degré de durabilité de la ferme en tant qu'agroécosystème.

Dans un premier temps, nous avons abordé les différentes approches énergétiques afin de comprendre les principes qui régissent l'agroécosystème et les outils de l'analyse énergétique agricole. Ainsi, nous avons pu développer une approche énergétique qui prend en considération les mécanismes naturels et technologiques dans la production agricole. À cet effet, une approche systémique de la ferme a été proposée qui différencie les processus de stockage énergétique, produisant des services, et les processus de production énergétique, transformant un produit en un autre. Nous avons mis en avant que la résilience de l'agroécosystème dépend de la relation circulaire entre l'activité agricole et son écosystème associé à travers la biomasse investie pour maintenir ses fonctionnalités et les services qu'elle fournit, et que nous avons mesuré à travers la minéralisation du sol. Des indicateurs d'efficacité et de circularité ont été établis pour permettre le pilotage des paramètres de l'agroécosystème. La méthode a été appliquée à la ferme et à l'échelle régionale fournissant des informations qui valident le modèle.

Ainsi, la méthode développée pourrait devenir un outil utile dans la prise en compte des bénéfices offerts par les pratiques agroécologiques et une façon pour l'agriculture conventionnelle de les intégrer.

> Perspectives

Pour aller plus loin dans la caractérisation des services énergétiques, la dissipation énergétique pourrait être mobilisée pour mesurer des services rendus par des composantes de l'agroécosystème autre que le sol, par exemple une culture servant de support à une autre plante (technique Milpa) ou les couverts végétaux pour limiter l'érosion. Par ailleurs, il serait intéressant de se placer à l'échelle de la parcelle pour prendre en compte la succession des cultures et la dynamique dans le temps pour mieux caractériser les flux énergétiques. En effet, intégrer le temps dans l'analyse énergétique serait un moyen pour mieux faire coïncider les phases de charge et de décharge en énergie. Sur cette même ligne, les technologies de l'information et de la communication (TIC) pourraient avoir un rôle à jouer, mais qui impliquerait un changement de logique pour passer de la recherche de minimisation des intrants à la maximisation des flux internes. Pour finir, la circularité abordée dans ce travail s'est située à l'échelle de l'agroécosystème, prenant en compte la relation entre l'activité agricole et son écosystème associé, mais il serait nécessaire dans un futur d'intégrer la circularité de l'activité agricole avec les autres systèmes d'un même territoire et avec le marché, le retour d'une partie des flux de biomasse exportés pouvant être un autre moyen pour renforcer la durabilité des systèmes de production agricole.

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Annexes

ANNEX A. Supplementary material for Chapter 3:

“Identifying the resource use and circularity in farm systems: focus on the energy analysis of agroecosystem”

A1. Equation used to measure energy flows

$$\text{External inputs}_i(\text{GJ}) = \frac{\text{External inputs}_i(\text{kg}) \cdot \text{CED}_i(\text{MJ} \cdot \text{kg}^{-1})}{1000}$$

$$\text{Internal inputs}_i(\text{GJ}) = \frac{\text{Internal inputs}_i(\text{kg}) \cdot \text{GCV}_i(\text{MJ} \cdot \text{kg}^{-1})}{1000}$$

$$\text{Associated ecosystem}_{\text{stock}}(\text{GJ}) = \frac{\sum \text{SOM}_i \cdot \text{GCV}_{\text{organic matter}}(\text{MJ} \cdot \text{kg}^{-1})}{1000}$$

$$\text{Facilities \& tools}_{\text{stock}}(\text{GJ}) = \sum \text{equipement}_i \cdot \text{CED}_i \cdot \left(1 - \frac{\text{time use}}{\text{lifetime}}\right)$$

$$\text{SOM}_i = \text{Soil}_{\text{density}} \cdot \text{earth}_{\text{fine}} \cdot \text{OM}_i \cdot 10000 \cdot 0,3$$

Where

$\text{Soil}_{\text{density}}$ (T/m³) corresponds to the soil density, $\text{earth}_{\text{fine}}$ id the fine-grained earth ratio and OM (%) is the rate of organic matter present in the soil according to the area i, and measured through soil samples express in g/kg. In the present case study, $\text{Soil}_{\text{density}}$ is equivalent to 1,45 T/m³ and $\text{earth}_{\text{fine}}$ to 0,95.

A2. System boundaries representation and main energetic flows

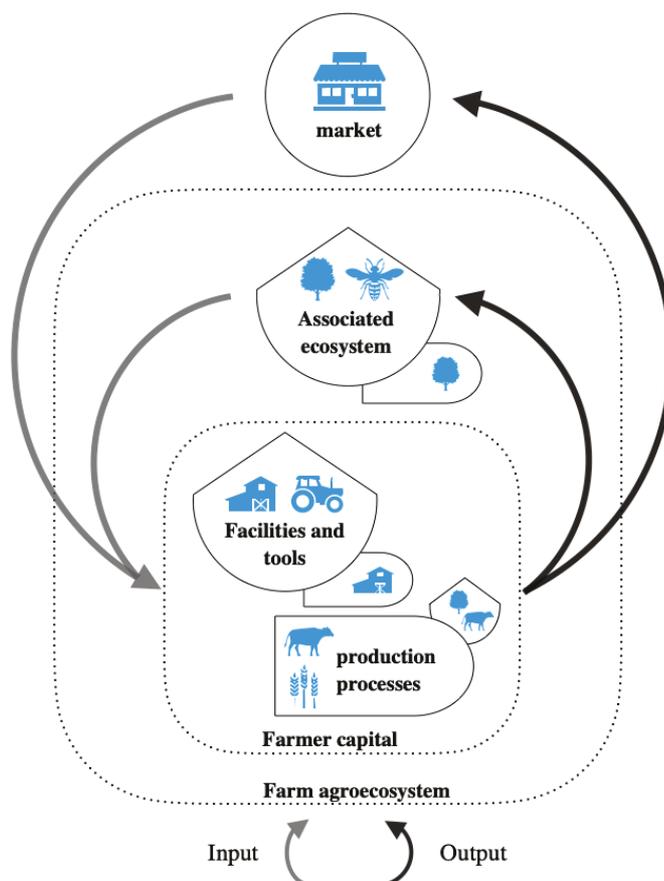


Figure S1: Farm system boundaries and general flows

A3. Case study specific data

Table S1: External inputs of the case study

Express in Cumulative Energy Demand	Qty.	CED (MJ/U)	CED (GJ)	Reference
Consumable products			486,9	
Purchased seeds (0,63ha Fodder beet) (kg)	5,04	255,08	1,3	Ecoinvent3
Purchased seeds (4ha meadow) (kg)	120	30,04	3,6	Ecoinvent3
Purchased forage (kg)	25000	19,28	482,0	Ecoinvent3
Energy carrier			416,9	
Tractor & combine consumption (L)	4640	47,9	222,4	Ecoinvent3
Vehicles consumption (L)	264	47,9	12,7	Ecoinvent3
Milkmaid (kWh))	9600	13,78	132,3	Ecoinvent3
mill (kWh)	3600	13,78	49,6	Ecoinvent3
Services (for animal production)			13,2	
Veterinary expense (\$)	1760	7,48	13,2	Bonny 1986 (Planet Method)

Table S2: Cultivated biomass outputs of the case study

<i>production (fresh matter)</i>			<i>Yield (KG) dry matter</i>			<i>Yield (MJ) dry matter</i>			<i>Grain (MJ)</i>			<i>Aerial biomass (MJ)</i>		<i>Roots (MJ)</i>	
	(kg/ha)	area	Aerial			Aerial			VP	AP	FT	AP	AE	AP	AE
			Grain	biomass	Roots	Grain	biomass	Roots	(seeds)	(feed)	(transfo)	(forage)	(residue)	(feed)	(Unharv.)
Land use		39,0				376762	3039002	2492076	20932	154409	201420	2489287	549715	97978	2394099
Old wheat	2000	4,3	7533	19754	17464	139365	365444	306837	12194	0	127171	0	365444	0	306837
Sun flower	1400	1,6	2053	4579	5637	58914	85624	99039	1052	0	57861	0	85624	0	99039
Rapeseed	1400	0,4	569	1358	752	16506	25400	13208	118	0	16388	0	25400	0	13208
Maslin	2300	1,4	2775	3510	3143	52170	64941	55216	3969	48200	0	64941	0	0	55216
Rye	2000	0,6	1040	1435	2104	18727	26264	36972	1639	17089	0	26264	0	0	36972
Maize	4000	1,2	4039	3959	1920	75122	73247	33726	563	74559	0	0	73247	0	33726
Barley	2000	0,5	872	1080	410	15958	19656	7202	1396	14561	0	19656	0	0	7202
Fodder beet	60000	0,6	0	423	6048	0	6602	97978	0	0	0	6602	0	97978	0
Temporal Pasture (DM)	6000	18,5	0	111240	88992	0	2013444	1563589	0	0	0	2013444	0	0	1563589
Permanent Pasture (DM)	2000	9,9	0	19800	15840	0	358380	278309	0	0	0	358380	0	0	278309

Table S3: Domestic animals outputs of the case study

<i>Livestock</i>		<i>Productivity (fresh matter)</i>				<i>Yield (fresh matter)</i>				<i>Yield (MJ)</i>			
Type	Qty.	Weight (kg/u)	Milk (L/u/year)	Manure (kg/u/year)	Slurry (kg/u/day)	Milk (L)	Meat (kg)	Manure (kg)	Slurry (kg)	Milk	Meat	Manure	Slurry
Total	30					99400	3750	258780	173040	299194	27813	859150	43779
Milk cows	20	550	5400	9125	6205	108000	0	182500	124100	325080	0	605900	31397
Heifers	12	400	0	5110	3285	0	0	61320	39420	0	0	203582,4	9973
Calves (livestock)	4	150	-1625	2007,5	1277,5	-6500	0	8030	5110	-19565	0	26659,6	1293
Culled cows	3	550	0	0	0	0	1650	0	0	0	14982	0	0
Calves (sold)	14	150	-150	495	315	-2100	2100	6930	4410	-6321	12831	23007,6	1116

Table S5: Facilities and Tools outputs of the case study

Production process of biomass (F&T output)	Qty. (kg)	GCV (GJ)
Vegetal output sold		145,9
Wheat Flour	6263,4	102
Sun flower oil	955,9	35
Rapeseed oil	256,872	10
Biomass reuse (to animal production)		55,4
Wheat Bran	1565,85	26
Sunflower cake	1216,6	23
Rapeseed cake	354,728	7

Table S7: FT services provided to F&T

Support to F&T	Quantity	CED (GJ)
Total electric consumption	kWh	13,0
Mill	3600	13
Total amortization	kg	1,52
Process equipment	400	2
General mobility	L	12,7
Car vehicles	264	13

Table S4: FT services provided to CB

Support to cultivated biomass	ha	L/ha	CED (GJ)
Total fuel consumption			211,7
1-Wheat after meadow	4,3	163,5	34
2-Cereals after crops	2,5	93,5	11
3-Maize	1,2	194,0	11
4-Sunflower & rapeseed	2,0	225,0	22
5-Fodder beet	0,6	116,0	4
6-Forage	39,0	70,0	131
Total amortization			49,8
Amortization engines			17
Amortization vegetal prod. Tools			32

Table S6: FT services provided to DA

Support to domestic animal	Quantity	CED (GJ)
Total electric consumption	kWh	132,3
Tank cooling	4128	57
Hot water	2592	36
Pump	1440	20
Others	1440	20
Total fuel consumption	L	10,6
Barnyard circulation (5%)	221	11
Total amortization		102
New Barn		91
Old barn		11

Table S8: FT amortization and repair

Equipment	Characteristic						Energy used in capital (GJ)			Energy used in repair		
	Qty.	Mass (kg)	Lifetime	Total time-use	Annual time-use	repair ratio	Capital cost	Stock actual	Annual amortization	Total Energy (GJ)	Total Energy already used	Annual Energy used
Total							7377	2664	135	1732	824	43
Engines		11800,0						17				
Tractors (lifetime in hour)	1	3600	12000	3000	311	0,49	411	308	11	201	151	5
Renault captura (lifetime in km)	1	1200	300000	100000	5280	0,21	115	77	2	24	16	0
Hold tractor (lifetime in hour)	1	1500	12000	12000	92	0,49	171	0	1	84	84	1
Combines	1	5500	3000	2800	16	0,24	628	42	3	151	10	1
Equipment for vegetal production		15250,0						32				
Moldboard plows	1	950	2000	1500	15	0,97	78	19	1	76	19	1
Stubble cultivator	1	1100	2000	1500	12	0,6	90	23	1	54	14	0
Medium tools (Cultivator, harrow, hoe,...)	5	900	2000	1500	67	0,51	369	92	12	188	47	6
Press roller	1	1100	2000	1500	11	0,33	90	23	0	30	7	0
Light tools (Cutter, tedder, swather, planter)	4	600	2000	1500	125	1,44	197	49	12	284	71	18
Balers	1	1200	2000	1500	46	0,39	98	25	2	38	10	1
Manure sprayer	1	4000	3000	1500	36	0,37	328	164	4	121	61	1
Process equipment		400						2				
Tank cooling (lite time in year)		200	12	4	1	0,12	14	9	1	2	1	0
Mill (lite time in year)		200	40	2	1	0,12	14	13	0	2	2	0
Facilities (m2)		936						84				
New building (lite time in year)		714	50	20	1	0,10	3640	1820	73	364	218	7
Old barnyard (lite time in year)		222	100	100	1	0,10	1132	0	11	113	113	1

* Mass and lifetime of agricultural equipment based on Bowers 1992 and Mikkola 2012

* repair ratio of agricol engine based on Fluck 1992

Table S9: Calculation of Soil Organic Matter and mineralization

SOM reported in the field	area (ha)	Soil samples from case study			SOM			Mineralization		
		Min.	Max.	Avg.	SOM (T/ha)	Stock (T)	Stock (GJ)	SOM mineral. (T/ha/an)	Mineralization (T)	Mineralization (GJ)
Total					5070,41	89087,14			192,68	3385,31
SOM 1: Permanet Pasture	9,9	2,70 %	6,30 %	4,50 %	186,0	1841,03	32347	7,07	69,96	1229
SOM 2: Temporal Pasture	18,54	1,80 %	4,00 %	2,90 %	119,8	2221,88	39038	4,55	84,43	1483
SOM 3: Crop	10,6	1,80 %	2,80 %	2,30 %	95,0	1007,50	17702	3,61	38,29	673

Where:

$$SOM_i(T/ha) = \text{Soil sample average}_i (\%) \cdot \text{Soil density} \cdot \text{fine earth ratio} \cdot 10,000 (m^2) \cdot \text{soil depth}(m)$$

For the case study:

- Soil density for Sandy clay loam: 1.45 T/m³
- Fine grained earth ratio: 0.95
- Soil depth of 30 cm

We used 17,57 MJ.kg⁻¹ as energetic value for organic matter (dry matter). It is an approximation value on the assumption that the plant biomass is composed fundamentally of carbohydrates (Guzmán et al. 2014).

Table S10: Calculation of the accumulated biomass

Associated ecosystem stock in hedge				
Typology	ml	(m3/km/an)	m3	GCV (GJ)
implented hedge	3613	5,6	20,2	221
young hedge	698	3,7	1,3	14

To considered the accumulated biomass on perennial trees of the system, we estimate the biomass present on hedge, lone trees and on the trees from the agroforestry system. The GCV is calculated using a volume weight for walnut trees (640 KG/m³) and a GCV for broad-leaves trees of 17 MJ/kg (at 88% DM) (Guzmán et al., 2014).

Table S11: Typologies of hedges and equivalent volumes

Typologie IGN 2017	Typologie Bouvier 2008	(m3/km/an)
Haies de hauts jets à 2 ou 3 strates	Haies mixtes taillis- futaie	5,6
Haies de hauts jets à 1 strate	Haies de futaies	3,7
Haies de cépées à 2 strates	Pas de regroupement possible	6,5
Haies de cépées à 1 strate	Taillis	7,4

Table S12: Inventory of trees present in the farm and there equivalent energetic value

Typology	Qty.	Trees characteristic					Total weight (kg)	GCV (GJ)
		trunk (m3)	Trunk (kg)	branch (30%)	Roots (45%)	Weight (kg)		
Agroforestry	316	0,010	6	1,9	2,9	11	3556	61
lone tree	10	1,130	723	217	326	1266	12660	216

*Young trees with trunk of 8cm diameter and 2 meters high

*Lone trees with trunk of 60 cm diameter et 2 meters high

Agroforestry trees are considered as part of the cultivated biomass stock when lone trees are integrated into the associated ecosystem stock. We use the same energetic value above (17 MJ/kg).

A4. General data

Table S13: Data used for Cultivated Biomass

Vegetal biomass	Grain (DM)		Straw		Residue:product	Root:shoot ratio	Seeds reuse
	MJ/kg	% DM	MJ/kg	% DM			
Wheat	18,5	0,878	18,5	0,91	2,53	0,64	175
Sun flower	28,7	0,928	18,7	0,9	2,3	0,85	25
Rapeseed	29,0	0,924	18,7	0,9	2,45	0,39	10
Maslin (tritic.oat, pea, ves.)	18,8	0,868	18,5	0,9	1,22	0,5	175
Rye	18,0	0,867	18,3	0,92	1,3	0,85	175
Maize	18,6	0,863	18,5	0,9	0,94	0,24	30
Barley	18,3	0,872	18,2	0,9	1,2	0,21	175
Fodder beet (root)	16,2	0,16	15,6	0,18		14,29	8
Grass (Pastured & forage)	18,1	not used				0,8	30
Organic matter (roots)	17,6	not used					

The GCV value is based on dry matter from INRA-CIRAD-AFZ feed table (<https://feedtables.com>)

The ratio and conversion factor of biomass (aerial, roots,...) is based on Guzman et al. 2014: *Methodology and conversion factors to estimate the net primary productivity of historical and contemporary agroecosystems*

Data for fodder beet (leaves) is based on feedipedia table (<https://www.feedipedia.org/node/534>)

Table S14: Data used for Domestic animals

Energetic coefficient in GCV	MJ/kg	% (DM)	Reference
Cow milk	3,01		Guzman et al.2014
Cow bright weight	9,08		Planete (poids vif)
Veal bright weight	6,11		Planete (poids vif)
Dairy Manure	16,6	20 %	Aguilera et al. 2015, 26,7% dry matter
Slurry (MJ/L)	0,253		Alonso and Guzman 2010

Animal dejection value (from Planet method)	Manure (kg/day)	Slurry (kg/day)
Cows dejection	25	17
Heifer dejection	14	9
Livestock veal	5,5	3,5
Sold veal dejection	5,5	3,5

Table S15: Data used for Infrastructure and tools output

Process product	GCV	%DM	deviation ratio	Reference
Wheat flour (dm)	19,1	0,87	0,976	https://feedtables.com/fr/content/farine-basse-de-ble-dur
Wheat Brans (dm)	19,3	0,866	0,976	https://feedtables.com/fr/content/son-de-ble-dur
Rapeseed oil (99,9%dm)	39,2		0,961	https://feedtables.com/fr/content/huile-de-colza
Sunflower oil (99,3%dm)	39		0,93	https://feedtables.com/fr/content/huile-de-tournesol
Sunflower cake (dm)	22,2	0,923	0,93	https://feedtables.com/content/sunflower-meal-oil-5-20-non-dehulled
Rapeseed cake (dm)	21,5	0,915	0,961	https://feedtables.com/content/rapeseed-meal-oil-5-20

Table S16: Cumulative Energy Demand used (Ecoinvent 3)

Product: 1 kg Fodder beet seed, for sowing {GLO}| market for | Cut-off, S (of project Ecoinvent 3 - allocation, cut-off by classification - system)

Method: Cumulative Energy Demand V1.11 / Cumulative energy demand

Impact category	Unit	Total	Fodder beet seed, for sowing {GLO} market for Cut-off, S	
Non renewable, fossil	MJ	32,515374	32,515374	13 %
Non-renewable, nuclear	MJ	1,7565606	1,7565606	1 %
Non-renewable, biomass	MJ	0,002157661	0,002157661	0 %
Renewable, biomass	MJ	219,91884	219,91884	86 %
Renewable, wind, solar, geother	MJ	0,1617891	0,1617891	0 %
Renewable, water	MJ	0,72727472	0,72727472	0 %
		255,08	255,08	

Product: 1 kg Grass seed, organic, for sowing {GLO}| market for | Cut-off, S (of project Ecoinvent 3 - allocation, cut-off by classification - system)

Method: Cumulative Energy Demand V1.11 / Cumulative energy demand

Impact category	Unit	Total	Grass seed, organic, for sowing {GLO} market for Cut-off, S	
Non renewable, fossil	MJ	12,19	12,19401	41 %
Non-renewable, nuclear	MJ	0,85	0,85448902	3 %
Non-renewable, biomass	MJ	0,00	0,000791482	0 %
Renewable, biomass	MJ	16,52	16,520941	55 %
Renewable, wind, solar, geother	MJ	0,09	0,092042738	0 %
Renewable, water	MJ	0,38	0,37944487	1 %
		30,04171911		

Product: 1 kg Grass, organic {GLO}| market for | Cut-off, S (of project Ecoinvent 3 - allocation, cut-off by classification - system)

Method: Cumulative Energy Demand V1.11 / Cumulative energy demand

Impact category	Unit	Total	Grass, organic {GLO} market for Cut-off, S	
Non renewable, fossil	MJ	1,15	1,1478955	6 %
Non-renewable, nuclear	MJ	0,03	0,031403215	0 %
Non-renewable, biomass	MJ	0,00	0,000165755	0 %
Renewable, biomass	MJ	18,08	18,081589	94 %
Renewable, wind, solar, geother	MJ	0,00	0,002767117	0 %
Renewable, water	MJ	0,02	0,015995938	0 %
		19,28		

Product: 1 kg Diesel {RER}| market group for | APOS, S (of project Ecoinvent 3 - allocation at point of substitution - system)

Method:		Cumulative Energy Demand V1.11 / Cumulative energy demand			
Impact category	Unit	Total	Diesel (RER) market group for APOS, S		
Non renewable, fossil	MJ	56,485443	56,485443	99 %	
Non-renewable, nuclear	MJ	0,38483221	0,38483221	1 %	
Non-renewable, biomass	MJ	0,000180487	0,000180487	0 %	
Renewable, biomass	MJ	0,049428191	0,049428191	0 %	
Renewable, wind, solar, geother	MJ	0,030237781	0,030237781	0 %	
Renewable, water	MJ	0,10597421	0,10597421	0 %	0,84 density
		57,05609588			47,9 MJ/L

1 MJ Electricity, low voltage (FR) market for Cut-off, S (of project Ecoinvent 3 - allocation, cut-off by classification - system)

Product:		- system)			
Method:		Cumulative Energy Demand V1.11 / Cumulative energy demand			
Impact category	Unit	Total	Electricity, low voltage (FR) market for Cut-off, S		
Non renewable, fossil	MJ	0,18495627	0,18495627	5 %	
Non-renewable, nuclear	MJ	3,4355794	3,4355794	90 %	
Non-renewable, biomass	MJ	2,21E-006	2,21E-006	0 %	
Renewable, biomass	MJ	0,010507906	0,010507906	0 %	
Renewable, wind, solar, geother	MJ	0,047593652	0,047593652	1 %	
Renewable, water	MJ	0,14857307	0,14857307	4 %	
		3,83			13,78 MJ/kWh (CED)

1 m2 Shed (CH) construction Cut-off, S (of project Ecoinvent 3 - allocation, cut-off by classification - system)

Product:		- system)			
Method:		Cumulative Energy Demand V1.11 / Cumulative energy demand			
Impact category	Unit	Total	Shed (CH) construction Cut-off, S		
Non renewable, fossil	MJ	1403,5362	1403,5362	28 %	
Non-renewable, nuclear	MJ	176,88002	176,88002	3 %	
Non-renewable, biomass	MJ	0,29483828	0,29483828	0 %	
Renewable, biomass	MJ	3428,1108	3428,1108	67 %	
Renewable, wind, solar, geother	MJ	9,0868683	9,0868683	0 %	
Renewable, water	MJ	80,4356	80,4356	2 %	
		5098,3			

1 kg Tractor, 4-wheel, agricultural (CH) production Cut-off, S (of project Ecoinvent 3 - allocation, cut-off by classification - system)

Product:		- system)			
Method:		Cumulative Energy Demand V1.11 / Cumulative energy demand			
Impact category	Unit	Total	Tractor, 4-wheel, agricultural (CH) production Cut-off, S		
Non renewable, fossil	MJ	83,983432	83,983432	74 %	
Non-renewable, nuclear	MJ	18,072029	18,072029	16 %	
Non-renewable, biomass	MJ	0,034982689	0,034982689	0 %	
Renewable, biomass	MJ	4,0900626	4,0900626	4 %	
Renewable, wind, solar, geother	MJ	0,60776216	0,60776216	1 %	
Renewable, water	MJ	7,4006343	7,4006343	6 %	
		114,2			

1 kg Passenger car, diesel (GLO) market for Cut-off, S (of project Ecoinvent 3 - allocation, cut-off by classification - system)

Product:		- system)			
Method:		Cumulative Energy Demand V1.11 / Cumulative energy demand			
Impact category	Unit	Total	Passenger car, diesel (GLO) market for Cut-off, S		
Non renewable, fossil	MJ	80,440101	80,440101	84 %	
Non-renewable, nuclear	MJ	8,0924385	8,0924385	8 %	
Non-renewable, biomass	MJ	0,004477028	0,004477028	0 %	

Renewable, biomass	MJ	2,108304	2,108304	2 %
Renewable, wind, solar, geother	MJ	0,6384883	0,6384883	1 %
Renewable, water	MJ	4,5572057	4,5572057	5 %
		95,8		

1 kg Agricultural trailer {GLO} market for 1 Cut-off, S (of project Ecoinvent 3 - allocation, cut-off by classification - system)

Product:

Method:

Cumulative Energy Demand V1.11 / Cumulative energy demand

Agricultural trailer {GLO} market for 1 Cut-off,

Impact category	Unit	Total	S	
Non renewable, fossil	MJ	70,571079	70,571079	86 %
Non-renewable, nuclear	MJ	4,9402229	4,9402229	6 %
Non-renewable, biomass	MJ	0,034031641	0,034031641	0 %
Renewable, biomass	MJ	1,15012	1,15012	1 %
Renewable, wind, solar, geother	MJ	0,38956543	0,38956543	0 %
Renewable, water	MJ	4,9660964	4,9660964	6 %
		82,1		

1 kg Nitrogen fertiliser, as N {GLO} market for 1 Cut-off, S (of project Ecoinvent 3 - allocation, cut-off by classification - system)

Product:

Method:

Cumulative Energy Demand V1.11 / Cumulative energy demand

Impact category	Unit	Total	Nitrogen fertiliser, as N {GLO} market for 1 Cut-off, S	
Non renewable, fossil	MJ	63,322178	63,322178	92 %
Non-renewable, nuclear	MJ	3,0551252	3,0551252	4 %
Non-renewable, biomass	MJ	0,001831695	0,001831695	0 %
Renewable, biomass	MJ	1,3698629	1,3698629	2 %
Renewable, wind, solar, geother	MJ	0,25245568	0,25245568	0 %
Renewable, water	MJ	1,1529571	1,1529571	2 %
		69,2		

A5. Summary description of the scenarios

Table S17: Comparative description of scenarios with the case study

	Case study	Scenario 1	Scenario 2	Scenario 3
Farm land				
Permanente pasture	9,9 ha	0,0 ha	0,0 ha	0,0 ha
Temporal pasture	18,5 ha	9,0 ha	0,0 ha	22,5 ha
Crop production	10,6 ha	30,0 ha	39,0 ha	16,5 ha
Vegetal production				
Wheat	2000 kg/ha	5000 kg/ha	5000 kg/ha	2000 kg/ha
Corn silage	0 kg/ha	45000 kg/ha	0 kg/ha	0 kg/ha
Temporal pasture (DM)	6000 kg/ha	10000 kg/ha	0 kg/ha	6000 kg/ha
Livestock				
milk production	5400 L/u	6500 L/u	0 L/u	4212 L/u
milk cows	30 UGB	90 UGB	0 UGB	10 UGB
Facilities and tools				
facilities	714 m2	1714 m2	714 m2	714 m2
Engines (kg of metal)	11800 kg	11800 kg	11800 kg	11800 kg
Engine tools (kg of metal)	15250 kg	15250 kg	15250 kg	15250 kg
Soil Organic Matter				
SOM permanent pasture	1841 T	0 T	0 T	0 T
SOM temporal pasture	2222 T	1079 T	0 T	2696 T
SOM crop field	1008 T	2851 T	3707 T	1568 T
External inputs				
Fuel engines consumption	4640 L	9272 L	7028 L	2784 L
Electric milking consumption	9600 Kwh	29000 Kwh	0 Kwh	1920 Kwh
Electric mill consumption	3600 Kwh	3600 Kwh	53734 Kwh	6576 Kwh
Purchased animal feed	25000 kg	123000 kg	0 kg	0 kg
veterinary expenses	1760 €	5280 €	0 €	366 €
Fertilizer (kg of N)	0 kg	0 kg	4508 kg	0 kg

A6. Energy diagram flow and related input output table of the different scenarios

Figure S2: Energy flow diagram: scenario1 (intensive breeding)

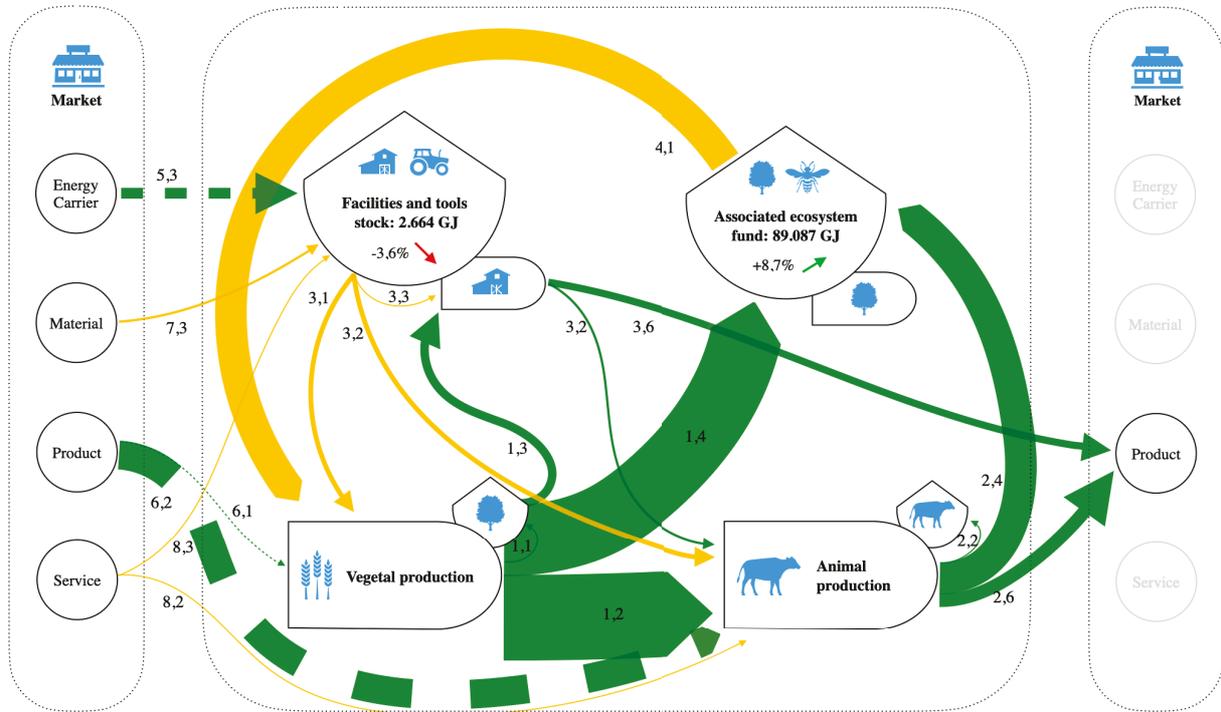


Table S18: Input Output table: scenario1 (intensive breeding)

		1	2	3	4	5	6	7	8	
		INTERNAL INPUT				EXTERNAL OUTPUT				
		Cultivated biomass	Domestic animal	Facilities & tools	Associated Ecosystem	Energy Carrier	Products	Materials & equipment	Services	Flows provided
INTERNAL OUTPUT	1 Cultivated biomass	28,4	7128,0	783,7	5953,6	0,0	0,0	-	(0,0)	13894 (0)
	2 Domestic animals	0,0	90,6 (0,0)	0,0	2670,3	-	1138,5	-	(0,0)	3899 (0)
	3 Facilities & tools	(423,0)	157,4 (420,7)	0,0 (62,3)	0,0	0,0	626,0	0,0	(0,0)	783 (906)
	4 Associated Ecosystem	(2623,9)	0,0 (0,0)	-	0,0 (0,0)	-	0,0	-	(0,0)	0 (2624)
EXTERNAL INPUT	5 Energy carriers	-	-	906,2	-	-	-	-	-	906
	6 Products	50,7	2371,4	0,0	-	-	-	-	-	2422
	7 Materials & equipment	-	-	0,0 (277,5)	-	-	-	-	-	0 (278)
	8 Services	(0,0)	(39,5)	(73,9)	(0,0)	-	-	-	-	(113)
Flows received		79 (3046,9)	9747 (460,2)	1690 (413,7)	8624 (0,0)	0 (0)	1765 (0)	0 (0)	- (0)	

Figure S3: Energy flow diagram: scenario2 (intensive vegetal production)

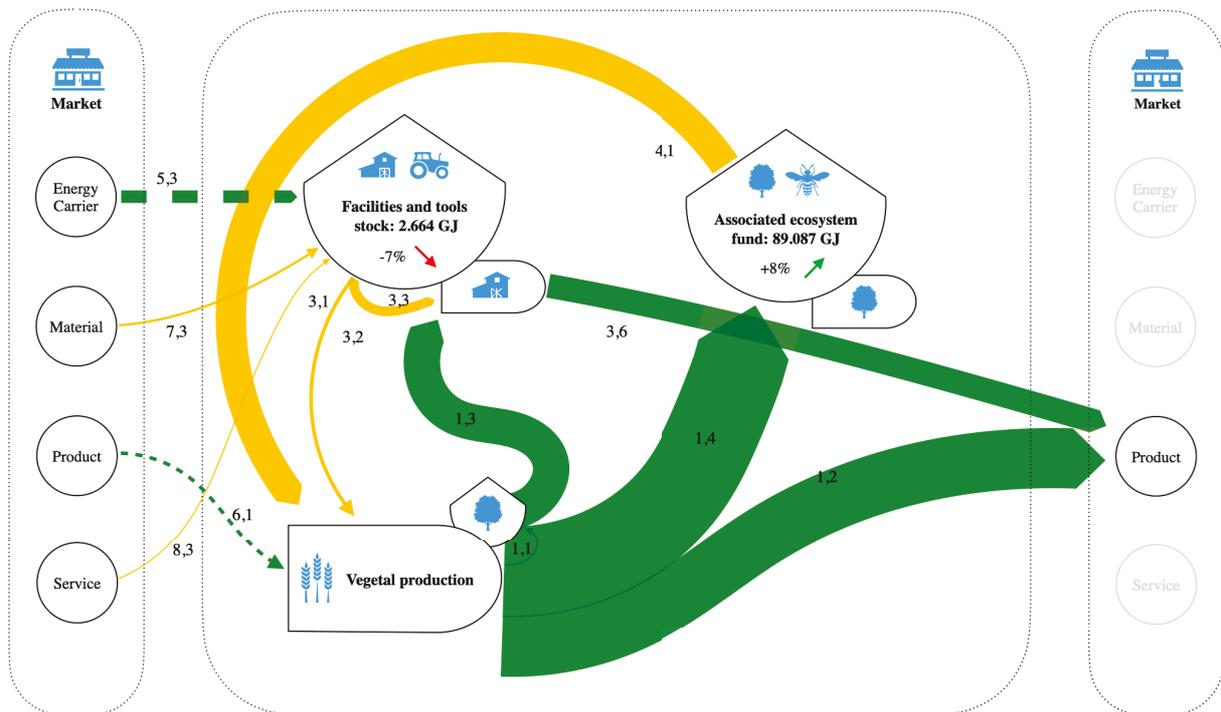


Table S19: Input Output table: scenario2 (intensive vegetal production)

		1	2	3	4	5	6	7	8	
		INTERNAL INPUT				EXTERNAL OUTPUT				
		Cultivated biomass	Domestic animal	Facilities & tools	Associated Ecosystem	Energy Carrier	Products	Materials & equipment	Services	Flows provided
INTERNAL OUTPUT	1 Cultivated biomass	77,6 (0,0)	0,0	3006,1	7637,0	0,0	5027,4	-	(0,0)	15748 (0)
	2 Domestic animals	0,0	0,0 (0,0)	0,0	0,0	-	0,0	-	(0,0)	0 (0)
	3 Facilities & tools	(324,0)	0,0	0,0	0,0	0,0	2066,8	0,0	(0,0)	2067 (1077)
	4 Associated Ecosystem	(2474,9)	0,0 (0,0)	-	0,0 (0,0)	-	0,0	-	(0,0)	0 (2475)
EXTERNAL INPUT	5 Energy carriers	-	-	1077,0	-	-	-	-	-	1077
	6 Products	315,4	0,0	0,0	-	-	-	-	-	315
	7 Materials & equipment	-	-	0,0 (197,3)	-	-	-	-	-	0 (197)
	8 Services	(0,0)	(0,0)	(61,4)	(0,0)	-	-	-	-	(61)
Flows received		393 2798,9	0 0,0	4083 1011,7	7637 0,0	0 0	7094 0	0 0	- 0	

Figure S4: Energy flow diagram: scenario3 (extensive mixed-farming system)

ANNEX B. Supplementary material for Chapter 4:

“Agroecosystem energy assessment of two contrasting territories”

B1. Share of production consumed, exported and imported by regions

Table S21: Eure-et-Loir production and related use in Tones

	Production	regional auto-consumption				External	
		Cow milk	Cow meat	Pig	Poultry		
Export	Triticale	1501749	1626	3378	0	7488,5	1489256
	Wheat durum	204041	0	1	2	3	204035
	Barley	518316	1409	2858	0	7488,5	506560
	Maize (grain)	222130	759	1559	0	748,85	219064
	Rapessed	344840	0	0	0	0	344840
	Sun flower	372	0	0	0	0	372
	Protein peas	34040	650	520	0	748,85	32121
	Forage maize	117500	73912	43588	0	0	0
	Meadows	494776	111186	383590	0	0	0
	Sugar beet	902060	0	0	0	0	902060
	Potatoes	352495	0	0	0	0	352495
	Import	Triticale		0	0	0	0
Barley			0	0	0	0	0
Maize (grain)			0	0	0	0	0
Protein peas			0	0	0	0	0
Forage maize			9352	5515	0	0	14867
Meadows			92745	319970	0	0	412715
Soy bean meal			7047	6235	0	8237,35	21520

Table S22: Finistère production and related use in Tones

	Production	regional auto-consumption				External	
		Cow milk	Cow meat	Pig	Poultry		
Export	Triticale	410901	15934	10363	330667	53938	0
	Wheat durum	0	0	0	0	0	0

	Barley	203525	15496	9840	117656	60528	0
	Maize (grain)	386858	14162	9110	353302	10273	0
	Rapessed	20937	0	0	0	0	20940
	Sun flower	12	0	0	0	0	12
	Protein peas	3573	606	152	2302	513	0
	Forage maize	3439582	1812898	334807	0	0	1291877
	Meadows	8906519	3343210	3611975	0	0	0
	Sugar beet	6524	0	0	0	0	6524
	Potatoes	194507	0	0	0	0	194510
Import	Triticale		19475	12666	404152	65925	502218
	Barley		15191	9646	115335	59334	199506
	Maize (grain)		2362	1519	58914	1713	64508
	Protein peas		13557	3391	51465	11473	79887
	Forage maize		0	0	0	0	0
	Meadows		1096973	1185160	0	0	2282134
	Soy bean meal		153435	42515	519750	131849	847549

B2. Energetic value of inputs and outputs

Table S23: Energy equivalent of inputs and outputs used in the study

Products	Unit	Equivalent Energy (MJ)	Reference
<i>Consumable products</i>			
Nitrogen fertilizer	kg	69,2	Ecoinvent 3 CED cut-off
Phosphate fertilizer	kg	34,9	Ecoinvent 3 CED cut-off
Potassium fertilizer	kg	4,0	Ecoinvent 3 CED cut-off
Triticale (wheat grain equivalent)	kg	22,7	Ecoinvent 3 CED cut-off
Barley	kg	21,5	Ecoinvent 3 CED cut-off
Maize grain	kg	22,0	Ecoinvent 3 CED cut-off
Protein peas	kg	20,5	Ecoinvent 3 CED cut-off
Forage maize	kg	6,4	Ecoinvent 3 CED cut-off
Soy bean meal	kg	39,0	Ecoinvent 3 CED cut-off
<i>Energy carrier</i>			
Diesel	L	47,9	Ecoinvent 3 CED cut-off
Electricity (French mix)	kWh	13,8	Ecoinvent 3 CED cut-off
Propane	kg	52,0	Ecoinvent 3 CED cut-off
<i>Material</i>			
Shed construction (year)	m2	5098,3	Ecoinvent 3 CED cut-off
<i>Vegetal Output dry matter</i>			
Triticale	kg	18,1	INRA-CIRAD-AFZ feed table
Wheat durum	kg	18,5	INRA-CIRAD-AFZ feed table
Barley	kg	18,3	INRA-CIRAD-AFZ feed table
Maize (grain)	kg	18,6	INRA-CIRAD-AFZ feed table
Rapeseed	kg	29,0	INRA-CIRAD-AFZ feed table

Sun flower	kg	28,7	INRA-CIRAD-AFZ feed table
Protein peas	kg	18,3	INRA-CIRAD-AFZ feed table
Sugar beet	kg	16,9	INRA-CIRAD-AFZ feed table
Potatoes	kg	16,8	INRA-CIRAD-AFZ feed table
Organic matter (roots)	kg	17,6	INRA-CIRAD-AFZ feed table
<i>Animal Output fresh matter</i>			
Cow milk	kg	3,0	Planet method
Cow bright weight	kg	9,1	Planet method
Pig bright weight	kg	13,6	Planet method
Poultry bright weight	kg	6,5	Planet method
Eggs	kg	6,2	Planet method
Dairy manure (DM 20%)	kg	16,6	Aguilera et al. 2015
Beef cattle manure (DM 20%)	kg	16,1	Aguilera et al. 2015
Pig Manure (DM 9%)	kg	19,4	Aguilera et al. 2015
Broiler Manure (DM 81,5%)	kg	17,9	Aguilera et al. 2015

B3. Fuel consumption

Table S24: Fuel consumption in Eure-et-Loir

	ha	Fertilizing		Spraying		Ploughing		Total operation	Total	
		N. pass	L/ha	N. pass	L/ha	% of land	L/ha	L/ha	MJ/ha	GJ
Total										1119265
Triticale	174835	2	5,0	3	3,0	61	12,4	54,3	2600	454598
Wheat durm	27355	3	7,5	5	5,0	53	10,7	57,1	2736	74842
Barley	62350	2	5,0	5	5,0	66	13,5	57,4	2748	171367
Maize (grain)	21095	2	5,0	4	4,0	79	16,0	58,9	2823	59553
Rapessed	86210	2	5,0	6	6,0	50	10,2	55,1	2641	227662
Sun flower	155	1	2,5	3	3,0	78	15,8	55,2	2644	410
Protein peas	9240	0	0,0	5	5,0	67	13,7	52,6	2518	23264
Forage maize	5000	2	5,0	2	2,0	69	13,9	54,8	2626	13131
Pasture	25500	0	0,0	0	0,0	0	0,0	33,9	1624	41407
Sugar beet	9805	1	2,5	9	9,0	88	17,8	63,2	3026	29674
Potatoes	7351	1	2,5	10	10,0	98	19,9	66,3	3177	23357

Table S25: Fuel consumption in Finistère

	Fertilizing		Spraying		Ploughing		Cultural pract	Total		
	Ha	N of pass*	L/ha	N of pass	L/ha	% of land	L/ha	L/ha	MJ/ha	GJ
Total										954623
Triticale	56385	2	5,0	3	3,0	79	15,9	57,8	2770	156205
Wheat durum	0	3	7,5	5	5,0	0	0,0	46,4	2223	0
Barley	27470	2	5,0	5	5,0	77	15,5	59,4	2848	78225
Maize (grain)	45502	2	5,0	4	4,0	74	15,1	58,0	2776	126332
Rapessed	6360	2	5,0	6	6,0	55	11,2	56,1	2688	17098
Sun flower	5	1	2,5	3	3,0	78	15,8	55,2	2646	13
Protein peas	940	0	0,0	5	5,0	84	17,1	56,0	2681	2520
Forage maize	60770	2	5,0	2	2,0	78	15,9	56,8	2719	165205
Pasture	157359	0	0,0	0	0,0	88	17,9	51,8	2479	390171
Sugar beet	87	1	2,5	9	9,0	91	18,4	63,8	3057	266
Potatoes	5850	1	2,5	10	10,0	98	19,9	66,3	3177	18588

Table S26: Fuel consumption per field operation from Aguilera et al. 2015

Field operation	L/ha
Cultivating	10,8
Ploughing	20,3
Rolling	1,3
Seeding	4,1
Fertilizing	2,5
Spraying	1
Harvest	17,7
Total	57,7

B4. Net Primary production

The allocation of biomass produce (consumed by the local DA or exported) is based on the table 1 and 2.

Table S27: Calculation of the NPP of Eure-et-Loir and its related use

<i>Eure et Loire Production (fresh matter)</i>		<i>Production (T) dry matter</i>			<i>Yeld (GJ) dry matter</i>			<i>Grain (GJ)</i>		<i>Aerial vegetative biomass (GJ)</i>			<i>Roots (GJ)</i>	
<i>Production</i>	<i>(T)</i>	<i>Grain</i>	<i>Aerial biomass</i>	<i>Roots</i>	<i>Grain</i>	<i>Aerial biomass</i>	<i>Roots</i>	<i>DA</i>	<i>Market</i>	<i>DA</i>	<i>Market</i>	<i>AE</i>	<i>Market</i>	<i>AE</i>
Total					24944341	37993349	46805842	267538	24676802	2445133	14628442	20919774	4262743	42543100
Triticale	1501749	1303518	1667241	564444	23593670	30843962	9934218	196263	23397407	0	30587387	256574	0	9934218
Wheat durum	204041	179148	252521	86334	3314237	4671640	1519475	97	3314140	0	4671502	137	0	1519475
Barley	518316	451971	559781	212468	8271072	10188010	3739435	187594	8083478	0	9956939	231072	0	3739435
Maize (grain)	222130	191698	187922	91109	3565592	3476562	1603518	49225	3516367	0	0	3476562	0	1603518
Rapessed	344840	318632	760372	420812	9240333	14218960	7406286	0	9240333	0	0	14218960	0	7406286
Sun flower	372	345	770	948	9908	14400	16684	0	9908	0	0	14400	0	16684
Protein peas	34040	29683	47457	46284	543199	858979	814603	30622	512577	0	0	858979	0	814603
Forage maiez	117500	0	25263	3789	0	474935	66693	0	0	474935	0	0	0	66693
Meadows	494776	0	108851	1555478	0	1970199	27376405	0	0	1970198	1	0	0	27376405
Sugar beet	902060	0	98550	169587	0	1645786	2984736	0	0	0	0	1645786	2984736	0
Potatoes	352495	0	28376	72614	0	473877	1278006	0	0	0	0	473877	1278006	0

Table S28: Calculation of the NPP of Finistère and its related use

<i>Finistère production (fresh matter)</i>		<i>Production (T) dry matter</i>			<i>Yield (GJ) dry matter</i>			<i>Grain (GJ)</i>		<i>Aerial vegetative biomass (GJ)</i>			<i>Roots (GJ)</i>	
<i>Production</i>	<i>(T)</i>	<i>Grain</i>	<i>Aerial biomass</i>	<i>Roots</i>	<i>Grain</i>	<i>Aerial biomass</i>	<i>Roots</i>	<i>DA</i>	<i>Market</i>	<i>DA</i>	<i>Market</i>	<i>AE</i>	<i>Market</i>	<i>AE</i>
Total					10018879	60651062	35064634	9457542	561415	44146785	5221766	11282634	726790	34337844
Triticale	410901	356662	456182	154440	6455583	8439372	2718152	6455583	0	0	0	8439372	0	2718152
Wheat durum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Barley	203525	177474	219807	83429	3247774	4000492	1468351	3247774	0	0	0	4000492	0	1468351
Maize (grain)	386858	333858	327282	158674	6209767	6054715	2792657	6209767	0	0	0	6054715	0	2792657
Rapessed	20937	19346	46166	25550	561031	863311	449676	0	561108	0	0	863429	0	449676
Sun flower	12	11	24	29	306	445	516	0	306	0	0	445	0	516
Protein peas	3573	3116	4981	4858	0	90161	85503	0	0	0	0	90161	0	85503
Forage maiez	3439582	0	739510	110927	0	13902790	1952307	0	0	8681025	5221766		0	1952307
Meadows	8906519	0	1959434	1567547	0	35465760	27588834	0	0	35465760	0		0	27588834
Sugar beet	6524	0	713	1227	0	11903	21587	0	0	0	0	11903	21587	0
Potatoes	194507	0	15658	40068	0	261485	705203	0	0	0	0	261489	705203	0

B5. Generic Input/Output table

		1	2	3	4	5	6	7	8
		INTERNAL INPUT				EXTERNAL INPUT			
		Cultivated biomass	Domestic animal	Facilities & tools	Associated Ecosystem	Energy Carrier	Products	Materials & equipment	Services
INTERNAL OUTPUT	1	Cultivated biomass	Seeds and accumulated biomass	Animal feed	Biomass for processing	Unharvested biomass	Biomass for heating	Biomass without process	- - (Farming class)
	2	Domestic animals	(Animal labour)	Animal birth (Herding)	Biomass for processing	Animal dejection	Animal dejection	Meat, milk	- (Animal labour)
	3	Facilities & tools	(Cultural practices support)	Animal feed (Animal production support)	On-farm energy carrier (Support to farm process)	Compost, digestate	Biofuels, electricity	Biomass processed	Wood lumber & tools (Housing, rental of tools)
	4	Associated Ecosystem	(Nutrient & water recycle)	Natural pasture	-	Unharvested, accumulated biomass	-	Foraging (medical and food plant)	- (Ecotourism)
EXTERNAL OUTPUT	5	Energy carriers	-	-	Energy carrier (Fuel, electricity)	-	-	-	-
	7	Products	Purchased seeds, fertilizer, pesticide	Purchased animal feed	Paint, grass, replacement	-	-	-	-
	6	Materials & equipment	-	-	Purchased material (Amortization)	-	-	-	-
	8	Services	(Plant assessment)	(Veterinary)	(Repair)	(Ecological assessment)	-	-	-