Identifying the resource use and circularity in farm systems: Focus on the energy analysis of agroecosystems

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Identifying the resource use and circularity in farm systems: focus on the energy analysis of agroecosystems

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Highlights:

- A farm was analyzed using a new systemic energy assessment that includes both socio-economic and agroecosystemic flows.
- With energy flows associated to mineralization, natural mechanisms are taken into account in the energetic assessment.
- Circularity is a promising indicator for assessing the resilience of resources in an agricultural production system.

Keywords:

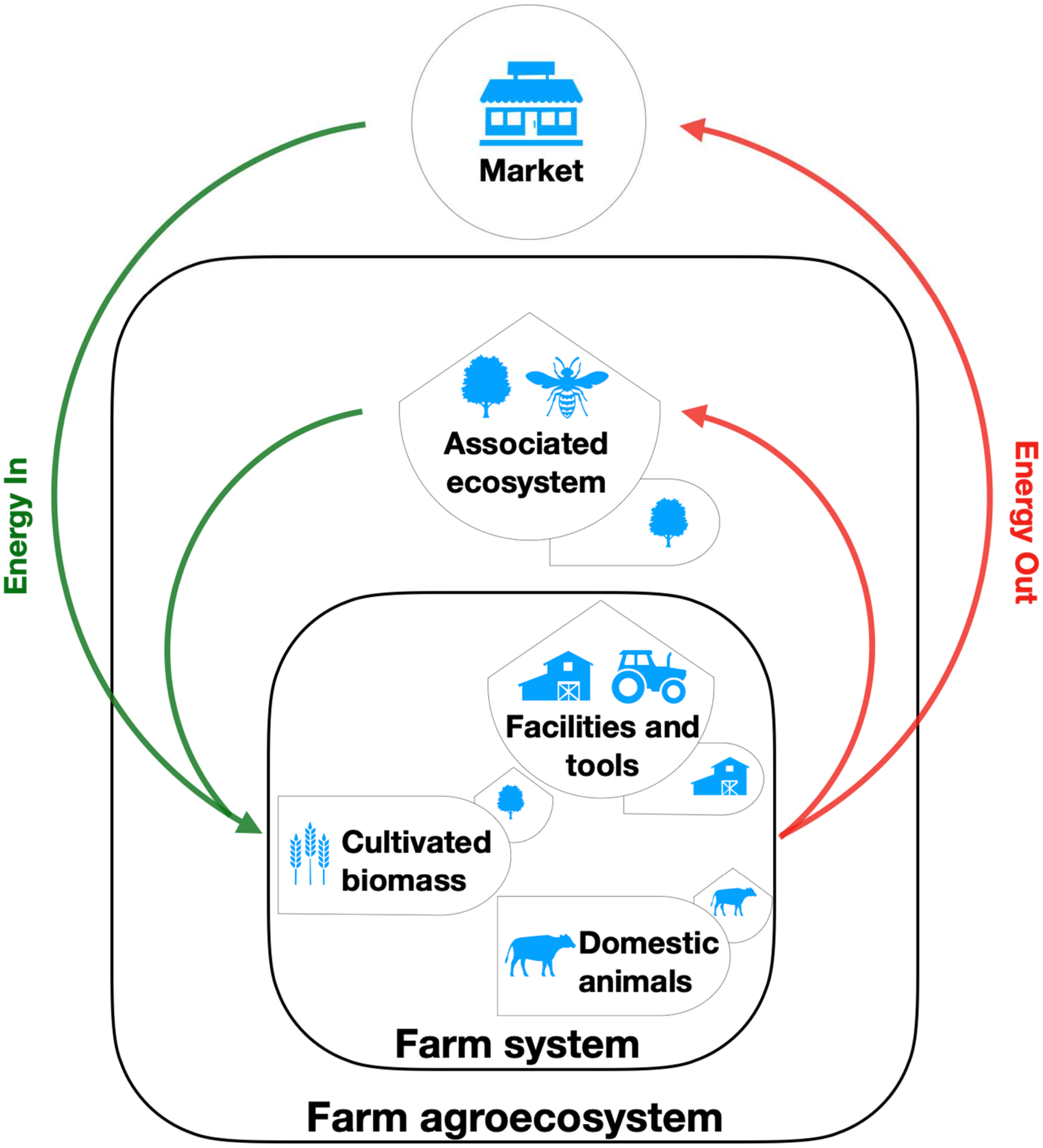
Agricultural production system, energy stocks, energy flows, associated ecosystem, circularity, soil mineralization.

Abstract:

An innovative method is described, assessing the energy flows in farm systems. These systems represent both a socio-economic activity and an agroecosystem. Both market and ecosystem flows are inventoried, focusing on farm agroecosystem circularity of the reinvested biomass. An original system representation is proposed, where process and energy storage sub-systems are distinguished. Biotic energy storage, identified as an Associated Ecosystem (AE) is included. Soil mineralization, reflecting soil activity, was selected as a proxy for services provided by the AE. The present approach was tested on an existing French mixed farm case study. Contrasting scenarios were proposed to test the model and the two sets of selected indicators. EROIs (Energy Return On Energy Invest) evaluate the current system performance through resource use efficiency. Circularities reflect the system resilience. $Circ_{in}$ (Inflow Circularity)indicates the system self-sufficiency and the extent to which the farm activity is based on the AE. Temporal stability is assessed by the steadiness of the $Circ_{in}$ versus $Circ_{out}$ (Outflow Circularity) relationship. The Crop production scenario presents best performance. Specialized and intensive systems present lower $Circ_{in}$ values. Furthermore, contrasting Circularities were observed for the intensive breeding scenario, while homogenous results were obtained for the extensive mixed-farming scenario. This method takes a new step towards the integration of circularity and ecosystem support functions in the energy analysis of farm systems.

Firstly, it provides indicators of performance and resilience. Secondly, as a key feature for sustainable agriculture, it highlights the relationship between agricultural activity and its associated ecosystem.

Graphical abstract:



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 an agricultural production system, which will henceforth be referred to as a farm agroecosystem, involves both dimensions, i.e. natural resources (i.e. sun, water, organic matter) and socio-economic inputs.

Different tools and methods such as Ecological Network Analysis (ENA) or Life Cycle Assessment (LCA) can be used for assessing the performance of agricultural systems (Huysveld et al., 2015; Stark et al., 2019). However, for two main reasons, energy analysis is particularly relevant when the efficiency of resource exploitation and sustainability of the farm agroecosystem are to be assessed (Hercher-Pasteur et al., 2020). On one hand, for a given ecosystem, energy represents a thermodynamic state variable (Jørgensen, 2015) characterizing 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 bases its framework on the assessment of direct (e.g. fuels) and indirect (i.e. the embodied energy of the production and transport of an input) energy requirements, with particular focus on the socio-economic inputs and outputs (Dalgaard et al., 2001; Fathollahi et al., 2018; Pimentel, 1976). 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 (Stolarski et al., 2018), and is used as a proxy for environmental performance (Green House Gas, GHG, emissions) (Arrieta et al., 2018; Gomiero et al., 2011). 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. emergy) by considering natural renewable and non-renewable resources (Martin et al., 2006). Recent studies have presented a circular perspective on energy assessment, based on the internal biomass reinvested in the agroecosystem (i.e. the unharvested biomass), and involved in the maintenance of its functionalities (Guzmán et al., 2015; Harchaoui and Chatzimpiros, 2019; Parcerisas and Dupras, 2018). With its role in biotic energy storage, soil organic matter has also become a significant component in the energetic balance (Fan et al., 2018; Jordan, 2016).

According to these new features, and to an extensive review of the different energetic assessments applied to agricultural production systems (Hercher-Pasteur et al., 2020), the research question to address is: "How can energy analysis be used for assessing and establishing an efficient and sustainable agricultural production system?" The objectives of the present work are to combine external input-output flows, internal flows, circularity and internal energy stocks and to assess the services provided by the agroecosystem. A generic and operational method is proposed for evaluating the energy profile and sustainability of a farm agroecosystem. Through energy, the following framework contributes towards an exhaustive evaluation of the resources mobilized by the agricultural production system, both from the ecosystem (internal flows) and from the market (external flows). Sustainability is assessed via two temporal dimensions (Therond et al., 2017): the first is related to short term and current performance, the second is based on long term and resilience (i.e., stability over time and the capacity to resist to external shocks). Current performance was measured by focusing on resource use efficiency through a set of *EROIs,* and integrating the agroecosystem in the flow inventory. To evaluate the resilience of the system, the circularity between farm activity and its agroecosystem was selected by distinguishing two steps in the circularity: Inflow Circularity and Outflow Circularity, respectively $Circ_{in}$ and $Circ_{out}$. The operational objective aims at providing a set of accessible indicators of performance, stability and self-sufficiency, in order to support decision-making, to reduce the dependence on fuel and chemical-based inputs and to 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 (i.e., intensive breeding, intensive crop production and extensive mixed-farming systems) have been 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.

2. Material and Method

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 can provide 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 represent the sum of useful work plus energy dissipation.

Moreover, as for LCA, flow inventory 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.

The proposed method combines the circular energy flow perspective of the AEA, several elements of system representation in emergy analysis and the flow inventory as performed in LCA. It can be applied following 5 steps: i) flow inventory, ii) energy conversion, iii) flow representation, iv) calculation of the indicators and v) interpretation. Concerning flow inventory, a farm audit crossed over with all available administrative documents is performed in order to describe the characteristics of the farm (e.g. building, tools, fertilizer consumption, etc.) and of the agroecosystem (e.g. pedo-climatic conditions, land configuration, soil samples). According to the vegetal biomass yields, all biomass production can be calculated using product:residue ratios and root:shoot ratios from the literature (Guzmán et al., 2014). Energy conversion, based on heating values, is computed using the Cumulative Energy Demand (CED) (e.g. Ecoinvent database) for external inputs, and the Gross Calorific Value (GCV) for internal flows of biomass (e.g. Feedipedia or Feedtable database). Finally, the energy flow configuration and indicators are computed and discussed.

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 1 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 1 depicts an aggregated energy system diagram, based on the Odum's (1971) scheme convention, and on the input-output table (Tab. 1). 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 1: 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 Carriers**	**Products**	**Materials & equipment**	**Services**

1	**INTERNAL OUTPUT**	**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	-	Meat, milk, animal dejection	-	*(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)*
5	**EXTERNAL OUTPUT**	**Energy carriers**	-	-	Fuel, electricity	-	-	-	-	-
6		**Products**	Purchased seeds, fertilizers, pesticides	Purchased animal feed	Paint, grass, replacement	-	-	-	-	-
7		**Materials & equipment**	-	-	Purchased material *(Amortization)*	-	-	-	-	-
8		**Services**	*(Plant assessment)*	*(Veterinary)*	*(Repair)*	*(Ecological assessment)*	-	-	-	-

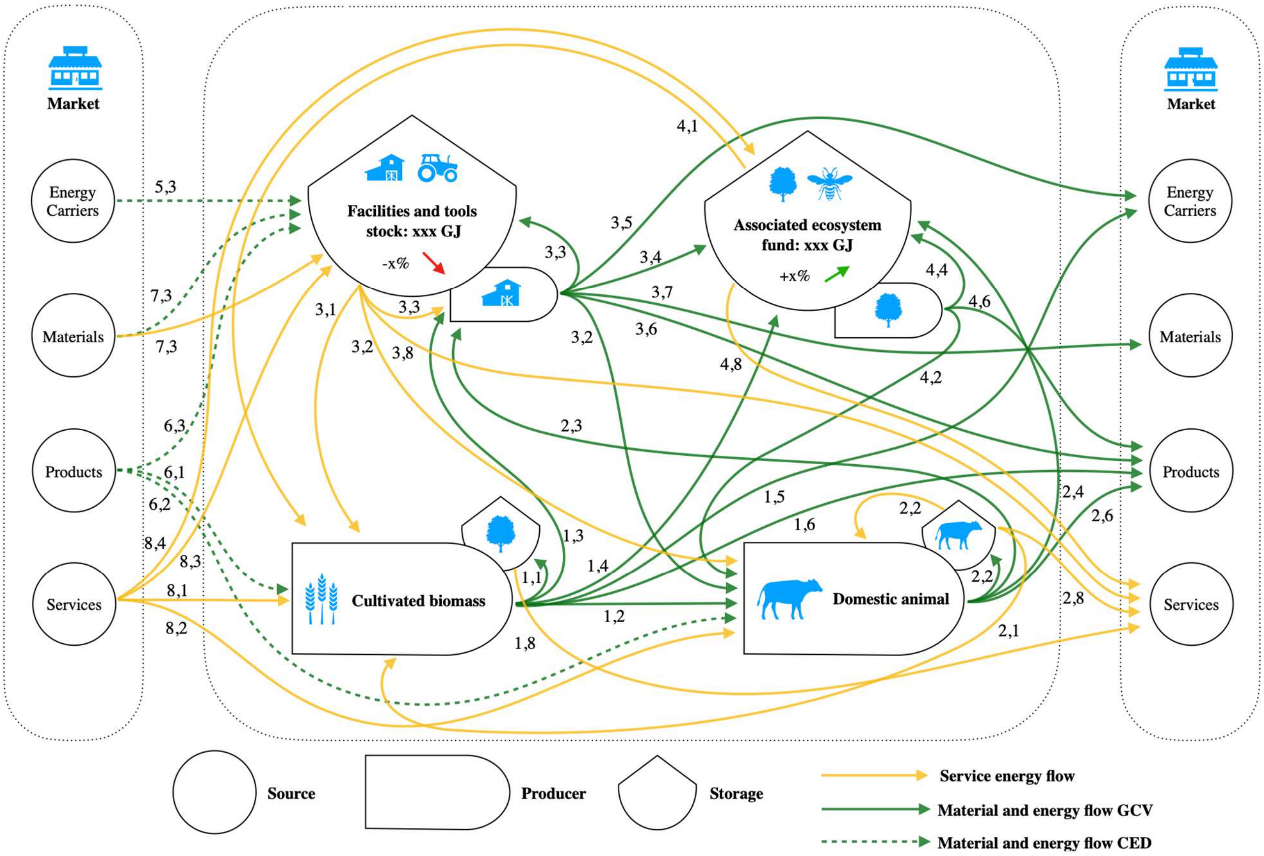


Figure 1: Generic energy flow diagram of the farm system. Arrow numbers refer to the input-output table (line, column).

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.

An energy carriers comprise all inputs necessary for operating tools and machines (see table 1, 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 1).

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 (see Tab.1 and Fig.1). 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 utilized, 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 (see Tab.1 and Fig.1). 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. The energy services provided by the AE are characterized using soil mineralization processes (see flow (4,1) in Tab.1). Soil provides essential ecosystem services (Vidal Legaz et al., 2017) including nutrients and water regulation, food and fiber 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 availably, water-holding capacity, etc.… (Barrios, 2007; Dominati et al., 2010; Oldfield et al., 2019; Vogel et al., 2018). Nonetheless, soil mineralization indicates soil activity and is a measurable and available type of data. 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 (k2) 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; Mary and Guerif, 1994) or through a model such as AMG (Saffih-Hdadi and Mary, 2008) (See supplementary material, section 1).

2.4. Taking energy stocks into account

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., 2017). 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). 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).

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 the performance, focus is put on the Energy Return On Investment ratio (EROI) (Hall, 2017), i.e. the efficiency of the system.

$$EROI = \frac{O_{\mathrm{M}}}{I_{\mathrm{M}}} \tag{1}$$

with O_M (MJ) the sum of the outputs from the farm to the market and I_M (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:

$$EROI_{Ag} = \frac{O_M + O_{AE}}{I_M + I_{AE}} \tag{2}$$

where O_{AE} (MJ) is the sum of the outputs from the farm to the associate ecosystem and I_{AE} (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.

In order to better assess circularity within the system, circularity indicators proposed by Tanzer (2020) were selected. In the present framework, circularity characterizes the relationship between the flows issued or invested from/to the associated ecosystem (AE) and the total energy consumed or produced. Two indicators are used. Inflow circularity (eq. 4) describes the portion of energy provided by the AE (i.e. soil mineralization) relative to the total energy consumed by the agroecosystem. It can be associated to an indicator of self-sufficiency which would reveal to what extent the farm system depends on flows coming from the AE. Outflow circularity (eq. 5) describes the portion of vegetal biomass left to the AE relative to the total biomass produced (i.e. the NPP).

$$Circ_{in} = \frac{I_{AE}}{I_M + I_{AE}} \tag{3}$$

$$Circ_{out} = \frac{O_{AE}}{O_M + O_{AE}} \tag{4}$$

2.6. Case study

The case study concerns a real 39 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 mineralization coefficient (k2) is 2.2% and has been calculated according to the equation of Mary and Guerif (1994) (see supplementary material). 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 detailed data).

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).

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 m^2).

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 order to preserve a certain degree of comparability.

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. RESULTS

3.1. Energetic flows of the farm agroecosystem and studied scenarios

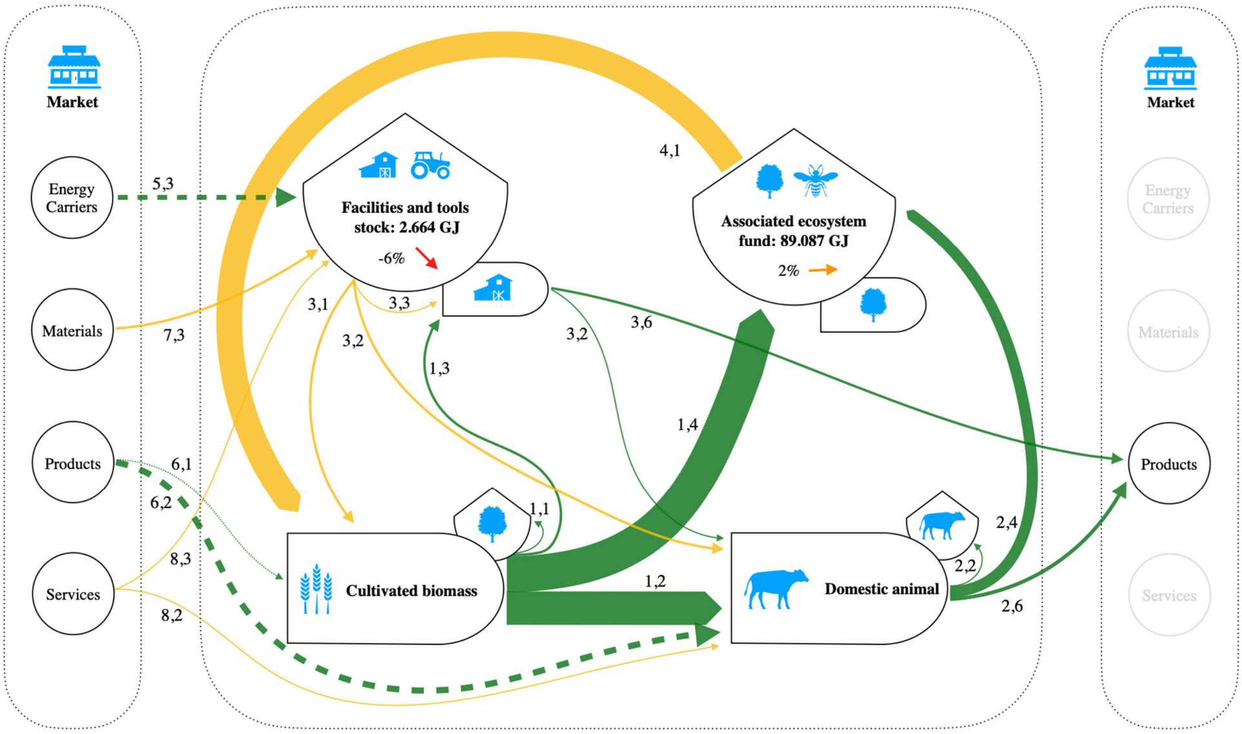


Figure 2: Energy flow diagram of the case study (see energy flow diagram of the scenarios in supplementary material). The width of the arrows is proportional to the amount of energy

Figure 2 represents the energy flow diagram of the farm case study. 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 services. 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 (6,2), 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). 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) 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 2: Input Output table of the case study in GJ. Energetic services are in *italic* (see input/output table of the different scenarios in supplementary material)

			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 *(142.9)*	0.0 *(62.3)*	0.0	0.0	145.9	0,0	*(0.0)*	**201** ***(417)***
	4	**Associated Ecosystem**	*(1964.8)*	0.0	-	0.0	-	0.0	-	*(0.0)*	0 ***(1965)***
EXTERNAL INPUT	5	**Energy carriers**	-	-	416.9	-	-	-	-	-	**417**
	6	**Products**	4.9	482.0	0.0	-	-	-	-	-	**487**
	7	**Materials & equipment**	-	-	0.0 *(135)*	-	-	-	-	-	0 ***(135)***
	8	**Services**	*(0.0)*	*(13.2)*	*(43)*	*(0.0)*	-	-	-	-	***(56)***
		Flows received	**26** ***(2176)***	**3306** ***(58)***	**618** ***(204)***	**3847** 0	0	**473** 0	0	-	

3.2. Farm agroecosystem efficiency and circularity

In the case study, the $EROI$ (0.43) is low (Tab.3), 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 greater than one (1.41). This can be explained by important flows reinvested within the farm (3847 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 64% of the input coming from the agroecosystem.

The intensive breeding scenario presents a similar $EROI$ (0.47) to that of the case study and a higher $EROI_{ag}$ (1.98). 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 29% 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 (7678 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 $EROI_{ag}$ (4.77) 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 $Circ_{in}$ (47%). 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 (2664 GJ).

The Extensive mixed-farming scenario presents an $EROI$ of (2.11) and an $EROI_{ag}$ of (2.79). 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 78%.

Table 3: Indicators and Stocks for the Case study and for the 3 scenarios

		Mixed-farming case study			**Scenario 1: intensive breeding**			**Scenario 2: intensive vegetal production**			**Scenario 3: extensive mixed-farming**		
EROI	**EROI**	0.43			0.47	112 %		4.30	1013 %		2.11	498 %	
	Agroecosystem EROI	1.41			1.98	141 %		4.77	340 %		2.79	199 %	
	Output circularity	89 %			83 %			52 %			83 %		
	Input circularity	64 %			29 %			47 %			78 %		
		GJ	**ΔStock**		**GJ**	**ΔStock**	**%**	**GJ**	**ΔStock**	**%**	**GJ**	**ΔStock**	**%**
k relati ve	**Associated Ecosystem**	89287	1882	2.1 %	69050	7101	10.3 %	65129	6201	9.5 %	74931	3270	4.4 %
	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 %	42	36	0 %
Cultivated biomass	73	4	5.7 %	80	4	5.2 %	129	4	3.2 %	84	4	4.9 %

4. Discussion

4.1. Capacity of indicators to support decision making in favor 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 of sustainability have been considered (see introduction) to which answers will be given via the proposed indicators.

With the $EROI$ ratio, the current performance of the system (i.e. short term sustainability) 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 (Fig.3). The introduction of soil organic matter in the $EROI_{ag}$ flattens $EROI$ variations between scenarios thus reflecting the capacity of the agroecosystem to produce biomass. 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 $EROI_{ag}$. Modifications in land use tended to increase biomass production (corn silage) while, simultaneously, energetic services provided by the AE (pastured land to crop land with lower SOM) decreased. This resulted in a higher $EROI_{ag}$ compared to the case study. However, the unbalanced situation in the circularity ratio of the intensive scenario (Fig.3) calls for a closer investigation on 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 $AE\ \Delta\ stock$ 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 (Fig.3). 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.

4.2. Interpretation of the proposed indicators

Regarding the interpretation of the indicators, no direct relationship seems to exist between $EROI$ and Circularity. However these two indicators each present complementary information. EROI allows for the system current performance to be quantified, while circularity reflects the resilience of the system (See supplementary material, figure 6). The value of $Circ_{in}$ indicates to what extent the system is based on internal flow from the AE and is self-sufficient. The lower the $Circ_{in}$, the more the system will be governed by external inputs and sensitive to external socio-economic shocks. Moreover, a system based on its AE implies a functional agroecosystem with reinforced capacity to resist to external environmental shocks (e.g. better water retention in a soil makes it more resistant to drought episodes). Another interesting outcome concerns the degree of balance between $Circ_{in}$ and $Circ_{out}$. On one hand, low $Circ_{in}$ and high $Circ_{out}$ suggest investment in the AE without relying on it (i.e. intensive breeding scenario) and eventually causing deterioration (e.g. risk of pollution such as eutrophication). On the other hand, high $Circ_{in}$ and low $Circ_{out}$ suggest that the farm activity depends on its AE without any investment on it and that this may compromise farm agroecosystem stability over time. On the contrary, a strong and balanced circularity suggests a highly resilient system.

In the light of the case study and different scenarios, the purchase of animal feed (i.e. the case study and the intensive breeding scenario) generates low $EROI$. On the other hand, the presence of animals promotes high values of $Circ_{out}$ (Fig.3), thus favoring the establishment of a strong and balanced circular system. Nevertheless, it is the production of vegetal biomass that appears to be the most efficient system. Consequently, a sustainable agricultural production system could enhance the production of plant biomass with the introduction of a minimum amount of animal production. This is the case for scenario 3 (extensive mixed-farming system) that presents the most balanced dimensions for sustainability (see a radar graph representation in supplementary material, section 6)

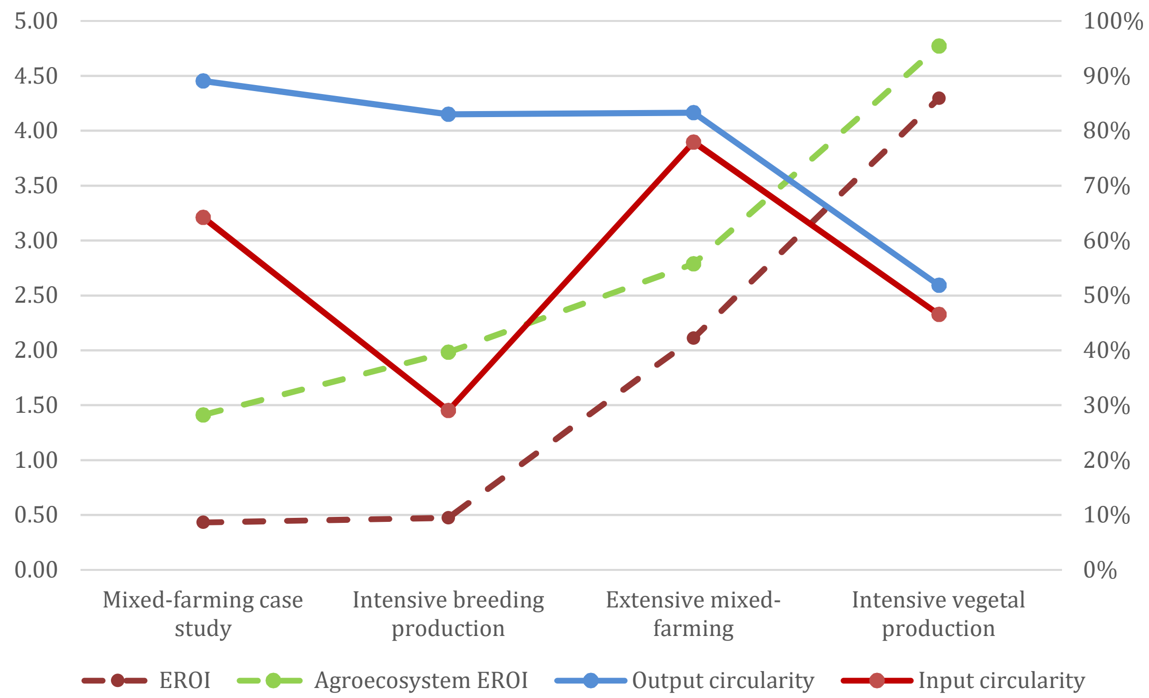


Figure 3: Graphical representation of EROIs and Circularity indicators for the case study and different scenarios. The EROI value is represented on the left. The circularity value is indicated on the right.

4.3. 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 agroecosystem 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 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).

4.4. 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 table1). 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. A comparison of the different scenarios was performed on the same agricultural land area with the aim of providing decision support elements for the farmer to design an efficient and resilient system. The sustainability of the system should depend on the correct balance between vegetal biomass production (perennial and annual), animal biomass production, technical capital and natural capital. However, other indicators could be integrated to support farmers' decisions since the studied strategies do not provide the same products or quantities. For example, this can lead to differences in the farmers' income. Integration of economic indicators would provide guidelines for the implementation of agricultural policies to adjust the short-sightedness of markets facing long-term sustainability strategies. In addition, a site specific approach does not highlight the market integration effort performed by the farmer who transforms 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?).

5. Conclusion

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 agroecosystem. 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.

The trends revealed by the Circularity indicators are promising and could play a fundamental role in the assessment of the resilience of a system in its management of resources. Unbalanced circularity should affect the energy stock equilibrium and the temporal stability of the farm agroecosystem. In addition, low inflow circularity results would point to systems depending on external inputs, with low self-sufficiency and a reduced capacity to resist to external shocks. In such a case, the analysis of the renewability of these flows becomes necessary.

The proposed method represents a step forward in energy analysis and characterization of the flows involved in an agricultural production system. A key service provided by the agroecosystem has been integrated here: this concerns soil fertility, where the mineralization of soil organic matter is used as a proxy to express soil microbial activity. The proposed model also depicts a vision of agricultural activity as a farm agroecosystem where the nature and function that a subsystem may have are differentiated. On this basis, 4 indicators have been defined for a rapid first assessment to be made on the sustainability of the farm over a short term (i.e., resource use efficiency), and over a long term via its temporal stability (i.e., balanced circularity) and degree of self-sufficiency (i.e., $Circ_{in}$).

The framework encourages 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.

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Conflict of Interest:

The authors declare that they have no conflict of interest.

Authors contribution:

Conceptualization, J.H.P, CS, E.L. and A.H.; Methodology, J.H.P., A.H.; Investigation, J.H.P. and A.H.; Writing – original draft, J.H.P.; Writing – review and editing, A.H. and E.L.; Supervision, A.H. and C.S.

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