Diversification of an integrated crop-livestock system: Agroecological and food production assessment at farm scale

Thomas Puech, Fabien Stark

Agriculture, Ecosystems and Environment 344 (2023) 108300

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Diversification of an integrated crop-livestock system: Agroecological and food production assessment at farm scale

Thomas Puech [a,1,*], Fabien Stark [b]

[a] ASTER, INRAE, 88500 Mirecourt, France
[b] SELMET, Institut Agro Montpellier, University Montpellier, INRAE, CIRAD, 34060 Montpellier, France

ARTICLE INFO

Keywords:
Crop-livestock integration
Ecological network analysis
Resilience
Food efficiency
Organic farming

ABSTRACT

Mixed farming systems are of interest in the search for sustainability because of their species diversity and the potential for synergy from integrating crops with livestock. However, their ability to maximize food production has been little addressed in the literature and deserves to be explored further. The issue of nutrient recycling raises questions about resource allocation between food crops, feed and animal products. This study, based on a whole farm system experiment conducted for approximately fifteen years in northeastern France, assesses the biotechnical processes and food production performance of two integrated mixed system configurations. These configurations differed both in their types of production (diversity in both livestock and crops) and in their overall strategies (striving for self-sufficiency vs. maximizing food-crop output). Taking a metabolic approach, the study evaluates biotechnical processes (by ecological network analysis and nutrient balances) and food production efficiency. Our results show that the configuration geared to maximizing food production is not the more productive but is the more efficient. In both cases, efficiency at the farm system scale is better than the efficiencies of each production. This confirms the importance of combining systemic and analytical approaches to better understand and act on the development of agroecological farming systems. We also show the importance, for a self-sufficient system, of having stocks in reserve to cope with unfavorable years. Finally, our study confirms the value of integrated mixed farming systems in terms of agroecology but highlights the need for (i) a closer consideration of their food production aspect and (ii) an analysis of the temporal dynamics of agrosystems and the trade-offs between food production and nutrient cycling.

1. Introduction

During the second half of the 20th century, agricultural systems in Western Europe became highly specialized in response to public policies, technical innovations and low energy costs (Jepsen et al., 2015). The specialization was fostered by a progressive disconnection between agricultural and food systems, which are now organized on a global scale (Billen et al., 2014). Territorial specialization resulted in a marked disconnection between crop and livestock production, with each territory divided into large and specialized farming areas (cereals, livestock, etc.). This trend was encouraged by the concentration of industrial processing facilities for reasons of economy of scale. Such disconnection makes farms more dependent on inputs (mineral fertilizer, animal feed) and on markets. These developments have had consequences both for the environment (water pollution, erosion of biodiversity, etc.) and for agricultural systems (Therond et al., 2017).

Many institutions are calling for agricultural systems to transition to more sustainable systems (Tomich et al., 2011; Sijpestijn et al., 2022). Systems based on the principles of agroecology are among the main avenues to be explored to improve sustainability (Gliessman, 2004). They are mainly based on the diversification of species (more complex food webs), cycling of nutrients (crop-livestock integration), biological regulation and the reconnection of agricultural systems with food systems (Le Roux et al., 2008; Kremen et al., 2012; Altieri et al., 2012). These principles should contribute to some of the emerging properties expected of sustainable agricultural systems: self-sufficiency, productivity, efficiency and resilience (López-ridaura et al., 2005; Lin, 2011; Cabell and Oelofse, 2012; Bonaudo et al., 2014; Meuwissen et al., 2019).

We make the assumption that mixed crop-livestock systems have some useful features for achieving sustainability and their

* Correspondence to: ASTER, 662 Avenue Louis Buffet, 88500 Mirecourt, France.
E-mail address: thomas.puech@inrae.fr (T. Puech).
[1] https://orcid.org/0000–0003-2192–9719

https://doi.org/10.1016/j.agee.2022.108300
Received 14 April 2022; Received in revised form 28 November 2022; Accepted 29 November 2022

agroecological processes, namely, diversity of species (plant and animal) and synergies achieved by integrating crop and livestock production (Bonaudo et al., 2014). The issue of crop-livestock integration and nutrient recycling raises the question of resource use and their priority to produce food, particularly the role of intermediate resources such as fodder for animal feed (Barbieri et al., 2022).

From a methodological standpoint, agricultural systems have frequently been analyzed using a combination of indicators to assess their performance with regard to the three pillars of sustainability (WCED, 1987; López-ridaura et al., 2005; Zahm et al., 2019). These so-called multicriteria assessment methods have been criticized because (i) they are highly standardized and normative (they incorporate, more or less explicitly through the indicators and thresholds used, the definition of "a" sustainable system - Barbier and López Ridaura, 2010), (ii) they focus on assessing average agricultural output (Urruty et al., 2016), and (iii) they do not help to explain the functioning and complexity of agrosystems (Binder et al., 2010). From our point of view, the capacity of agricultural systems to use resources to produce food, from both animals and crops, and to exploit the range of possible complementarities needs to be specifically studied.

We assume that agrosystems based on agroecological principles are more complex systems. Consequently, the analysis of such a system must be systemic and holistic. This means characterizing the system's various components, the interactions between them, and the interactions between the system and its ecological and socioeconomic environment. Until now, metabolic and flow analysis approaches have mainly been applied at the scale of agri-food systems (Fernandez-Mena et al., 2016; Gabriel et al., 2020), whose spatial scope extends from the farming system (Steinmetz et al., 2021), local territory (Verger et al., 2018), and watersheds (Kim et al., 2018) to global scales (Billen et al., 2021). Metabolic approaches developed in economics and ecology (Rutledge et al., 1976; Finn, 1980; Ulanowicz et al., 2009) have been adapted for assessing agroecological performance at the farm scale (Rufino et al., 2009a; Stark et al., 2016; Steinmetz et al., 2021). However, nature-based systems are inherently sensitive to environmental conditions, which can have a strong impact on their performance levels (Darnhofer et al., 2010; Duru et al., 2015, 2013). Taking into account the activity of the system, in terms of nutrient flows between biological components, seems to be an interesting way to analyze these systems and design agroecological ones.

The purpose of this paper is to assess the agroecological and food production performance of two configurations of integrated crop-livestock farming systems. They were conducted asynchronously on an experimental farm at the whole-farm scale. The first configuration (2004–2015) was designed to close the nutrient cycles to achieve self-sufficiency and integrate crops and livestock. The second configuration (2016–2020) had more diverse crops and herds, with more land used directly for food production, to avoid feed-food competition. To make this assessment, we analyze nutrient flows (expressed as nitrogen) using two complementary approaches: ecological network analysis (to assess the systems' agroecological performance) and food production efficiency.

2. Materials and methods

2.1. One system experiment, two mixed farming system configurations

The analysis is based on a whole farm experiment conducted on the INRAE ASTER research station in Mirecourt, France (48°17'41.287''N, 6°07'19.66''E). This farm is composed of 135 ha of permanent grassland and 106 ha of arable land, mainly on clay and clay-loam soils. It lies at an altitude of 285 m in a crop-livestock area typical of northeastern France. The climate is semicontinental. Over the period 2011–2021, the average rainfall was 790 mm, and the average temperature was 10.4 °C, with cold, wet winters and hot, relatively dry summers.

This farm-scale experiment consisted of designing and implementing coherent systems to meet a number of objectives (Debaeke et al., 2009). These systems were designed according to a 'step-by-step' design mode whose aim was to constantly improve the system on the basis of experience acquired during the experiment (Coquil et al., 2014). The study was based on two organic farm system configurations implemented over the last fifteen years: The main resources in the first configuration are allocated to dairy production, whereas the second configuration is more diversified and aims at the direct use of land for human consumption. Table 1 summarizes their main characteristics.

The dairy configuration, conducted between 2006 and 2015, consisted of a grazing subsystem and a mixed crop-livestock subsystem. Its main aim was to achieve self-sufficiency: No animals, fodder or organic fertilizers were purchased during the period. In the grazing system, approximately 40 dairy cows were exclusively grass-fed on 78 ha of permanent grassland, with a goal of maximizing grazing. The mixed crop-livestock system consisted of 60 dairy cows on 57 ha of permanent grassland and 106 ha of arable land (on average, 21 ha of alfalfa-grass, 27 ha of clover-based temporary grassland and 59 ha of annual crops), mainly for animal feed (except for the wheat and rye). For this study, we have taken these two subsystems together (we will later refer to them as the "dairy system" even if some crops are sold for human food) to be consistent with the diversified system.

The diversified configuration has been conducted since 2016 on the same experimental farm (135 ha of permanent grassland and 106 ha of arable land). This configuration also aims for self-sufficiency but with a wider range of crop and livestock products (Coquil et al., 2019). This

Table 1
Main characteristics of the systems studied.

	Dairy system (2011–2015)	Diversified system (2018–2020)
Strategic choices		
Self-sufficiency	No fertilizer or feed inputs. The number of livestock units is the adjustment variable depending on the amount of fodder produced	
Degree of diversification	**Lower** System are specialised in dairy cattle production (pastures and annual feed crops) and milling wheat	**Higher** 3 animal species (dairy cattle, meat sheep, pig) and 20 annual food crops
Food/feed principles	Annual crops divided between feed (for dairy cattle) and food	Annual crops for human consumption only Ruminants strictly grass-fed Pigs fed on waste
Cropping systems		
Permanent Grassland (ha)	135	135
Arable land (ha)	106.5	106.5
Temporary grassland (ha)	47.2	41.8
Annual feed crops (ha)	33.3	0
Annual food crops (ha)	26.0 (wheat and rye)	64.7 (20 crops: wheat, oats, barley, lentils, peas, vegetables…)
Livestock systems		
Cattle (LU)	170.7	124.2
Heifers (LU)	73.9	28.1
Milking cows (LU)	89.0	79.1 (5.3 suckling cows)
Grazing (days. year^{-1})	225	224
Concentrate (kg. cow^{1}.year^{-1})	431	0
Milk production (L.cow^{1}.year^{-1})	5507	3313 Once-a-day milking
Sheep (LU)	0	18.8
Pigs (LU)	0	3.9

*LU: livestock unit.

system used land to produce human food directly: All the annual crops were strictly for human food. Some 20 species were grown (milling wheat, malting barley, oats for flaking, einkorn, lentils, green peas, oilseed rape, sunflower, camelina, potatoes, onions, etc.). A sheep herd (19 livestock units) was introduced at the end of 2017 and kept in the open air to most efficiently use grassland resources that were difficult to be grazzed by cattle (123 livestock units), especially in winter. The dairy cows were kept on full-season once-a-day milking, with heifers suckled by nurses (this frees up working time for crop and livestock diversification, which was achieved without increasing the workforce). All sheep and cattle were strictly grass-fed. Finally, approximately thirty pigs were fattened each year. The pigs were raised in the open air, grazing on a plot of alfalfa grass and making use of products unmarketable for human consumption (annual crop waste, milk with high cell counts, etc.). We will later refer to this system as the "diversified system".

2.2. System modeling as a nutrient flow network

2.2.1. Conceptual modeling

To analyze both configurations on a common basis and to assess their agroecological properties and food production capacity, we modeled them as nutrient flow networks. By analyzing nutrient flows, one can account for both the metabolism of the systems and their capacity to produce and utilize nutrients.

To model these systems as networks of nutrient flows, we perform two formalization steps: (i) conceptual modeling of the systems studied and then (ii) quantification of the nutrient flows between system components and between the system and socioecological environment (inputs, produce sold, losses).

Both configurations are represented using the same formalism (Fig. 1). While the values of some system-scale indicators, such as inputs and outputs, are independent of the formalism chosen, indicators of internal functioning, such as the intensity of flows between production processes, depend on the relevant components and flows. The aim here is to compare these configurations according to their different degrees of diversification and integration, so we have used a single formalism based on the most diversified system.

Given that one of our strategic choices for managing the systems was to seek complementarities between the crop and livestock components, we distinguish between animal species because they use the available resources in different ways depending on their metabolism (monogastric or ruminant). Regarding crop production, we distinguish between non-

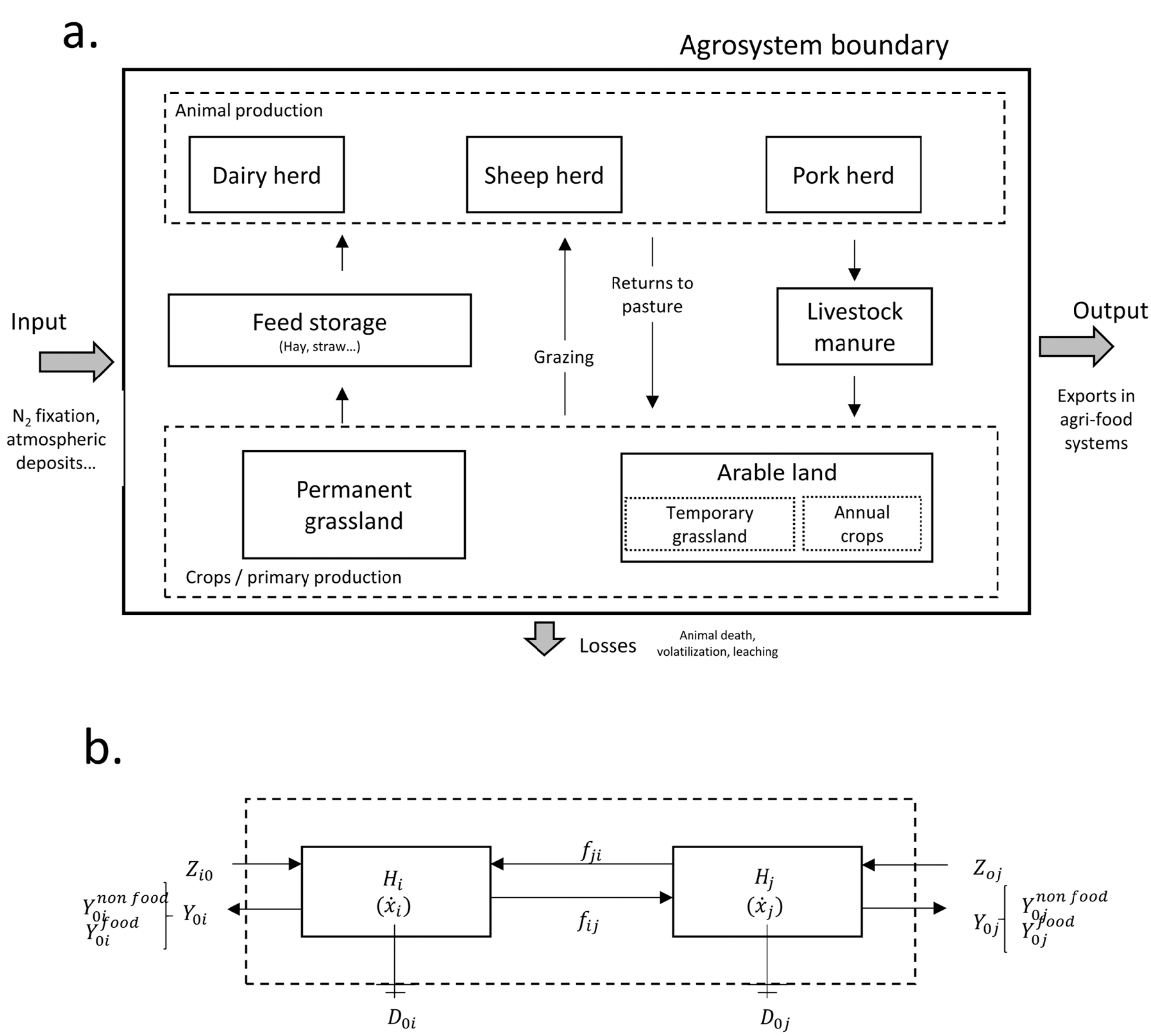

Fig. 1. Conceptual model for representing the metabolism of the systems studied. a : conceptual organisation of the components of the systems studied. b : conceptual model of the flows between two component with the information required for ecological network analysis (adapted from Finn, 1980). In accordance with the conventions described by Latham (2006), each system is characterised by n components; Hi and Hj correspond to component i and j; $\dot{x}_i$ et $\dot{x}_j$ correspond to the storage of materials of i and j over the study period, f_{ij} correspond to internal flows from component i to component j; Z_{0i} and Z_{0j} correspond to inputs from the environment to component i and j (distinguished according to whether or not they are food products); Y_{0i} et Y_{0j} correspond to exports from component i and j (distinguished according to whether or not they are food products); L_{0i} and L_{0j} correspond to the losses of component i and j.

arable areas under permanent grassland and arable land alternating between temporary grassland and crops.

The systems represented are therefore composed of 5 productive components (cattle, sheep, pigs, permanent grassland and arable land) and 3 storage components, i.e., storage of roughage (hay, straw), grain (consumed by the farm's animals) and livestock waste (manure). We assume that a system's capacity to store certain resources will be central to its self-sufficiency, as it allows the system to regulate its metabolism over a period of several years. Therefore, in line with Rufino et al. (2009a) and Stark et al., (2016, 2018), we consider that the systems studied are not in a state of equilibrium: The size of each component may vary over the study period (increase/decrease in herd size, increase/-decrease in forage stocks or nutrients stored in the soil, etc.).

Different kinds of nutrient flows are considered: (i) internal flows transiting between two components of the system (e.g., flow of fodder from storage component to cattle, return of organic waste to the soil on grazing land, etc.), (ii) inputs (e.g., purchase of animals but also atmospheric deposits, symbiotic fixation), (iii) flows of products intended for export from the system (e.g., sale of animal products and crops), and (iv) losses (e.g., animal deaths, losses into the environment).

2.2.2. Data acquisition

In the proposed conceptual model, nutrient flows between system components and between the system and environment are quantified by means of flow matrices to analyze them.

We used nitrogen (N) as the unit for quantifying nutrient flows. N is commonly used to characterize the metabolism of agricultural and food systems (Garnier et al., 2016; Stark et al., 2016; Tedesco et al., 2017; Billen et al., 2018) in assessing the functioning of crop systems (fertilization) and livestock systems (feeding). Nitrogen is also a proxy of interest for human nutrition when assessing protein coverage from animals or plants (a widely debated issue, particularly regarding changes in the human diet – Couturier et al., 2016; Poux and Aubert, 2018), especially since it is one of the main limiting factors in biological systems (Barbieri et al., 2021; Morais et al., 2021).

This experiment and the configurations implemented are documented by a particular information system (Trommenschlager and Gaujour, 2010; Trommenschlager et al., 2010) that allows quantification of most of the material (and hence nutrient) flows within the systems. Crop production performances are known at the plot level (grain and straw yields of annual crops, hay yields of grasslands). The nitrogen content of wheat and fodder is known through annual analyses. For animal production, the quantities and protein content of milk marketed and the weight of sold animals are known. Regular animal weighing makes it possible to monitor herd stock variations and losses (deaths). The composition and location (plot and land use) of the animals is known on a daily basis, which makes it possible to calculate and locate the animals' grazing intake and output. The quantities of fodder (hay or concentrates) provided to the animals are measured daily, and the composition of the fodder (proportion of legumes, chemical composition) is regularly analyzed. Restitutions by manure/slurry spreading are known because they are systematically weighed and analyzed. Finally, meteorological data are collected (temperature, rainfall, nitrogen composition of rainwater) at the site to calculate N deposits.

In addition to the data collected by direct observation, we made several assumptions to estimate missing data and quantify all nitrogen flows. For some products without protein content analysis (e.g., lentils, peas, and einkorn), we rely on data from the open database Feedipedia for crops (Sauvant et al., 2013) and Table A.1 in the appendix of Stark et al. (2016) for animal production. Soil nutrient return at pasture is estimated on the basis of annual loads (known at the plot level), estimated at 95 kg N.livestock unit^{-1}.year^{-1} for dairy cows, 85 kg N.livestock unit^{-1}.year^{-1} for other ruminants (including sheep) and 20 kg. livestock unit^{-1}.year^{-1} for pigs, in line with various studies (Giovanni and Dulphy, 2008; Anglade, 2015). Grazing consumption is estimated as the average daily consumption of dry matter, 2 kg of dry matter for pigs (Puech et al., 2021) and 16 kg of dry matter for ruminant livestock units (from which any supplemental hay is deducted to cattle in the pasture). We estimate symbiotic fixation by legumes (food or fodder crops) using the "Biological Nitrogen Fixation" indicator developed by Anglade et al. (2015). Leaching losses are estimated using the method developed by Anglade in organic farming systems (Anglade, 2015); we estimate volatilization losses from the synthesis work on livestock waste and emissions by Peyraud et al. (2012).

Data were collected over the period 2011–2015 for the dairy configuration and over the period 2018–2020 for the diversified configuration. The years 2016 and 2017 were transition years between the two configurations and are not included in this study.

2.3. Agroecological performance and food production

To compare the functioning of the two configurations and the resulting agroecological and food production performance, we used indicators from several theoretical frameworks.

Indicators for the characterization of crop-livestock integration and for the associated performances are derived from Ecological Network Analysis (ENA). ENA was initially developed in ecology to study the functioning of ecosystems and the emergent properties associated with their configurations (Latham, 2006; Ulanowicz et al., 2009). Agronomists first adopted ENA to study the functioning of tropical agroecosystems (Rufino et al., 2009b), drawing parallels between the functioning of diversified farming systems and that of mature ecosystems, with the aim of identifying the agroecological properties that would result (Stark et al., 2016; Steinmetz et al., 2021). Based on flow matrices (Fig. 1), several algorithms can be used to calculate a range of indicators that reflect both systems metabolism (integration between the system's components, cycling and recycling of nutrients) and the agroecological performance of these systems in terms of productivity, self-sufficiency, efficiency, and resilience (Bonaudo et al., 2014).

Three aspects of these approaches seem particularly relevant to address our research question.

The first aspect lies in the fact that they consider the functioning of the system (total system throughflows, TST, Eq. (1)) as the activity of the system through the intensity of the biological processes involved, i.e., the sum of all nutrient flows circulating within the system (throughflows, T_i, Eq. (2)).

$$TST = \sum_{i=1}^{n} T_i \tag{1}$$

$$T_i = \sum_{j=1}^{n} f_{ij} + Z_{i0} - \dot{x}_i \tag{2}$$

This results in a recycling indicator (internal circulation rate, ICR, Eq. (3)) that takes account of the contribution crop-livestock integration makes to the overall functioning of the system, i.e., the nutrient flows between crop and livestock components (total internal activity, TT, Eq. (4)), which contribute to the whole system activity (TST).

$$ICR = TT/TST \tag{3}$$

$$TT = \Sigma_{ij} f_{ij} \tag{4}$$

The second aspect is that these approaches also characterize the functioning of the system in terms of the linkages between these processes. This leads to a "network" type approach to flows in addition to the analysis of flow intensity. The realized uncertainty (AMI.Hr^{-1}) thus makes it possible to quantify the actual pattern of flows (average mutual information, AMI, Eq. (5)) with respect to the potential distribution of flows divided equally among all components (statistical uncertainty, Hr, Eq. (6)). This indicator allows us to characterize the configuration of the flow network and assess the distribution of nutrient flows between the components of the system (connectivity and intensity of all the circulating flows). The closer that the realized uncertainty is to 1, the more the overall intensity of flows is concentrated on few flows, and the network is considered heterogeneous. Conversely, the closer the realized uncertainty is to 0, the more the overall intensity of flows is equally distributed among flows, and the network is considered homogeneous (see Rufino et al., 2009a for a simple numerical application).

$$AMI = k\sum_{i=1}^{n+2}\sum_{j=0}^{n}\frac{T_{ij}}{T_{..}}\log_2\left(\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right) \quad (5)$$

$$H_r = \sum_{j=0}^{n}\frac{T_{.j}}{T_{..}}\log_2\left(\frac{T_{.j}}{T_{..}}\right) \quad (6)$$

The Total System Throughput (T.., Eq. (7)) corresponds to the total circulating flows of the network in terms of inflows and outflows (unlike the TST, which considers only inflows).

$$T_{..} = \sum_{j=1}^{n}\sum_{i=1}^{n}f_{ij} + \sum_{i=1}^{n}Z_{i0} + \sum_{i=1}^{n}Y_{0i} + \sum_{i=1}^{n}L_{0i}) \quad (7)$$

In a complementary way, the third aspect is the ascendency suite developed by Ulanowicz et al. (2009) for evaluating the sustainability of this flow network. It is based on theories developed in ecology, which consider that the sustainability of an ecosystem is further supported by its level of efficiency and resilience, formalized and demonstrated by a system of equations. In line with our objective of evaluating the sustainability of the systems studied and their performance in terms of efficiency and resilience in particular, the theoretical framework proposed by Ulanowicz et al. (2009) and used to assess some complex agricultural systems (Steinmetz et al., 2021; Stark et al., 2018; Alomia-Hinojosa et al., 2020) seems to us to be the most relevant.

The development capacity (C, Eq. (8)) of the flow network is thus seen as its current level of development. It made up of both 'effective' flows (ascendancy, A, Eq. (8)), corresponding to the most efficient flow paths, and redundant flows contributing to the reserve capacity of the system (overhead, Φ, Eq. (9)), corresponding to paths that are less efficient in terms of nutrient conversion but that contribute indirectly to the level of development of the system (indirect effects). As defined by Ulanowicz et al. (2009), an ecosystem "*must be capable of exercising sufficient directed power (ascendency) to maintain its integrity over time. Simultaneously, it must possess a reserve of flexible actions (overhead) that can be used to meet the exigencies of novel disturbances*". In line with Ulanowicz et al. (2009), in this study, we consider an agrosystem's resilience ($\Phi.C^{-1}$) as its reserve capacity according to its current level of development (see Ulanowicz et al., 2009 for a simple illustrated application). This means that the closer the resilience indicator ($\Phi.C^{-1}$) is to 1, the more system activity is provided by redundant activities, and the closer it is to 0, the more system activity is provided by efficient flow paths.

$$A = \Sigma_{ij}T_{ij}\log\left(\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right) \quad (8)$$

$$\Phi = -\Sigma_{ij}T_{ij}\log\left(\frac{T_{ij}^2}{T_{i.}T_{.j}}\right) \quad (9)$$

$$C = \Phi + A \quad (10)$$

From an agronomic standpoint, we propose to supplement these approaches with indicators classically used to account for an agrosystem's productivity (its capacity to export food products) and efficiency (its capacity to produce food - animal or plant products - according to the resources harnessed to produce it). Productivity (P, Eq. (11)) is defined as the sum of food outputs divided by the cultivated area:

$$P = \Sigma_i Y_{oi} \quad (11)$$

For the second approach, we propose to use Nitrogen Use Efficiency (NUE, Eq. (12)), an indicator conventionally used to characterize the efficiency of nitrogen use at the component or at the farm scale (Watson and Atkinson, 1999; Godinot et al., 2014). This indicator corresponds to the value of all the products that can be used in relation to the resources mobilized to produce them. We include in the numerator all outputs except for losses (leaching, volatilization, animal deaths): (i) food products, (ii) fertilizing products (manure, grazing returns, hays, straws), in the same way as Schröder et al. (2003), and (iii) stock variations (positive or negative, such as changes in the number of livestock) to overcome the difficulties noted by Godinot et al. (2020). These outputs are related to all the inputs of the system or subsystem (organic fertilizers, fodder, symbiotic fixation, etc.).

$$NUE = \frac{\Sigma_{i=1}^{n}Y_{oi} + \Sigma_{i=1}^{n}\dot{x}_i}{\Sigma_{i=1}^{n}Z_{io}} \quad (12)$$

However, while NUE takes into account both food and non-food production (livestock manure), it seems to us important to specifically characterize the efficiency of the system in terms of food production. We therefore define a Food Conversion Efficiency (FCE) indicator corresponding to the food part of NUE, reflecting the capacity of a system or its components to produce food products from inputs. This indicator is similar to the food chain NUE (Erisman et al., 2018; Congreves et al., 2021), except that it does not incorporate losses due to processing and consumption within the food system.

$$FCE = \frac{\sum_{j=1}^{n}Y_{0j,food} + \sum_{i=1}^{n}\dot{x}_{i,food}}{\sum_{i=1}^{n}Z_{i0} + \sum_{j=1}^{n}f_{ij}} \quad (13)$$

Although FCE can account for a system's capacity to convert resources into food products, it does not take into account the environmental conditions in which the system operates. We assume (i) that the agronomic potential of an environment is dynamic, since agricultural production is dependent on weather conditions (especially in self-sufficient grazing systems that make little use of inputs such as fertilizers or irrigation) and (ii) that primary production (from photosynthesis in grasslands and annual crops) is a proxy for the interannual dynamics of these environmental conditions (Dardonville et al., 2020). Thus, we define Food Production Efficiency (FPE) as the total food exported or stored in the system (animal and plant products) compared to the primary production consumed during the production process (annual crops and conserved or grazed forage, produced on the farm or imported). FPE thus makes it possible to account for the efficiency of a system in producing food from its environment. In particular, it makes it possible to compare asynchronously managed configurations that have benefited from different weather conditions for their production processes and the construction of their agro-ecological and food production performance.

$$FPE = \frac{\sum_{j=1}^{n}Y_{0j}^{food} + \sum_{i=1}^{n}\dot{x}_i^{food}}{\sum_{\varphi}Y_{0j} - \sum_{\varphi}\dot{x}_i + \sum_{\varphi}Z_{i0}} \quad (14)$$

The ENA indicators presented above were calculated using the algorithms described by Rufino et al. (2009a) from a spreadsheet developed in 2009 by M. Lubbers (Wageningen University and Research), adapted and completed by the authors for the other indicators described.

3. Results and discussion

3.1. Agrosystem metabolism

The forage area of the diversified system (177 ha) was 18% less than that of the dairy system (216 ha). This reduction was the direct consequence of prioritizing the use of arable land for food production (cessation of feed grain and meslin). As a result, while both systems had the same stocking rates (0.8 livestock unit.ha^{-1} of forage area), the diversified system had fewer animals than the dairy system (171 exclusively bovine livestock units in the dairy system compared to 124 dairy livestock units, 19 sheep livestock units and 4 pig livestock units in the diversified system, i.e., a 21% decrease – Table 1). Fig. 2 shows a decrease in sales of animal products in the diversified system (- 36% compared to the dairy system), due to the decrease in livestock numbers and to the switch to once-a-day milking (35% less milk produced per dairy cow in the grazing subsystem) and partly due to the evolution of the diet for cows in the crop-livestock subsystem of the dairy system. This decrease in the sale of animal products was accompanied by an increase in the sale of crop products (+ 40%) due to the prioritization of land use for direct human food production and the choice of a strictly grass diet for ruminants. Fig. 2 shows that sheep and pig production have slightly altered the internal metabolism of the diversified system compared to the dairy system (though cattle remain the majority in the diversified system).

Based on the data from the experimental systems, we established the flow matrices used to calculate the various indicators (one matrix per year and per system). The details of the matrices are available in the INRAE DataSet (Puech, 2021).

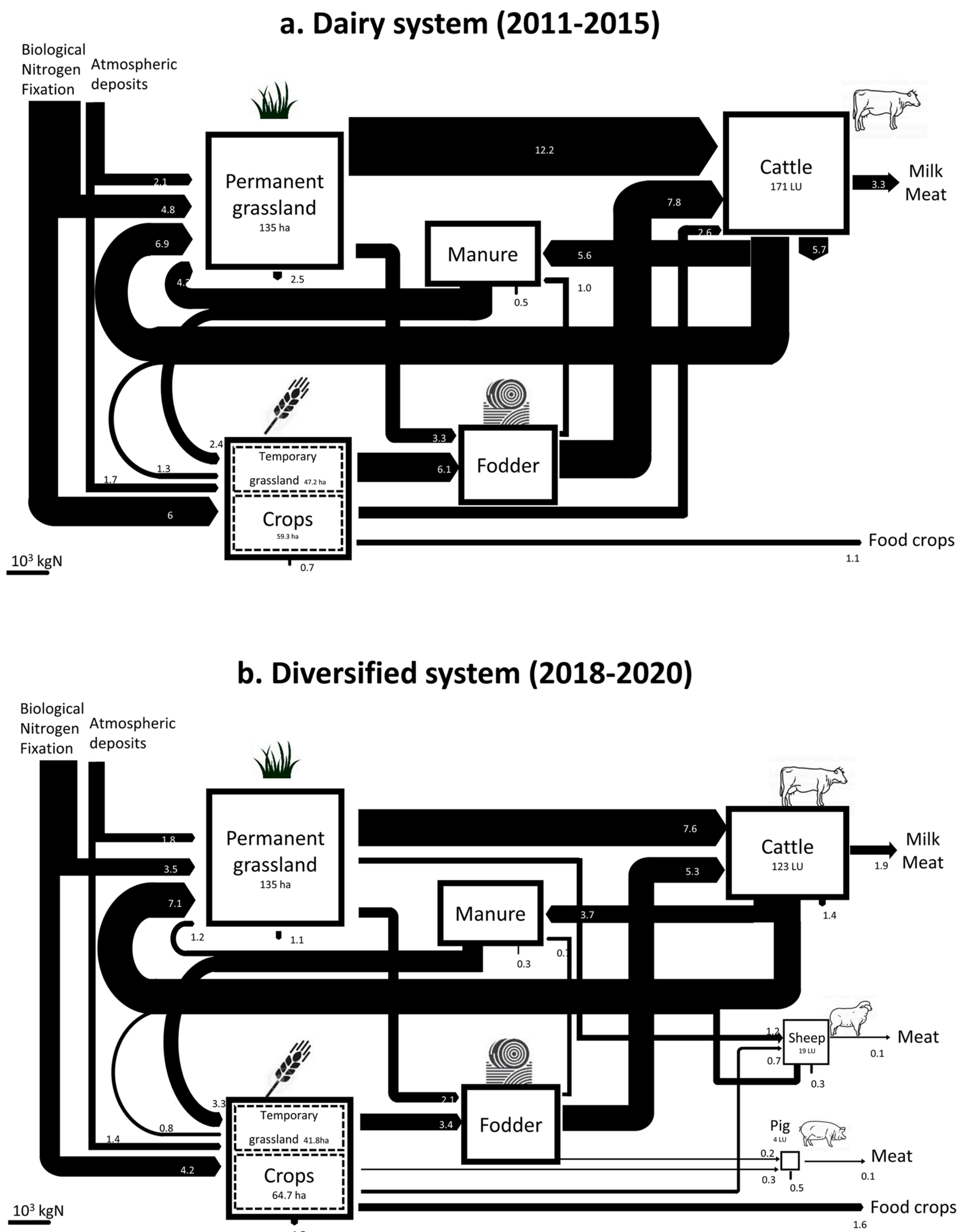

Fig. 2. Metabolism of dairy (a.) and diversified (b.) systems. The flows represent annual flows averaged over the respective study periods of the two systems, expressed in 10^3 kg N. Component size is proportional to agricultural area (permanent grassland and arable land) and herd size. Arrow thickness is proportional to flow intensity. *LU: Livestock Unit.*

Table 2 shows that the total activity (TST) of the diversified system is 27% lower than that of the dairy system. This difference is due to (i) the decrease in animal numbers (less fodder consumed, less manure produced) and (ii) a 33% decrease in primary production, particularly grassland production (permanent and temporary). It seems to us that the main factor explaining this drop in grassland production is a worsening of the water deficit in the summer period (April - October). Indeed, over the three years of the diversified system study, this deficit was 140% greater (−346 mm) than during the dairy system period (−143 mm).

Both configurations are self-sufficient due to the absence of imported nitrogenous fertilizers and fodder (Fig. 3). Nearly 75% of this self-sufficiency is ensured by closing N cycles within the system (78% for the dairy system, 76% for the diversified system), and 25% is ensured by renewable inputs. The majority (70%) of these inputs are provided by symbiotic fixation (annual and perennial legumes, a drop of 29% from the dairy system to the diversified system due to the drop in primary productivity, in which the legumes are a component). The other 30% of N inputs came from atmospheric deposition (no difference between systems). The symbiotic N fixation of legumes in permanent grassland represents an annual average of 26.2 kg $N.ha^{-1}$ for the diversified system and 35.9 kg $N.ha^{-1}$ for the dairy system. These values are consistent with those of Billen et al. (2021) and Garnier et al. (2016), who show respective values of 33 kg $N.ha^{-1}.yr^{-1}$ and 30 kg $N.ha^{-1}.yr^{-1}$. Similarly, the average annual symbiotic fixation on arable land represents 51.0 kg $N.ha^{-1}$ for the diversified system and 56.8 kg $N.ha^{-1}$ for the dairy system. These values are lower than those proposed by Billen et al., (2018, 2021) and Garnier et al. (2016) – 86.4 kg $N.ha^{-1}·yr^{-1}$, 81.3 kg $N.ha^{-1}·yr^{-1}$ and 121 kg $N.ha^{-1}.yr^{-1}$, respectively – due to the nature of the rotations modeled by these authors, where the amount of annual and multiannual legumes in the rotations are higher than in the two systems conducted. On the other hand, the fluxes linked to atmospheric deposition (13.7 kg $N.ha^{-1}.yr^{-1}$ for the diversified system and 15.8 kg $N.ha^{-1}$ for the dairy system) are similar to those of the authors cited above. These natural processes have rarely been taken into account in agrosystem studies based on ecological network analysis, even though they are central to nutrient transfers, especially in crop-livestock systems with low synthetic input use (Rufino et al., 2009a; b; Stark et al., 2016; Grillot et al., 2018a; Steinmetz et al., 2021). The calculation of nitrogen fixation by legumes seems to be essential to take into account in future studies. The relationship reported by Anglade et al. (2015) appears to be an interesting and robust proxy from this perspective (Herridge et al., 2022), insofar as their field of definition is concerned, in particular from the point of view of practices (organic and mineral fertilization). Indeed, taking into account fertilization and its consequences on symbiotic fixation could help to refine this relationship.

Table 2
Summary of indicators for the analysis of the dairy and diversified systems.

	Dairy system	Diversified system
Crop-livestock integration indicators		
Total system throughflows (TST – kg $N.ha^{-1}$)	291.7	213.8
Total internal throughflows (TT – kg $N.ha^{-1}$)	226.6	161.9
Internal circulation rate (ICR – %)	77.7	75.7
Average Mutual Information (AMI*)	1.22	1.35
Statistical Uncertainty (Hr*)	2.52	2.71
Realized uncertainty ($AMI.Hr^{-1}$ – %)	0.49	0.50
Biotechnical performance		
Ascendancy (A – kg $N.ha^{-1}$)	427	332
Overhead (Φ – kg $N.ha^{-1}$)	964	700
Development capacity (C – kg $N.ha^{-1}$)	1391	1032
Resilience (R*)	0.69	0.68
Productivity (P – kg $N.ha^{-1}$)	18.4	15.4
Nitrogen Use Efficiency (NUE – %)	34.0	53.2
$Losses.TST^{-1}$ (%)	14.0	10.2
Food efficiency indicators		
Food Conversion Efficiency (FCE – %)	29.6	32.7
Food Production Efficiency (FPE – %)	17.4	19.8

* indicators without units.

3.2. Internal metabolism

With respect to internal system activity (TT – Fig. 3), the activity generated is well distributed and similar between forage production (60% for the dairy system, 56% for the diversified system) and organic fertilization (40% in the dairy system, 44% the diversified system). Although few studies have been conducted to date on systems in temperate regions, the activity levels (TT and TST) observed in the dairy system and the diversified system are comparable to those found by Steinmetz et al. (2021), although they did not take into account atmospheric deposition and symbiotic fixation.

At a more detailed level, the distribution changed between the two systems (Fig. 3). On the one hand, with regard to the activity generated by fodder, the proportion of roughage in the conserved fodder was greater in the diversified system (87%) than in the dairy system (79%). This can be explained by the fact that ruminants were not fed concentrates in the diversified system but differed little in terms of the proportion of forage taken directly from pasture (66% and 65%, respectively). We also note that the dairy system has an overall surplus of fodder (production of conserved fodder 7% higher than requirements), whereas the diversified system has a deficit of approximately 10% and therefore had to draw on reserves acquired prior to the study period. One of the main reasons for this was the primary production deficit observed over the three years of the diversified system study (hay deficit). On the other hand, concerning the activity generated by livestock manure, there was a change in the manure recycling pattern: 64% of soil nutrient return occurred directly at pasture in the diversified system, compared to 59% in the dairy system. These differences can be explained by (i) the choice of fully free-range management of sheep and pigs and (ii) the choice of maximum grazing in the diversified system, inspired by the grazing management decisions for the dairy "grazing subsystem" (69% of direct nutrient return at pasture, compared to 54% in the "mixed crop-livestock subsystem").

Crop-livestock integration flows mainly correspond to non-food production. In the diversified system, none of the internal flows of fodder involve food crops, while in the dairy system, some of the annual crops (grain legumes, coarse grains such as barley, rye and triticale) are grown for cattle feed. Food production generates feed resources in both systems. Areas directly producing food crops (all annual crops in the diversified system, milling wheat in the dairy system) also produce feed in various ways: commercial crop sorting, straw, and fodder in the crop rotation (i) in grazed intercropping (sheep and pigs) and (ii) in the form of temporary grassland (grazed or mowed). The role of the animals in these systems, especially in the diversified one, is to make use of feed resources (including permanent grassland that cannot be used to grow food crops) to produce milk or meat, while their byproducts (manure), used to fertilize the cultivated areas, are one of the main factors in the production of food. The production of 1 kg N of food requires, directly or indirectly, 12 kg N of internal flows for the dairy system and 10 kg N of internal flows for the diversified system.

There is little difference between the two configurations in the way their nutrient flow networks are organized, even though the diversified system has a greater diversity of livestock. This can be explained by the fact that despite an increase in the number of productions, the flow network configuration is not fundamentally different, and the quantity of nutrients transiting through these new productions (sheep, pigs) is small compared to the total quantity of transiting nutrients.

The values of the indicators used to account for the configuration of the flow network ($AMI.Hr^{-1}$) correspond to intermediate situations ($AMI.Hr^{-1} = 0.5$); this indicator varies between 0 and 1. Indeed, the two systems are based on a large range of flows (Fig. 3), which connect all the components together. However, the amount of N is not equitably distributed among the flows, leading to an intermediate value of the realized uncertainty. Note that the values of the average mutual

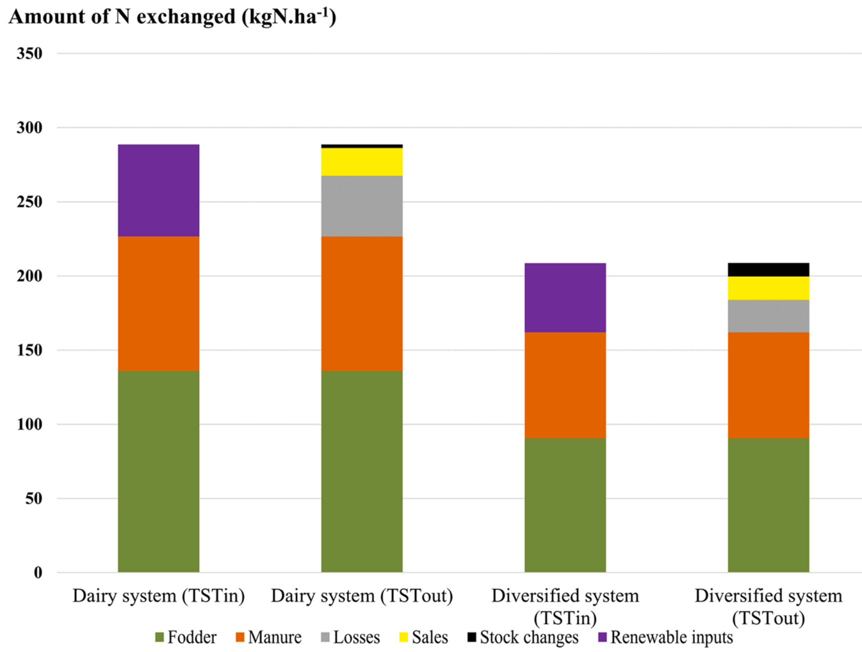

Fig. 3. Nature of the flows exchanged within dairy and diversified systems. For each system, we represent the sum of inflows (TST in) and outflows (TST out), according to their nature (crop-livestock integration, renewable inputs, outputs (food sales or losses) or stock variations).

information and the statistical uncertainty are slightly higher for the diversified system due to a higher number of components and flows, even if the total activity (TST) and crop-livestock integration (TT) are lower for this system.

If we compare these values with those obtained by Stark et al. (2018) on mixed crop-livestock systems in tropical environments, they are similar to the systems found in Cuba, with diversified flow networks of varying intensity. The question of the target value in terms of flow network organization remains unknown. Ecological approaches consider that more complex ecosystems are more stable and more sustainable. In the case of farming systems, the degree of optimal complexity, called the “vitality window”, remains to be defined both from a theoretical point of view and from empirical studies (Ulanowicz et al., 2009).

3.3. Productivity, efficiency and internal flow configuration

With respect to total productivity (which only includes sales of food and animals, as non-food products such as manure or fodder are not exported from the system), the productivity of the diversified system is lower (P = 15.4 kg N.ha^{-1}) than the productivity of the dairy system (P = 18.3 kg N.ha^{-1}). The percentage of animal protein exported was reduced from 74% for the dairy system to 57% for the diversified system, owing to the strategy of diversifying crops for human food, having fewer animals and keeping dairy cows (once-a-day milking).

The ascendancy suite indicators, which reflect the systems’ resilience levels, show a 35% greater development capacity (C) for the dairy system. These results are consistent with the fact that the dairy configuration has a greater flow intensity (TST) than the diversified configuration and consequently a higher level of development in terms of flow network activity. However, the resilience level is similar for the two systems ($\Phi.C^{-1} \approx 0.70$), meaning that the system’s current level of activity is covered mainly by redundant flows. These results are consistent with the fact that the two systems have similar flow network configurations (AMI.Hr^{-1}), which are supported by a consistent level of integration (ICR) and distributed among a wide range of flows. The results of this study support the hypothesis that more integrated farming systems are more resilient (Bonaudo et al., 2014). Even if the notion of resilience refers to a dynamic process (shock response), the notion of reserve capacity, as estimated by the ascendancy suite, brings interesting elements to qualify the resilience of an agrosystem, as is done in ecology. The capacity of a diversified farming system to substitute an input by another through internal flows is of interest for the development of sustainable and resilient farming systems.

With respect to nitrogen transformation efficiency, the diversified system is more efficient (NUE = 53%) than the dairy system (NUE = 34%). The diversified configuration is therefore more efficient at utilizing resources, especially at closing the N cycle (animal feed regimes). These results are consistent with the literature on mixed dairy systems, which shows that these systems are more efficient than specialized ones (Hristov et al., 2006; Powell et al., 2010; Godinot et al., 2014). The diversified system is among the most efficient systems (Godinot et al., 2014). Comparing the partial NUE of the dairy component, we find that the cattle herd is more nitrogen-efficient (cattle NUE = 89%) in the diversified system than in the dairy system (cattle NUE = 75%). From our point of view, (i) the increase in the levels of useful matter in milk and (ii) the decrease in the number of unproductive cows (elimination of the 24- to 36-month-old cohort of heifers linked to the 24-month-old calving of heifers reared under feeder cows; Puech and Brunet, 2020) largely compensate for the NUE decrease due to certain rearing practices in the diversified system (once a day milking, strict herbivory).

3.4. Food production efficiency

Fig. 4 shows that in both the dairy system and the diversified system configurations, the "system" FCE is greater than the FCE of the components taken alone. This result shows that harnessing functional complementarities between the components in mixed crop-livestock systems (e.g., recycling manure) increases the overall efficiency of the system. This increase is all the more important as the system is self-sufficient (importing few inputs such as animal feed and with the animal components playing an essential role in the food conversion efficiency of the system as a whole). On this point, the difference is even greater when the system utilizes components with a low or even zero FCE (permanent and temporary grasslands) or non-food byproducts of other components (sorting byproducts, straw, etc.).

At the system level, we show that the FCE of the diversified system is slightly higher than that of the dairy system (32.7% and 29.6%,

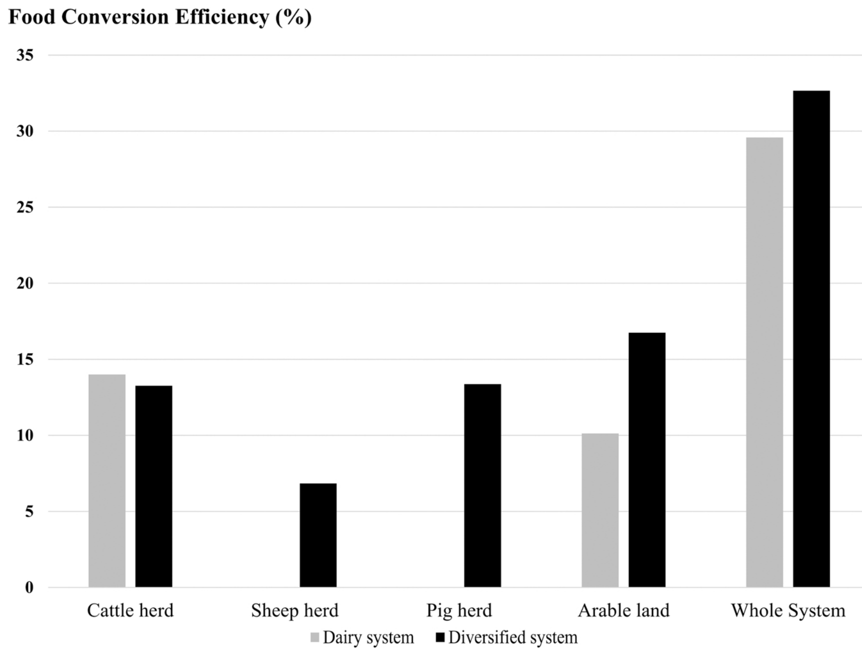

Fig. 4. Food Conversion Efficiency of the system and its components. Permanent grassland and storage component (effluent, fodder) do not produce food products, so the FCE of these components is zero for both systems; they are not shown in the figure.

respectively). These results reflect greater efficiency in utilizing the available resources. We also show that the diversified configuration generates less internal flows than the dairy configuration relative to its exported food products (10.3 and 12.1 kg N of internal N flows per kg of N exported, respectively). The reduction of these internal flows, 40% of which are related to livestock manure, reduces the sources of losses and the overall inefficiency of the system.

Regarding the animal components, the FCE of the cattle herd differs little between the two systems (14% for the dairy system, 13.3% for the diversified system – Fig. 4). In the same way as for NUE, the decrease in milk production (−35% of milk volume produced per cow due to the switch to once-a-day milking in the diversified system; see Table 1) is therefore largely compensated by (i) the greater efficiency of the strictly grass diet, (ii) a decrease in the number of unproductive cattle (21.6% versus 43.3% for the dairy system, mainly due to a decrease in the age at first calving) and (iii) an increase in the useful matter content of the milk (protein content of 35.7 $g.kg^{-1}$ versus 32.9 $g.kg^{-1}$ for the dairy system). The FCE of the pigs (13.4%) is equivalent to that of the cattle in the diversified system. In this system, the FCE of sheep (6.8%) is lower than that of cattle due to the nature of the production (the potential efficiency of dairy systems is higher than that of suckler systems – Godinot et al., 2015). Similarly, the FCE of sheep is lower than that of pigs due to the physiology of the animals (the potential efficiency of pig systems is higher than that of ruminant systems – Godinot et al., 2015). Finally, the FCE of arable land is greater for the diversified system than for the dairy system (16.8%, versus 10.1%). This difference is mainly due to a higher percentage of annual crops being exported for human food (89.6% of the grain produced in the diversified system was exported for human consumption vs. 47.2% in the dairy system). However, in both systems, the presence of temporary grasslands limits the FCE because these fields are also used for feed production.

As with FCE, we show that the FPE of the diversified configuration (19.8%) is greater than that of the dairy system (17.4%). This difference reflects a better efficiency in utilizing the system's primary production. FPE should be compared with the gross protein conversion efficiency indicator proposed by Laisse et al. (2019) for animal production. That study gave a value of 19% in a lowland grassland dairy system, similar to the values for our two dairy-dominant systems. However, using the indicator for human-consumable protein conversion efficiency (Laisse et al., 2019) to compare the two systems' use of agricultural land for food production, we show that the dairy system is a net resource producer, consistent with recent results for grazing systems (Lagel, 2016; Peyraud and Peeters, 2016; Steinwidder et al., 2016). This indicator is not theoretically calculable for the diversified system because, unlike the dairy system, it involves no competition between feed and food for land use. Indeed, on the one hand, 24% of arable land (44% of annual crops) is intended for human food in the dairy system, whereas 61% of arable land (whole annual crops) is intended for human food in the diversified system. On the other hand, animals are fed exclusively on non-food resources on the diversified system (ruminants that are strictly grass-fed, monogastrics that are fed on waste). More precisely,

- The food production byproducts downgraded for quality reasons (crop sorting rejects, milk with high cell counts, etc.) used in pig feed cannot be consumed by humans,
- Temporary grasslands have an essential role in crop rotations in maintaining soil fertility, carbon storage and weed control over the long term in organic farming systems (Schuster et al., 2020; Dominschek et al., 2021). The number of annual crops in the diversified system rotations is adapted to the potential of the plots, and temporary grasslands are replanted when experimenters consider the plots unsuitable for annual crops (low fertility, uncontrolled weeds). The crop rotation duration ranges from 6 years (including 3 years of crops) to 12 years (9 years of crops). Therefore, temporary grasslands cannot be entirely replaced by annual crops without recourse to inputs (organic or synthetic) to ensure soil fertility and to manage pests and weeds.
- Permanent grasslands cannot be plowed and sown owing to the very clayey nature of the soils, which are often shallow and hard to plow (the farmers call these soils "*terres à herbe*" or literally "grass soils"). Animals, and especially ruminants, play an essential role in utilizing certain resources, thereby ensuring to a large extent the fertility of the system by closing N cycles and consequently the self-sufficiency of the system.

3.5. Trade-off between biotechnical functioning and food production

3.5.1. Analyzing multiyear dynamics to highlight the role of reserve nutrient stocks in self-sufficient systems

In the preceding paragraphs, we have shown that part of the performance of the diversified system was acquired by harnessing resources set aside during a period prior to the study period (reduction in fodder stocks). In other words, performance is built on multiyear time steps: If there had been no fodder stocks, the number of animals would have been significantly reduced to match needs to available resources. This would have resulted in a reduction in food production (milk in particular) and, more generally, in the metabolism and performance of the system. Consequently, we posit that in self-sufficient systems, which are particularly dependent on environmental conditions for their metabolism, nutrient storage (fodder) is a major regulatory lever for limiting the impacts of environmental variability on the functioning and performance of the system (Aubron et al., 2010; Fiorelli et al., 2018). This regulatory lever is all the more important since (i) the components of diversified systems rely on various different operating cycles ranging from a few months to several years (depending on the nature of the productions) (Manoli, 2012; Sabatier et al., 2017) and (ii) their respective inertia makes it impossible to estimate the variability of the environmental conditions, especially as this variability is expressed both on an annual scale (marked seasons) and on a multiannual scale, given the variabilities linked to current and future global climate change (Arias et al., 2021). We therefore propose to extend this work with a dynamic study to analyze the transitions of agrosystems to highlight (i) the key role of storage components in the inter- and intra-annual regulation of diversified systems (Grillot et al., 2018b) and (ii) the logic of the step-by-step design of such complex systems (Coquil et al., 2014). In this connection, the wide variations observed in recent years (wet years in 2016 and 2021 not covered in this study, dry years in 2018–2020) constitute original situations to be explored. Multiannual farm-scale experiments conducted on experimental farms (their associated weather stations and information systems) are exceptional opportunities for exploring these temporal dynamics, which are difficult to access through surveys of commercial farms (generally represented by 'average' functioning due to the lack of reliable multiannual information) (Rufino et al., 2009b; Stark et al., 2018; Steinmetz et al., 2021). The analysis of the system and its adaptations to contrasting production situations (especially meteorological) will also make it possible to discuss the results presented in this article (which are based on a limited number of years for the diversified configuration).

3.5.2. Analyzing trade-offs between the productivity, efficiency and resilience of agrosystems

The two agrosystems studied in this article were designed with a view to self-sufficiency and cycle closure. We show that the dairy system is more productive than a diversified system (per unit area or per livestock unit) but less efficient in terms of resource use, particularly through better cycle closure. However, the three years of the diversified system studied show a primary production deficit linked to marked water deficits in the summer period. Ulanowicz et al. (2009) show, in the context of ecosystems studied with ENA, the existence of trade-offs between efficient pathways and redundant ones expressed in the form of a range (known as the "vitality window") within viable ecosystems (Fath et al., 2019). Furthermore, Ulukan et al. (2022) show the existence of optimal trade-offs between productivity and self-sufficiency in livestock systems. They suggest that these trade-offs are factors of resource use efficiency (especially efficiency in N input use). In line with this research, our results suggest that in a situation of limited resources, self-sufficient crop livestock systems are more efficient to the detriment of productivity. Conversely, where resources are less limited, we can suppose that these systems are more productive to the detriment of efficiency (reserves can serve to regulate some resources and transfer nutrients across time). Analysis of the multiannual dynamics of contrasting situations (particularly with regard to environmental potential and primary production) should make it possible to analyze the trade-offs between these emerging properties (productivity, efficiency, redundancy, and self-sufficiency; see Bonaudo et al., 2014) in diversified systems (Sabatier and Mouysset, 2018).

Ecologists, especially those who have developed ecological network analysis approaches, study ecosystems in terms of carbon and energy flows (Ulanowicz et al., 2009; Fath et al., 2019). Few studies have compared different nutrients. However, we can cite the work of Ulanowicz and Baird (1999), which highlights differences in dynamics between carbon cycling and nitrogen cycling in mesohaline ecosystems. Moreover, agronomists and livestock scientists are very keen to analyze agrosystems in terms of nitrogen flows (Rufino et al., 2009a; Stark et al., 2016; Grillot et al., 2018b; Steinmetz et al., 2021), especially since nitrogen is the main limiting factor in agricultural systems that make little use of synthetic inputs (organic farming, systems in tropical countries; Giller et al., 1997; Barbieri et al., 2021). To our knowledge, few studies analyzing the ecological networks of agrosystems have focused on energy flows (Bénagabou et al., 2017) or nutrients other than nitrogen (Fanjaniaina et al., 2022). Taking into account several types of nutrients, as well as energy, could enrich this type of approach and better respond to challenges according to specific limiting pedoclimatic and socioeconomic conditions.

We suggest continuing this work by studying the trade-offs to be found (i) in the use of nutrient or energy flows and (ii) between productivity, efficiency and resilience. In this respect, ecological network analysis is a useful approach and should be further developed, for example, with regard to food production (indicators proposed in this article) or soil organic matter storage (in relation to fertility maintenance or carbon sequestration in the context of climate change).

4. Conclusion

It is useful to study diversified agricultural systems integrating crops and livestock to produce knowledge in support of agricultural and food transitions. We assumed that metabolic analysis, along with additional methods, would be suitable for studying these complex systems and assessing their capacity to produce food with little use of nonrenewable resources. Based on the study of nitrogen flows in two asynchronously managed agrosystems, we show that for both systems studied, 'system' efficiency is greater than the efficiency of the individual components. Our results show (i) that crop-livestock integration is a key factor in some emergent properties of these systems and (ii) that to understand how performance is constructed, it is useful to couple a whole-system approach with investigation of each component. Farm-scale experiments (and data chronicles produced) are an essential tool for analyzing how the system's performance is constructed. We also suggest that environmental conditions are a first-order factor in the performance of self-sufficient agrosystems (symbiotic fixation) and that fodder storage capacity is a key factor in the pluriannual regulation of such systems as a measure against the hazards of weather and climate (primary production). Finally, we show that the system prioritizing the use of land for food production was less productive but more efficient in terms of resource use. We thus broaden the notion of biotechnical efficiency in an agricultural system by proposing indicators of food conversion efficiency and food production efficiency.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

A permanent data access link is included in the article.

Acknowledgments

The authors thank the anonymous reviewers for the quality of their review and suggestions on an earlier version of this manuscript. The authors also thank the technical team on the ASTER experimental farm for their commitment in managing the system (crops and livestock) and the quality of the data collected.

References

Alomia-Hinojosa, V., Groot, J.C.J., Speelman, E.N., Bettinelli, C., McDonald, A.J., Alvarez, S., Tittonell, P., 2020. Operationalizing the concept of robustness of nitrogen networks in mixed smallholder systems: A pilot study in the mid-hills and lowlands of Nepal. Ecol. Indic. 110, 105883 https://doi.org/10.1016/j.ecolind.2019.105883.

Altieri, M.A., Funes-Monzote, F.R., Petersen, P., 2012. Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron. Sustain. Dev. 32, 1–13. https://doi.org/10.1007/s13593-011-0065-6.

Anglade, J., 2015. Agriculture biologique et qualité des ressources en eau dans le bassin de la Seine: caractérisation des pratiques et applications territorialisées. Pierre Et. Marie Curie 303 (Paris).

Anglade, J., Billen, G., Garnier, J., 2015. Relationships for estimating N2 fixation in legumes: incidence for N balance of legume-based cropping systems in Europe. Ecosphere 6, 37. https://doi.org/10.1890/ES14-00353.1.

Arias, P.A., Bellouin, N., Coppola, E., Jones, R.G., Krinner, G., Marotzke, J., Naik, V., Palmer, M.D., Plattner, G.-K., Rogelj, J., Rojas, M., Sillmann, J., Storelvmo, T., Thorne, P.W., B. Trewin, K., et al., 2021. Technical Summary. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press,, Cambridge, United Kingdom and New York, NY, USA, pp. 33–144. https://doi.org/10.1017/9781009157896.002.

Aubron, C., Lurette, A., Moulin, C.-H., 2010. Simulation des conséquences économiques de différentes stratégies fourragères avec foin face aux aléas climatiques en élevage bovin laitier. Rencontres Autour Des. Rech. Sur Les. Rumin. 5 (Paris).

Barbier, J.-M., López Ridaura, S., 2010. Evaluation de la durabilité des systèmes de production agricoles: limites des démarches normatives et voies d'amélioration possibles. Presente Innov. Sustain. Dev. Agric. Food 10 (Montpellier).

Barbieri, P., Pellerin, S., Seufert, V., Smith, L., Ramankutty, N., Nesme, T., 2021. Global option space for organic agriculture is delimited by nitrogen availability. Nat. Food 2, 363–372. https://doi.org/10.1038/s43016-021-00276-y.

Barbieri, P., Dumont, B., Benoit, M., Nesme, T., 2022. Opinion paper: Livestock is at the heart of interacting levers to reduce feed-food competition in agroecological food systems. Animal 16, 100436. https://doi.org/10.1016/j.animal.2021.100436.

Bénagabou, O.I., Blanchard, M., Bougouma Yaméogo, V.M.C., Vayssières, J., Vigne, M., Vall, E., Lecomte, P., Nacro, H.B., 2017. L'intégration agriculture-élevage améliore-t-elle l'efficience, le recyclage et l'autonomie énergétique brute des exploitations familiales mixtes au Burkina Faso ? Rev. Elev. Med. Vet. Pays Trop. 70, 31. https://doi.org/10.19182/remvt.31479.

Billen, G., Lassaletta, L., Garnier, J., 2014. A biogeochemical view of the global agro-food system: Nitrogen flows associated with protein production, consumption and trade. Glob. Food Sect. 3, 209–219. https://doi.org/10.1016/j.gfs.2014.08.003.

Billen, G., Le Noë, J., Garnier, J., 2018. Two contrasted future scenarios for the French agro-food system. Sci. Total Environ. 637–638, 695–705. https://doi.org/10.1016/j.scitotenv.2018.05.043.

Billen, G., Aguilera, E., Einarsson, R., Garnier, J., Gingrich, S., Grizzetti, B., Lassaletta, L., Le Noë, J., Sanz-Cobena, A., 2021. Reshaping the European agro-food system and closing its nitrogen cycle: The potential of combining dietary change, agroecology, and circularity. One Earth 4, 839–850. https://doi.org/10.1016/j.oneear.2021.05.008.

Binder, C.R., Feola, G., Steinberger, J.K., 2010. Considering the normative, systemic and procedural dimensions in indicator-based sustainability assessments in agriculture. Environ. Impact Assess. Rev. 30, 71–81. https://doi.org/10.1016/j.eiar.2009.06.002.

Bonaudo, T., Bendahan, A.B., Sabatier, R., Ryschawy, J., Bellon, S., Leger, F., Magda, D., Tichit, M., 2014. Agroecological principles for the redesign of integrated crop–livestock systems. Eur. J. Agron. 57, 43–51. https://doi.org/10.1016/j.eja.2013.09.010.

Cabell, J.F., Oelofse, M., 2012. An indicator framework for assessing agroecosystem resilience. Ecol. Soc. 17 (1), 18. https://doi.org/10.5751/ES-04666-170118.

Congreves, K.A., Otchere, O., Ferland, D., Farzadfar, S., Williams, S., Arcand, M.M., 2021. Nitrogen use efficiency definitions of today and tomorrow. Front. Plant Sci. 12, 637108 https://doi.org/10.3389/fpls.2021.637108.

Coquil, X., Fiorelli, J.L., Blouet, A., Mignolet, C., 2014. Experiencing organic mixed crop dairy systems: a step-by-step design centred on a long-term experiment. Org. Farming, Prototype Sustain. Agric., S. Bello, S. Penvern. Ed. Springe 489, 201–217 (p., Germany).

Coquil, X., Anglade, J., Barataud, F., Brunet, L., Durpoix, A., Godfroy, M., 2019. TEASER-lab: concevoir un territoire pour une alimentation saine, localisée et créatrice d'emplois à partir de la polyculture - polyélevage autonome et économe. La Diversif. Des. Prod. sur Le. Dispos. expérimental ASTER-Mirecourt. Innov. Agron. 72, 61–75.

Couturier, C., Charru, M., Doublet, S., Pointereau, P., 2016. Afterres 2050. Solagro Toulouse 96.

Dardonville, M., Urruty, N., Bockstaller, C., Therond, O., 2020. Influence of diversity and intensification level on vulnerability, resilience and robustness of agricultural systems. Agr. Syst. 184, 102913 https://doi.org/10.1016/j.agsy.2020.102913.

Darnhofer, I., Bellon, S., Dedieu, B., Milestad, R., 2010. Adaptiveness to enhance the sustainability of farming systems. A review. Agron. Sustain. Dev. 30, 545–555. https://doi.org/10.1051/agro/2009053.

Debaeke, P., Munier-Jolain, N., Bertrand, M., Guichard, L., Nolot, J.-M., Faloya, V., Saulas, P., 2009. Iterative design and evaluation of rule-based cropping systems: methodology and case studies. A review. Agron. Sustain. Dev. 29, 73–86. https://doi.org/10.1051/agro:2008050.

Dominschek, R., Barroso, A.A.M., Lang, C.R., de Moraes, A., Sulc, R.M., Schuster, M.Z., 2021. Crop rotations with temporary grassland shifts weed patterns and allows herbicide-free management without crop yield loss. J. Clean. Prod. 306, 127140 https://doi.org/10.1016/j.jclepro.2021.127140.

Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M.-A., Justes, E., Journet, E.-P., Aubertot, J.-N., Savary, S., Bergez, J.-E., Sarthou, J.P., 2015. How to implement biodiversity-based agriculture to enhance ecosystem services: a review. Agron. Sustain. Dev. 35, 1259–1281. https://doi.org/10.1007/s13593-015-0306-1.

Erisman, J., Leach, A., Bleeker, A., Atwell, B., Cattaneo, L., Galloway, J., 2018. An Integrated Approach to a Nitrogen Use Efficiency (NUE) Indicator for the Food Production–Consumption Chain. Sustainability 10, 925. https://doi.org/10.3390/su10040925.

Fanjaniaina, M.L., Stark, F., Ramarovahoaka, N.P., Rakotoharinaivo, J.F., Rafolisy, T., Salgado, P., Becquer, T., 2022. Nutrient Flows and Balances in Mixed Farming Systems in Madagascar. Sustainability 14, 984. https://doi.org/10.3390/su14020984.

Fath, B.D., Asmus, H., Asmus, R., Baird, D., Borrett, S.R., de Jonge, V.N., Ludovisi, A., Niquil, N., Scharler, U.M., Schückel, U., Wolff, M., 2019. Ecological network analysis metrics: The need for an entire ecosystem approach in management and policy. Ocean Coast. Manag. 174, 1–14. https://doi.org/10.1016/j.ocecoaman.2019.03.007.

Fernandez-Mena, H., Nesme, T., Pellerin, S., 2016. Towards an Agro-Industrial Ecology: A review of nutrient flow modelling and assessment tools in agro-food systems at the local scale. Sci. Total Environ. 543, 467–479. https://doi.org/10.1016/j.scitotenv.2015.11.032.

Finn, J.T., 1980. Flow Analysis of Models of the Hubbard Brook Ecosystem. Ecol 61, 562–571. https://doi.org/10.2307/1937422.

Fiorelli, J.-L., Trommenschlager, J.-M., Lavé, R., Echampard, L., Godfroy, M., Bazard, C., 2018. Interactions cultures - élevage et autonomie alimentaire d'un troupeau laitier en agriculture biologique. Fourrages 235, 169–173.

Gabriel, A.W., Madelrieux, S., Lescoat, P., 2020. A review of socio-economic metabolism representations and their links to action: Cases in agri-food studies. Ecol. Econ. 178, 106765 https://doi.org/10.1016/j.ecolecon.2020.106765.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J., Godfray, H.C.J., 2013. Sustainable Intensification in Agriculture: Premises and Policies. Sci 341, 33–34. https://doi.org/10.1126/science.1234485.

Garnier, J., Anglade, J., Benoit, M., Billen, G., Puech, T., Ramarson, A., Passy, P., Silvestre, M., Lassaletta, L., Trommenschlager, J.-M., Schott, C., Tallec, G., 2016. Reconnecting crop and cattle farming to reduce nitrogen losses to river water of an intensive agricultural catchment (Seine basin, France): past, present and future. Environ. Sci. Pol. 63, 76–90. https://doi.org/10.1016/j.envsci.2016.04.019.

Giller, K.E., Beare, M.H., Lavelle, P., Izac, A.-M.N., Swift, M.J., 1997. Agricultural intensification, soil biodiversity and agroecosystem function. Appl. Soil Ecol. 6, 3–16. https://doi.org/10.1016/S0929-1393(96)00149-7.

Giovanni, R., Dulphy, J.-P., 2008. Présentation de références Corpen simplifiées pour l'évaluation des rejets et des pressions d'azote et de phosphore des troupeaux bovins. Fourrages 195, 357–372.

Gliessman, S.R., 2004. Agroecology and agroecosystems. In: Diane, R., Francis, C. (Eds.), Agronomy Monographs. American Society of Agronomy, Crop Science Society of America. Soil Science Society of America, Madison, WI, USA, pp. 19–29. https://doi.org/10.2134/agronmonogr43.c2.

Godinot, O., Carof, M., Vertès, F., Leterme, P., 2014. SyNE: An improved indicator to assess nitrogen efficiency of farming systems. Agr. Syst. 127, 41–52. https://doi.org/10.1016/j.agsy.2014.01.003.

Godinot, O., Leterme, P., Vertès, F., Faverdin, P., Carof, M., 2015. Relative nitrogen efficiency, a new indicator to assess crop livestock farming systems. Agron. Sustain. Dev. 35, 857–868. https://doi.org/10.1007/s13593-015-0281-6.

Godinot, O., Vertès, F., Leterne, P., Carof, M., 2020. Nouveaux indicateurs d'efficience de l'azote à l'échelle de l'exploitation. Fourrages 241, 45–56.

Grillot, M., Vayssières, J., Masse, D., 2018a. Agent-based modelling as a time machine to assess nutrient cycling reorganization during past agrarian transitions in West Africa. Agr. Syst. 164, 133–151. https://doi.org/10.1016/j.agsy.2018.04.008.

Grillot, M., Vayssières, J., Guerrin, F., Lecomte, P., 2018b. Modélisation conceptuelle de la gestion adaptative de la biomasse face à l'aléa climatique en systèmes agro-sylvopastoraux. Cah. Agric. 27, 55004. https://doi.org/10.1051/cagri/2018034.

Herridge, D.F., Giller, K.E., Jensen, E.S., Peoples, M.B., 2022. Quantifying country-to-global scale nitrogen fixation for grain legumes II. Coefficients, templates and estimates for soybean, groundnut and pulses. Plant Soil 474, 1–15. https://doi.org/10.1007/s11104-021-05166-7.

Hristov, A.N., Hazen, W., Ellsworth, J.W., 2006. Efficiency of Use of Imported Nitrogen, Phosphorus, and Potassiumand Potential for Reducing Phosphorus Imports on Idaho Dairy Farms. J. Dairy Sci. 89, 3702–3712.

Jepsen, M.R., Kuemmerle, T., Müller, D., Erb, K., Verburg, P.H., Haberl, H., Vesterager, J. P., Andrič, M., Antrop, M., Austrheim, G., Björn, I., Bondeau, A., Bürgi, M., Bryson, J., Caspar, G., Cassar, L.F., Conrad, E., Chromý, P., Daugirdas, V., Van Eetvelde, V., Elena-Rosselló, R., Gimmi, U., Izakovicova, Z., Jančák, V., Jansson, U., Kladnik, D., Kozak, J., Konkoly-Gyuró, E., Krausmann, F., Mander, Ü., McDonagh, J., Pärn, J., Niedertscheider, M., Nikodemus, O., Ostapowicz, K., Pérez-Soba, M., Pinto-Correia, T., Ribokas, G., Rounsevell, M., Schistou, D., Schmit, C., Terkenli, T.S., Tretvik, A.M., Trzepacz, P., Vadineanu, A., Walz, A., Zhllima, E., Reenberg, A., 2015. Transitions in European land-management regimes between 1800 and 2010. Land Use Policy 49, 53–64. https://doi.org/10.1016/j.landusepol.2015.07.003.

Kim, E., Arnoux, M., Chatzimpiros, P., 2018. Agri-food-energy system metabolism: a historical study for northern France, from nineteenth to twenty-first centuries. Reg. Environ. Chang. 18, 1009–1019. https://doi.org/10.1007/s10113-017-1119-3.

Kremen, C., Iles, A., Bacon, C., 2012. Diversified Farming Systems: An Agroecological, Systems-based Alternative to Modern Industrial Agriculture. Ecol. Soc. 17, 44. https://doi.org/10.5751/ES-05103-170444.

Lagel, A., 2016, Contribution de l'élevage bovin laitier à l'approvisionnement protéique pour l'être humain. Mémoire de fin d'études AgroSup Dijon-Idele, Dijon, France.

Laisse, S., Baumont, R., Dusart, L., Gaudré, D., Rouillé, B., Benoit, M., Veysset, P., Rémond, D., Peyraud, J.-L., 2019. L'efficience nette de conversion des aliments par les animaux d'élevage: une nouvelle approche pour évaluer la contribution de l'élevage à l'alimentation humaine. INRA Prod. Anim. 31, 269–288. https://doi.org/10.20870/productions-animales.2018.31.3.2355.

Latham, L.G., 2006. Network flow analysis algorithms. Ecol. Model. 192, 586–600. https://doi.org/10.1016/j.ecolmodel.2005.07.029.

Le Roux, X., Barbault, R., Baudry, J., Burel, F., Doussan, I., Garnier, E., Herzog, F., Lavorel, S., Lifran, R., Roger-Estrade, J., Sarthou, J.-P., Trommetter, M., 2008, Agriculture et biodiversité. Valoriser les synergies (Expertise scientifique collective INRA).

Lin, B.B., 2011. Resilience in agriculture through crop diversification: adaptive management for environmental change. BioScience 61, 183–193. https://doi.org/10.1525/bio.2011.61.3.4.

López-ridaura, S., Keulen, H.Van, Ittersum, M.K. van, Leffelaar, P.A., 2005. Multiscale methodological framework to derive criteria and indicators for sustainability evaluation of peasant natural resource management systems. Environ. Dev. Sust. 7, 51–69. https://doi.org/10.1007/s10668-003-6976-x.

Manoli, Cl, 2012. Le troupeau et les moyens de sécurisation des campements pastoraux. Ecole doctorale SIBAGHE. Montpellier 247.

Meuwissen, M.P.M., Feindt, P.H., Spiegel, A., Termeer, C.J.A.M., Mathijs, E., Mey, Y., de, Finger, R., Balmann, A., Wauters, E., Urquhart, J., Vigani, M., Zawalińska, K., Herrera, H., Nicholas-Davies, P., Hansson, H., Paas, W., Slijper, T., Coopmans, I., Vroege, W., Ciechomska, A., Accatino, F., Kopainsky, B., Poortvliet, P.M., Candel, J. J.L., Maye, D., Severini, S., Senni, S., Soriano, B., Lagerkvist, C.-J., Peneva, M., Gavrilescu, C., Reidsma, P., 2019. A framework to assess the resilience of farming systems. Agr. Syst. 176, 102656 https://doi.org/10.1016/j.agsy.2019.102656.

Morais, T.G., Teixeira, R.F.M., Lauk, C., Theurl, M.C., Winiwarter, W., Mayer, A., Kaufmann, L., Haberl, H., Domingos, T., Erb, K.-H., 2021. Agroecological measures and circular economy strategies to ensure sufficient nitrogen for sustainable farming. Glob. Environ. Chang 69, 102313. https://doi.org/10.1016/j.gloenvcha.2021.102313.

Peyraud, J.L., Peeters, A., 2016. The role of grassland based production system in the protein security. In: Proc. 26th Gen. Meet. Europ. Grassland Fed. Norway, pp. 29–43.

Peyraud, J.-L., Cellier, P., Aarts, F., Béline, F., Bockstaller, C., Bourblanc, M., Delaby, L., Donnars, C., Dourmad, J.Y., Dupraz, P., Durand, P., Faverdin, P., Fiorelli, J.-L., Gaigné, C., Girard, A., Guillaume, G., Kuikman, P., Langlais, A., Le Goffe, P., Le Perchec, S., Lescoat, P., Morvan, T., Nicourt, C., Parnaudeau, V., Peyraud, J.-L., Réchauchère, O., Rochette, P., Vertes, F., Veysset, P., 2012. Les flux d'azote liés aux élevages, réduire les pertes, rétablir les équilibres (Expertise scientifique collective).

Poux, X., Aubert, P.-M., 2018. Une Europe agroécologique en 2050: une agriculture multifonctionnelle pour une alimentation saine. Study. Iddri-AScA 9, 78.

Powell, J.M., Gourley, C.J.P., Rotz, C.A., Weaver, D.M., 2010. Nitrogen use efficiency: A potential performance indicator and policy tool for dairy farms. Environ. Sci. Policy 13, 217–228. https://doi.org/10.1016/j.envsci.2010.03.007.

Puech, T.. Modélisation matricielle de la structure et du fonctionnement des systèmes expérimentés sur l'IE ASTER Mirecourt. https://doi.org/10.15454/37TVKP.

Puech, T., Brunet, L., 2020. Valorisation des ressources fourragères d'un système de polyculture-polyélevage autonome: premiers éléments du dispositif biologique INRAE de Mirecourt. Journ. AFPF – Produire Des. Fourrag. Demain 2 (Paris).

Puech, T., Py, V., Durpoix, A., 2021. Elever des porcs pour valoriser des fourrages et des productions non commercialisables en alimentation humaine dans un système agricole diversifié et autonome: performances zootechniques et points critiques. Fourrages 248, 35–46.

Rufino, M.C., Hengsdijk, H., Verhagen, A., 2009a. Analysing integration and diversity in agro-ecosystems by using indicators of network analysis. Nutr. Cycl. Agroecosyst. 84, 229–247. https://doi.org/10.1007/s10705-008-9239-2.

Rufino, M.C., Tittonell, P., Reidsma, P., López-Ridaura, S., Hengsdijk, H., Giller, K.E., Verhagen, A., 2009b. Network analysis of N flows and food self-sufficiency—a comparative study of crop-livestock systems of the highlands of East and southern Africa. Nutr. Cycl. Agroecosyst. 85, 169–186. https://doi.org/10.1007/s10705-009-9256-9.

Rutledge, R.W., Basore, B.L., Mulholland, R.J., 1976. Ecological stability: An information theory viewpoint. J. Theor. Biol. 57, 355–371. https://doi.org/10.1016/0022-5193(76)90007-2.

Sabatier, R., Mouysset, L., 2018. A robustness-based viewpoint on the production-ecology trade-off in agroecosystems. Agr. Syst. 167, 1–9. https://doi.org/10.1016/j.agsy.2018.08.001.

Sabatier, R., Joly, F., Hubert, B., 2017. Assessing both ecological and engineering resilience of a steppe agroecosystem using the viability theory. Agr. Syst. 157, 146–156. https://doi.org/10.1016/j.agsy.2017.07.009.

Sauvant, D., Tran, G., Heuzé, V., Bastianelli, D., Archimède, H., 2013, Feedipedia: une encyclopédie mondiale des ressources alimentaires pour les animaux d'élevage. Presented at the 5st Journées d'Animation Scientifique Du Département Phase (JASPhase 2013), Paris (France).

Schröder, J.J., Aarts, H.F.M., ten Berge, H.F.M., van Keulen, H., Neeteson, J.J., 2003. An evaluation of whole-farm nitrogen balances and related indices for efficient nitrogen use. Eur. J. Agron. 20, 33–44. https://doi.org/10.1016/S1161-0301(03)00070-4.

Schuster, M.Z., Gastal, F., Doisy, D., Charrier, X., de Moraes, A., Médiène, S., Barbu, C.M., 2020. Weed regulation by crop and grassland competition: critical biomass level and persistence rate. Eur. J. Agron. 113, 125963 https://doi.org/10.1016/j.eja.2019.125963.

Sijpestijn, G.F., Wezel, A., Chriki, S., 2022. Can Agroecology Help in Meeting our 2050 Protein Requirements ? Livest. Sci., 104822 https://doi.org/10.1016/j.livsci.2022.104822.

Stark, F., Fanchone, A., Semjen, I., Moulin, C.-H., Archimède, H., 2016. Crop-livestock integration, from single practice to global functioning in the tropics: Case studies in Guadeloupe. Eur. J. Agron. 80, 9–20. https://doi.org/10.1016/j.eja.2016.06.004.

Stark, F., González-García, E., Navegantes, L., Miranda, T., Poccard-Chapuis, R., Archimède, H., Moulin, C.-H., 2018. Crop-livestock integration determines the agroecological performance of mixed farming systems in Latino-Caribbean farms. Agron. Sustain. Dev. 38, 4. https://doi.org/10.1007/s13593-017-0479-x.

Steinmetz, L., Veysset, P., Benoit, M., Dumont, B., 2021. Ecological network analysis to link interactions between system components and performances in multispecies livestock farms. Agron. Sustain. Dev. 41, 42. https://doi.org/10.1007/s13593-021-00696-x.

Steinwidder, A., Wolfthaler, J., Frey, H.J., Hofstetter, P., Gazzarin, C., Kirchweger, S., Kantelhardt, J., 2016. Stall- und weidebasierte Milchproduktionssysteme – Analysen zur Netto-Lebensmittelproduktion sowie zur Wirtschaftlichkeit. Österreichische Fachtag. für Biol. Landwirtsch. 31–36.

Tedesco, C., Petit, C., Billen, G., Garnier, J., Personne, E., 2017. Potential for recoupling production and consumption in peri-urban territories: The case-study of the Saclay plateau near Paris, France. Food Pol. 69, 35–45. https://doi.org/10.1016/j.foodpol.2017.03.006.

Therond, O., Duru, M., Roger-Estrade, J., Richard, G., 2017. A new analytical framework of farming system and agriculture model diversities. A review. Agron. Sustain. Dev. 37. https://doi.org/10.1007/s13593-017-0429-7.

Tomich, T.P., Brodt, S., Ferris, H., Galt, R., Horwath, W.R., Kebreab, E., Leveau, J.H.J., Liptzin, D., Lubell, M., Merel, P., Michelmore, R., Rosenstock, T., Scow, K., Six, J., Williams, N., Yang, L., 2011. Agroecology: A Review from a Global-Change Perspective. Annu. Rev. Environ. Resour. 36, 193–222. https://doi.org/10.1146/annurev-environ-012110-121302.

Trommenschlager, J.-M., Gaujour, E., Fontana, E., Harmand, M., Foissy, D., Huguet, J., Bazard, C., 2010. Gérer et organiser les données agricoles et de recherche d'un site expérimental. Cahier des Techniques de l'INRA. INRA 69, 5–27.

Trommenschlager, J.-M., Gaujour, E., 2010, ASTER-ix: Application pour la Saisie et le Traitement des Évènements Recensés sur l'Installation eXpérimentale (Version 2). IDDN.FR.001.130016.000R.P.2010.000.10300.

Ulanowicz, R.E., Baird, D., 1999. Nutrient controls on ecosystem dynamics: the Chesapeake mesohaline community. J. Mar. Syst. 19 (19), 159–172.

Ulanowicz, R.E., Goerner, S.J., Lietaer, B., Gomez, R., 2009. Quantifying sustainability: Resilience, efficiency and the return of information theory. Ecol. Complex. 6, 27–36. https://doi.org/10.1016/j.ecocom.2008.10.005.

Ulukan, D., Grillot, M., Benoit, M., Bernes, G., Dumont, B., Magne, M.-A., Monteiro, L., Parsons, D., Veysset, P., Ryschawy, J., Steinmetz, L., Martin, G., 2022. Positive deviant strategies implemented by organic multi-species livestock farms in Europe. Agr. Syst. 201, 103453 https://doi.org/10.1016/j.agsy.2022.103453.

Urruty, N., Tailliez-Lefebvre, D., Huyghe, C., 2016. Stability, robustness, vulnerability and resilience of agricultural systems. A review. Agron. Sustain. Dev. 36, 15. https://doi.org/10.1007/s13593-015-0347-5.

Verger, Y., Petit, C., Barles, S., Billen, G., Garnier, J., Esculier, F., Maugis, P., 2018. A N, P, C, and water flows metabolism study in a peri-urban territory in France: The case-study of the Saclay plateau. Resour. Conserv. Recycl. 137, 200–213. https://doi.org/10.1016/j.resconrec.2018.06.007.

Watson, C.A., Atkinson, D., 1999. Using nitrogen budgets to indicate nitrogen use efficiency and losses from whole farm systems: a comparison of three methodological approaches. Nutr. Cycl. Agroecosyst 53, 259–267. https://doi.org/10.1023/A:1009793120577.

WCED, 1987. Our Common Future. Report of the World Commission on Environment and Development. (Brundtland Report). Oxford University Press,, New York.

Zahm, F., Alonso Ugaglia, A., Barbier, J.-M., Boureau, H., Del'homme, B., Gafsi, M., Gasselin, P., Girard, S., Guichard, L., Loyce, C., Manneville, V., Menet, A., Redlingshöfer, B., 2019. Évaluer la durabilité des exploitations agricoles. La méthode IDEA v4, un cadre conceptuel combinant dimensions et propriétés de la durabilité. Cah. Agric. 28, 5. https://doi.org/10.1051/cagri/2019004.