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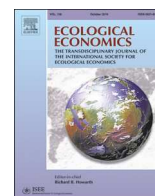
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Methodological and Ideological Options

SYNERGY: A regional bio-economic model analyzing farm-to-farm exchanges and legume production to enhance agricultural sustainability

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ABSTRACT

Agricultural specialization has disconnected crop and livestock production in many farms and regions. As a result, crop farms are deficient in nitrogen to fertilize their crops, while livestock farms are deficient in proteins to feed their animals. The increased consumption of nitrogen rich input raised economics and environmental questions. In this study, we tested two mechanisms to reconnect crop and livestock production: increasing legume production and developing farm-to-farm exchanges of crops and manure. To do so, we developed the SYNERGY bio-economic model, which represents specialized farm types in a region and models exchanges between them. Applied to western France, it analyzes economic, technical and environmental impacts.

When the legume share reached 10% of the region's area, legume production increased more on crop farms than on livestock farms and its use in feed was still limited. When farms could export more manure, legume production increased but N losses increased due to an intensification of pig production. This rebound effect offset the environmental benefits linked to the decrease in synthetic N fertilizers use. When local crop exchanges were possible, they remained limited and did not affect indicators. Thus, the two levers studied are insufficient to improve sustainability, mainly because of high livestock production.

1. Introduction

Over the past 50 years, European farms have increased in specialization and decreased in number due to an increase in productivity sustained by technological innovation, genetic improvement and low cost of chemical inputs. This specialization has disconnected crop and livestock production in many farms and regions (Naylor et al., 2005). As a result, specialized crop farms are deficient in nitrogen (N) to fertilize their crops, while specialized livestock farms are deficient in proteins to feed their animals. Therefore, specialized farms have become more dependent on purchases of N inputs such as synthetic N fertilizers on crop farms and N-rich feed (e.g., soybean meal) on livestock farms. This deficit in N-rich feed reaches 55% in the European Union (EU), while the consumption of synthetic N fertilizers reaches 59 kg N.ha⁻¹ on average (European Commission, 2019; Eurostat, 2011). This situation may raise questions about security of supply (Gale et al., 2014), imported deforestation (Pendrill et al., 2019) and environmental impacts related to N losses in ecosystems: loss of biodiversity (Bobbink et al., 2010), water pollution (Parris, 2011), and atmospheric pollution which negatively impacts the climate and human health (Bauer et al., 2016). The overall N pollution was estimated to cost €75–485 billion in the EU in 2008 (Van Grinsven et al., 2013).

Two mechanisms can be identified to reconnect crop and livestock production. The first is an increase in local production of legumes because it addresses both the deficit in N for fertilization and the deficit in proteins for feeding. Indeed, since legumes can fix atmospheric N, they do not need N fertilizers and they can also reduce the amount of N fertilizers applied on the following crop (Nemecek et al., 2008; Preissel et al., 2015). In addition, as they are N-rich feed, they can replace some feed purchases on livestock farms (Bues et al., 2013). Nonetheless, at the yearly scale, legumes are less profitable than cash crops such as wheat (Preissel et al., 2015) and, in Europe, their yields vary more (Cernay et al., 2015). In addition, regulatory constraints (e.g. EU Nitrates Directive 91/676/CEE) can discourage livestock farmers from producing legumes: in some livestock regions in the EU, manure cannot legally be spread on most legumes, which can be an issue if livestock-stocking rate is high and spreadable areas are limited. The second mechanism is local farm-to-farm exchanges. Livestock farms can export manure to crop farms deficient in N, while crop farms can produce legumes and sell them to livestock farms. This crop-livestock integration beyond the farm level (Leterme et al., 2019) would avoid regulatory constraints that prevent legume production on livestock farms.

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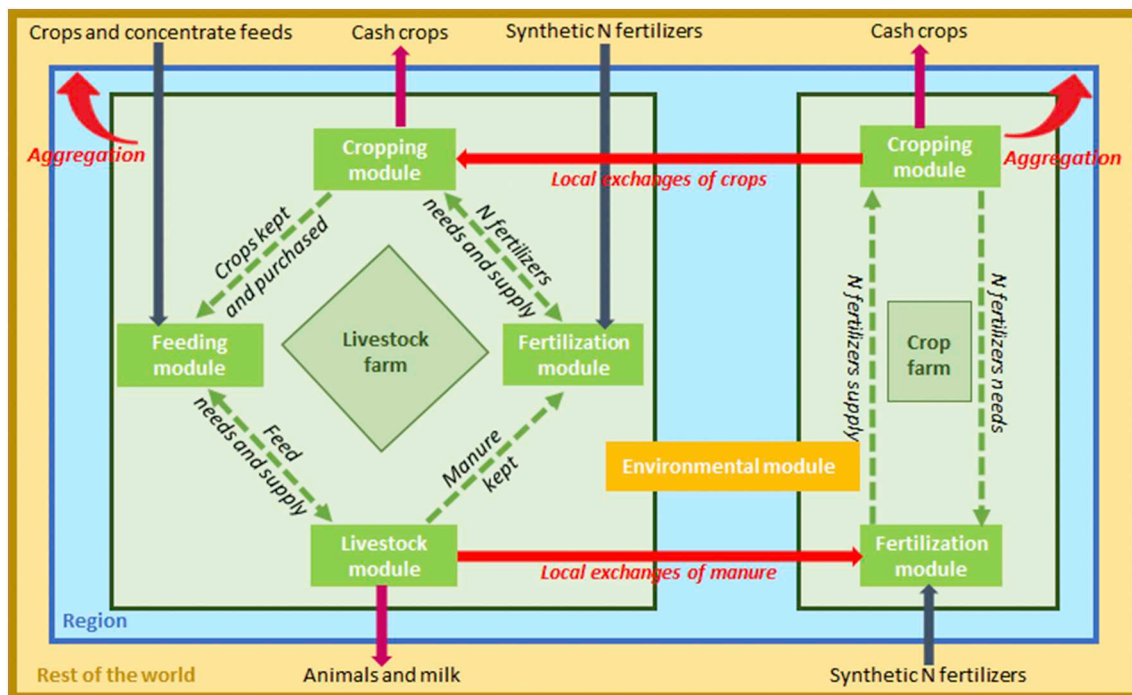


Fig. 1. Conceptual diagram of the SYNERGY model (adapted from Jouan et al. (2017)). Crop activities are described in cropping and fertilization modules, while livestock activities are described in livestock and feeding modules.

The objective of this study is to understand if legume production for feed and local farm-to-farm exchanges enhance the joint production of N-rich inputs, which benefits the agroecosystem both economically and environmentally. We tested this hypothesis by developing and using a bio-economic model that considers (i) local production of legumes and (ii) local farm-to-farm exchanges of crops (including legumes) and manure at the regional level. Mathematical programming models perform ex-ante analysis that can assess changes in agricultural practices even if they have not yet been adopted over large areas (Böcker et al., 2018; Delmotte et al., 2013). Among such models, bio-economic models assess both economic and environmental impacts since they aim to identify trade-offs between economic and environmental considerations (Janssen and van Ittersum, 2007). Several bio-economic models have been developed for legume production at the field level (Reckling et al., 2016) and farm level (Schläfke et al., 2014). However, they fail to identify impacts at higher levels (e.g., region, country) that may be useful to policy makers. Hybrid models address this issue by aggregating results from the farm level to higher levels (Britz et al., 2012). Hybrid bio-economic models have been developed mainly to study policy changes that impact agricultural production (Chopin et al., 2015; Gocht et al., 2017). These models usually consider the diversity of farm types (e.g., crop, livestock) and technologies, but none of them focuses on legume production. Finally, exchanges of manure between farms can be simulated using agent-based models (Happe et al., 2011) or analyzed using mathematical programming models with supply and demand functions either explicitly or endogenously described (Helming and Reinhard, 2009; Spreen, 2006). The bio-economic model SYNERGY developed in this study is in direct line with these considerations. First, it is a model that integrates farm and regional levels. Second, it considers multiple types of farms, technologies and soil and climatic conditions in the region. Third, it highlights the complementarity of farms by considering exchanges of crops and manure between them.

The second section of this article presents SYNERGY as a generic model, while the third section details how this model was adapted to the case-study region, in particular the data implemented. The fourth section presents the results. The fifth section consists of a discussion and a conclusion.

2. Method

2.1. Overview of SYNERGY

The bio-economic model SYNERGY (cross-Scale model using complementarity between livestock and crop farms to enhance regional nitrogen self-sufficiency) is a static non-linear programming model, which maximizes regional profit under constraints (see Section 2.2). It is calibrated to starting conditions using Positive Mathematical Programming (PMP) (Howitt, 1995).

SYNERGY is applied to a particular area called “region” that is divided into several “sectors” to consider a variety of soil and climate conditions. In each sector, arable land area is allocated among three specialized farm types: crop farm, dairy farm, and pig farm. Thus, each of these farm types represents the overall population of the related specialized farms in the sector. Depending on the scenario, the total area allocated to each farm type within a sector may change, as may animal numbers and crop areas inside each farm type. Farm-level outputs are aggregated to the regional level by averaging total output of each farm type, weighted by its relative area in the region. In addition to representing the high heterogeneity of multiple farm types and geographic sectors, SYNERGY can also represent multiple farm activities. Crop activities are defined as the combination of a crop and the rotation it belongs to, which determines the levels of inputs described in cropping and fertilization modules. Livestock activities are defined as the combination of an animal and its feed ration, which determines (i) the levels of input use described in the feeding module and (ii) milk and meat yields described in the livestock module. The model represents many crop and livestock activities, making it possible to represent both widespread and alternative technologies (see Section 3). SYNERGY’s main originality lies in its ability to represent farm-to-farm exchanges of intermediate products (manure and crops), which occur on a local market (i.e., intra-sector or intra-region). SYNERGY is composed of several modules that detail crop and livestock activities, as well as their impacts on N efficiency and potential losses of N (Fig. 1). It generates four types of indicators: (i) structural (e.g., crop areas, numbers of animals), (ii) technical (e.g., protein self-sufficiency, application of N

fertilizers) (iii) economic (e.g., regional profit, farm income, farm-to-farm exchanges) and (iv) environmental (i.e., N efficiency and potential losses of N). These outputs are provided for each farm type at the sector and regional levels.

2.2. The objective function

SYNERGY's objective function is a quadratic function maximizing profit at the regional level that is solved under resource and production constraints (main constraints are related to land of each sector, feeding, herd demography, rotations, and management of N fertilizers for crop production). It yields an optimal allocation of arable land area of each farm type f in each sector s , and of crop and animal activities of each farm type. Profit equals farm income $R_{f,s}$ minus two cost functions, one for crops $FC_{c,f,s}(X_{c,r,f,s})$. $X_{c,r,f,s}$ and one for animals $FC_{a,f,s}(N_{a,ra,f,s})$. $N_{a,ra,f,s}$ (Eq. (1)). These cost functions calibrate the model using PMP (see Section 2.4).

The quadratic profit-maximizing function is:

$$\text{Max } Z = \sum_f \sum_s \sum_c \sum_a \sum_{ra} \sum_r [R_{f,s} - FC_{c,f,s}(X_{c,r,f,s}) \cdot X_{c,r,f,s} - FC_{a,f,s}(N_{a,ra,f,s}) \cdot N_{a,ra,f,s}] \quad (1)$$

where Z is the regional profit; $R_{f,s}$ represents the income of farm f , in sector s ; $X_{c,r,f,s}$ is the crop activity level (area allocated to each crop c associated with each rotation r , per farm f per sector s); $N_{a,ra,f,s}$ is the animal activity level (number of each type of animal a associated with each ration ra , per farm f per sector s); $FC_{c,f,s}$ is the non-linear variable cost function for crops; and $FC_{a,f,s}$ is the non-linear variable cost function for animals.

Eq. (1) is subject to constraints:

$$\sum_c \sum_r Ac_{c,r,f,s} \cdot X_{c,r,f,s} \leq Bc_{f,s} \quad (2.1)$$

$$\sum_a \sum_{ra} Aa_{a,ra,f,s} \cdot N_{a,ra,f,s} \leq Ba_{f,s} \quad (2.2)$$

$$X_{c,r,f,s} \geq 0 \quad (3.1)$$

$$N_{a,ra,f,s} \geq 0 \quad (3.2)$$

where $Ac_{c,r,f,s}$ and $Aa_{a,ra,f,s}$ represent respectively a matrix of input-output coefficients for crops and animals (an example of an input-output coefficient is the quantity of wheat (529 kg.cow⁻¹) necessary to feed cows producing a defined quantity of milk (8600 l.cow⁻¹)); and $Bc_{f,s}$ and $Ba_{f,s}$ represent respectively a matrix of resource availability for crops and animals.

Farm income $R_{f,s}$ is calculated from sales of crops and animal products, minus purchases of crops, animals and synthetic N fertilizers, and minus the cost of exporting manure. This cost corresponds to the transport cost of manure multiplied by the quantity of manure exported. This cost is not explicitly correlated with the distance between farms, but we hypothesized that manure can only be exported to farms in the same sector, due to high transport costs. The local and world markets have the same selling price of crops, but the local market has a lower purchase price than the world market because transport costs on the world market are not included on the local market (Eq. (4)):

$$\begin{aligned} R_{f,s} = & \sum_c \sum_a \sum_{jc} \sum_{ra} (WcropSale_{f,s,c} \cdot ps_c - WcropBought_{f,s,c} \cdot pb_c) \\ & + (LcropSale_{f,s,c} \cdot ps_c - LcropBought_{f,s,c} (pb_c - tc_c)) \\ & + (WanimalSale_{f,s,a,ra} \cdot ps_{a,ra} - WanimalBought_{f,s,a,ra} \cdot pb_{a,ra}) \\ & - (LfertiSale_{f,s,fe} \cdot tc_{fe} + WfertiBought_{f,s,fe} \cdot pb_{fe}) \end{aligned} \quad (4)$$

where $WcropSale_{f,s,c}$ and $WcropBought_{f,s,c}$ represent respectively sales and purchases of crops on the world market; $LcropSale_{f,s,c}$ and $LcropBought_{f,s,c}$ represent respectively sales and purchases of crops on the local market; $WanimalSale_{f,s,a,ra}$ and $WanimalBought_{f,s,a,ra}$ represent respectively sales and purchases of animals on the world market;

$LfertiSale_{f,s,fe}$ and $WfertiBought_{f,s,fe}$ represent respectively local sales of fertilizers (i.e., manure) and purchases of synthetic N fertilizers on the world market; ps_c and pb_c represent respectively the selling price and purchase price of crops; $ps_{a,ra}$ and $pb_{a,ra}$ represent respectively the selling price and purchase price of animals; pb_{fe} represents the purchase price of synthetic N fertilizers; and tc_c and tc_{fe} represent respectively the transport cost of crops and fertilizers purchased on the local market.

2.3. SYNERGY modules

2.3.1. Cropping module

The cropping module sets the area of each crop activity for a farm type. Since SYNERGY is a static annual model, rotations are represented by combining different crops with constraints of crop share, which corresponds to each crop's minimum return period. The minimum return period is the maximum frequency of return of the same crop on the same plot over time. The cropping module also sets the outlets of crop production: kept on the farm, sold on the world market or sold on the local market. These local exchanges of crops can take place at the regional level i.e., between farms that are located in the same sector or in different sectors. The non-linear cost function considers costs of crop production (excluding fertilizer costs) and makes it possible to calibrate the model for the crop areas observed during a reference period (see Section 2.4).

2.3.2. Fertilization module

The fertilization module balances N-fertilization resources (manure and synthetic N fertilizers) with N-fertilization needs. It sets the quantity of manure produced by farm type and its outlets: kept on the farm to meet crop N requirements or exported locally. It also makes it possible to purchase and import the adequate quantity of manure from the local market and synthetic N fertilizers from the world market. Farms import manure free of charge but those who export it bear transport costs. Fertilization needs were based on crop N requirements estimated by the French method COMIFER (COMIFER, 2011), which considers multiple sources of N: fixed by legumes, produced in manure, purchased in synthetic N fertilizers and mineralized in the soil. N mineralization comes from humus, grassland turnover and crop residues, among which legume residues are especially rich in N. For some crops, a maximum percentage of organic fertilization out of total fertilization is set to avoid fertilization with only manure, in accordance with current practices. The fertilization module also includes regulatory constraints¹ (EU Nitrates Directive 91/676/CEE) that restrict the amount of manure spread on crops to 170 kg N.ha⁻¹. Thus, farms that reach this limit have to export their excess manure, but they can also do it if this limit is not reached. Manure can only be exported to farms in the same sector, due to high transport costs.

2.3.3. Animal module

The animal module sets the activities that result in production of animals and milk. The quantity of milk produced per cow, as well as milk quality (i.e., protein and fat contents), depend on the ration. The animal module also sets the outlets of animals: kept on the farm or sold on the world market. Demographic constraints ensure that the number of animals is consistent with standard productivity. The non-linear cost function considers breeding costs and makes it possible to calibrate the model for the animal activities observed during a reference period (see Section 2.4).

2.3.4. Feeding module

The feeding module balances feed resources (crops produced and kept on the farm, crops purchased on the local or world markets, and

¹ There is not a regulatory constraint for synthetic N fertilizers. However, the overall fertilization from manure and synthetic N fertilizers follows agronomic constraints.

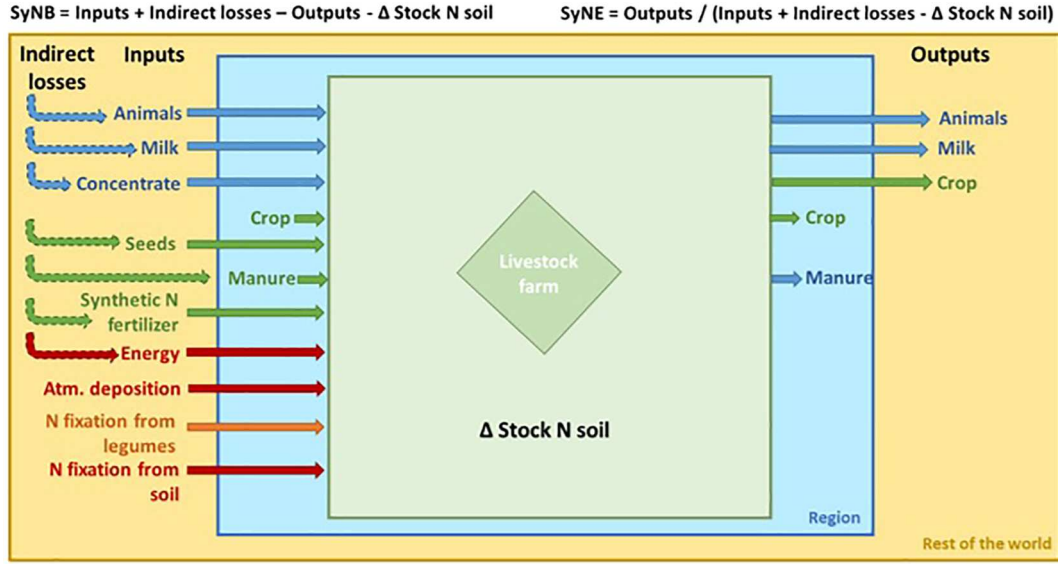


Fig. 2. Conceptual diagram of the N inputs, N outputs, indirect N losses, and variation of stock N soil (Δ Stock N soil) integrated in SYNERGY for computation of SyNE and SyNB indicators.

concentrate feeds purchased on the world market) with feed needs. Feed needs are detailed by ration, which differ by animal and farm type (the elaboration of rations is detailed in Section 3.2). The feeding module calculates protein self-sufficiency at the farm level, as the ratio of crude protein produced and consumed on the farm to all crude protein consumed on the farm.

2.3.5. Environmental module

Once the objective function maximized, the environmental module uses outputs of the other modules (e.g., numbers of animals, area of crops) to calculate two indicators developed by Godinot et al. (2014): SyNE (System N Efficiency) and SyNB (System N Balance). SyNE (range = 0–1) assesses the efficiency with which farming systems transform N inputs into desired agricultural products; as SyNE increases, farming-system efficiency increases. SyNB ($kg\ N.ha^{-1}$) reflects potential N losses from farming systems; as SyNB increases, potential N losses from a farming system increase. Both SyNE and SyNB take into account N of farm inputs and outputs, as well as indirect N losses (Fig. 2). These indirect N losses correspond to N losses occurring during the production and transport of inputs. Indirect N losses were proposed by Godinot et al. (2014) according to the principles of agricultural life cycle assessment (LCA), i.e. “from cradle to farm gate” (Cederberg and Mattsson, 2000).

2.4. Calibration of the SYNERGY model

SYNERGY was calibrated using the PMP method, developed by Howitt (1995) and then improved by later authors (see Frahan et al. (2007), Heckelei and Britz (2005) and Louhichi et al. (2013)) for critical reviews of different PMP approaches). We used the standard approach of Howitt (1995) to calibrate crop areas and numbers of breeding animals. We did not calibrate rotations or rations since no robust data were available for the region studied.

The first step of PMP consists of creating a linear model and adding to the set of resource constraints (on land, feeding, herd demography, rotations and N management), an additional set of calibrating constraints that bound crop areas and animal numbers to those observed during a reference period. Thus, in the first step, Eq. (5) was maximized, subject to constraints (2.1), (2.2), (3.1) and (3.2) and to PMP constraints (6.1) and (6.2).

$$\sum_f \sum_s \sum_c \sum_a \sum_r \sum_{ra} [R_{f,s} - co_{c,s} \cdot X_{c,r,f,s} - co_{a,s} \cdot N_{a,ra,f,s}] \quad (5)$$

$$\sum_r X_{c,r,f,s} \leq X_{c,f,s}^0 \cdot (1 + \varepsilon_c) [\lambda c_{c,f,s}] \quad (6.1)$$

$$\sum_{ra} N_{a,ra,f,s} \leq N_{a,f,s}^0 \cdot (1 + \varepsilon_a) [\lambda a_{a,f,s}] \quad (6.2)$$

where $co_{c,s}$ and $co_{a,s}$ represent respectively the linear-cost vector for crops and animal products; $X_{c,f,s}^0$ and $N_{a,f,s}^0$ represent respectively the non-negative vector of observed crop areas and animal numbers; and ε_c , ε_a are small positive vectors.

Then, in the second step of the PMP, the vectors of duals $\lambda c_{c,f,s}$ and $\lambda a_{a,f,s}$ are used to estimate parameters of non-linear cost functions that satisfy Eqs. (7.1) to (9.2):

$$co_{c,s} + \lambda c_{c,f,s} = d_{c,f,s} + Q_{c,f,s} \cdot X_{c,f,s}^0 \quad (7.1)$$

$$co_{a,s} + \lambda a_{a,f,s} = d_{a,f,s} + Q_{a,f,s} \cdot N_{a,f,s}^0 \quad (7.2)$$

$$d_{c,f,s} = co_{c,s} + \lambda c_{c,f,s} - kc \cdot \lambda c_{c,f,s} \quad (8.1)$$

$$d_{a,f,s} = co_{a,s} + \lambda a_{a,f,s} - ka \cdot \lambda a_{a,f,s} \quad (8.2)$$

$$Q_{c,f,s} = \frac{kc |\lambda c_{c,f,s}|}{X_{c,f,s}^0} \quad (9.1)$$

$$Q_{a,f,s} = \frac{ka |\lambda a_{a,f,s}|}{N_{a,f,s}^0} \quad (9.2)$$

where $d_{c,f,s}$ and $d_{a,f,s}$ represent respectively the vector of intercepts of the cost functions for crops and animals; $Q_{c,f,s}$ and $Q_{a,f,s}$ represent respectively the vector of slope of the quadratic cost function of crops and animals; and kc and ka represent respectively the vector of parameters that determine the weights of the non-linear part of the cost function for crops and animals.

Finally, the two cost functions are written as:

$$FC_{c,f,s}(X_{c,r,f,s}) = d_{c,f,s} + 0.5Q_{c,f,s} \cdot \sum_r X_{c,r,f,s} \quad (10.1)$$

$$FC_{a,f,s}(N_{a,ra,f,s}) = d_{a,f,s} + 0.5Q_{a,f,s} \cdot \sum_{ra} N_{a,ra,f,s} \quad (10.2)$$

3. The case study

3.1. Overview of the case study

SYNERGY was applied to a region corresponding to two EU NUTS 2 sub-regions in western France: Pays de la Loire and Brittany. Although containing only 14% of France's utilized agricultural area (UAA), this region contains 68% of its pig production and 38% of its cow milk production. Its area of grain legumes more than doubled from 2013 to 2017, but still represented only 1% of UAA in 2017 (French Ministry of Agriculture, 2018a). Agricultural production location in the region is heterogeneous: most animal production lies in the north, while most crop production lies in the south. Appendix A describes the sources of input data used. The region was divided into nine sectors, each representing an administrative department in the two sub-regions and numbered according to the French system (departments 22, 29, 35, 44, 49, 53, 56, 72 and 85).

3.2. Diversity of farms and activities

Three farm types were considered in the region: dairy cow, pig and crop. Dairy production had 20 potential rations, each differing in the main forage (i.e., forage maize, forage grass or both) and in the N-rich feed (soybean meal, peas, faba beans or dehydrated alfalfa). Regardless of the main forage, soybean-based rations were the basic rations used, based on regional references (IDELE - Inosys, 2018). Legume-based rations were alternative ones created by replacing soybean meal with legumes (here, pea, faba bean or dehydrated alfalfa) using INRation® software (INRA, 2003). If legumes could not replace all soybean meal due to nutritional constraints, some rapeseed meal was added. Appendix B lists examples of compositions of the dairy rations used. Pig production had two potential rations, each differing in the N-rich feed (soybean meal or a mixture of pea and faba bean) and calculated using Porfal® software (IFIP, 2018).

Crop production had 53 potential rotations, defined by expert knowledge, that included 11 crops. Some of these rotations were included to improve model flexibility and calibration, but are not yet common in the region. Crop yields differed only by sector, not by rotation. Only N fertilization of each crop differed by both sector and rotation. For example, after a pea crop, N fertilization of wheat was lower than that after a maize crop due to the preceding crop effect of pea. Furthermore, as explained in Section 2.3.2, we decided to limit the maximum percentage of organic N fertilization of crops by manure out of total N fertilization (Table 1).

3.3. Data and calibration specifications

SYNERGY was calibrated for each farm type at the sector level. Animal numbers and areas of each farm type were calibrated using data from the most recent agricultural census in France (French Ministry of Agriculture, 2018b). Due to the PMP technique used, all crop areas were set to non-zero values to be able to evolve in the scenarios. Thus,

Table 1
Maximum percentage of organic N fertilization out of total N fertilization.

Crop	Maximum percentage
Alfalfa	100%
Barley	85%
Faba beans	100%
Forage maize	98%
Grain maize	84%
Pea	100%
Permanent grassland	100%
Rapeseed	66%
Sunflower	100%
Temporary grassland	100%
Wheat	74%

for each legume studied (i.e., peas, faba beans and dehydrated alfalfa), the initial area was arbitrarily set at 0.5% of the area of each farm in each sector, which initialized the total legume share at 1.5% in each farm in each sector. Input and output prices were based on mean regional or national data for the reference years 2013–2017 (French Ministry of Agriculture, 2018a; La Dépêche - Le Petit Meunier, 2018).

3.4. Scenarios analyzed using the SYNERGY model

Four scenarios were analyzed using SYNERGY:

- BASE: The baseline scenario, which represents the situation observed after calibration. Manure is exchanged locally (i.e., intra-sector), but farms must meet regulatory constraints that restrict the amount of manure spread on crops to 170 kg N.ha⁻¹.
- LEG10: Legume area is set to 10% of the regional area, a share chosen according to a recent prospective that explores the possibility of generalizing agroecology at the European level (Poux and Aubert, 2019). To do so, the Eq. (11) was added as a constraint. The total amount of manure exchanged at the regional level is capped at the total amount predicted for BASE.

$$\sum_f \sum_s \sum_{leg} \sum_r X_{leg,r,f,s} \geq 0.10 \cdot \sum_s Land_s \tag{11}$$

- LEG10 + Ma: Legume area remains 10% of the regional area, and the total amount of manure exchanged can freely increase compared to those in BASE and LEG10. To do so, the constraint (Eq. (12)) limiting the manure exchanges to the amount calculated in BASE $SaleManure_{f,s,fe}^{BASE}$ was removed.

$$\sum_f \sum_s \sum_{fe} LfertSale_{f,s,fe} \geq SaleManure_{f,s,fe}^{BASE} \tag{12}$$

- LEG10 + MaC: Legume area remains 10% of the regional area, and local exchanges of crops are available in addition to exchanges of manure. To do so, the constraint limiting the local crop exchanges to a very small amount (Eq. (13)) was removed.

$$\sum_f \sum_s \sum_c \sum_r LcropSale_{f,s,c,r} \leq 0.001 \tag{13}$$

Results were analyzed either at the regional level or by farm type by averaging results of farms of the same type among sectors, weighted by the area of each farm type, or for a specific farm type by sector.

4. Results

4.1. Baseline scenario (BASE)

As set during initialization, legume share in BASE is 1.5% of the area of each farm in each sector (Fig. 3); crop and livestock production are detailed in Table 2. The share of legume-based rations is low: 0.4% for pig farms and 4.8% for dairy farms on average. These figures do not differ substantially from one sector to another, except for the dairy farm in sector 35 (“Dairy35”), where the share of legume-based rations reaches 15.3%. Indeed, a dehydration factory of alfalfa (namely, Déshyouest) is located in this sector, which is indirectly included into PMP constraints that favor alfalfa-based rations. Even so, most of the dehydrated alfalfa is purchased on the world market. Protein self-sufficiency at the regional level reaches 58%, with large differences in the mean among farm types: dairy farms are three-times more self-sufficient than pig farms on average (Table 2). In almost all sectors, pig farms export their manure, mainly to dairy farms. Potential N losses are by far the largest for pig farms (mean SyNB = 267 kg N.ha⁻¹). Crop farms are the most N efficient (mean SyNE = 0.55), followed by pig farms (0.41) and dairy farms (0.35).

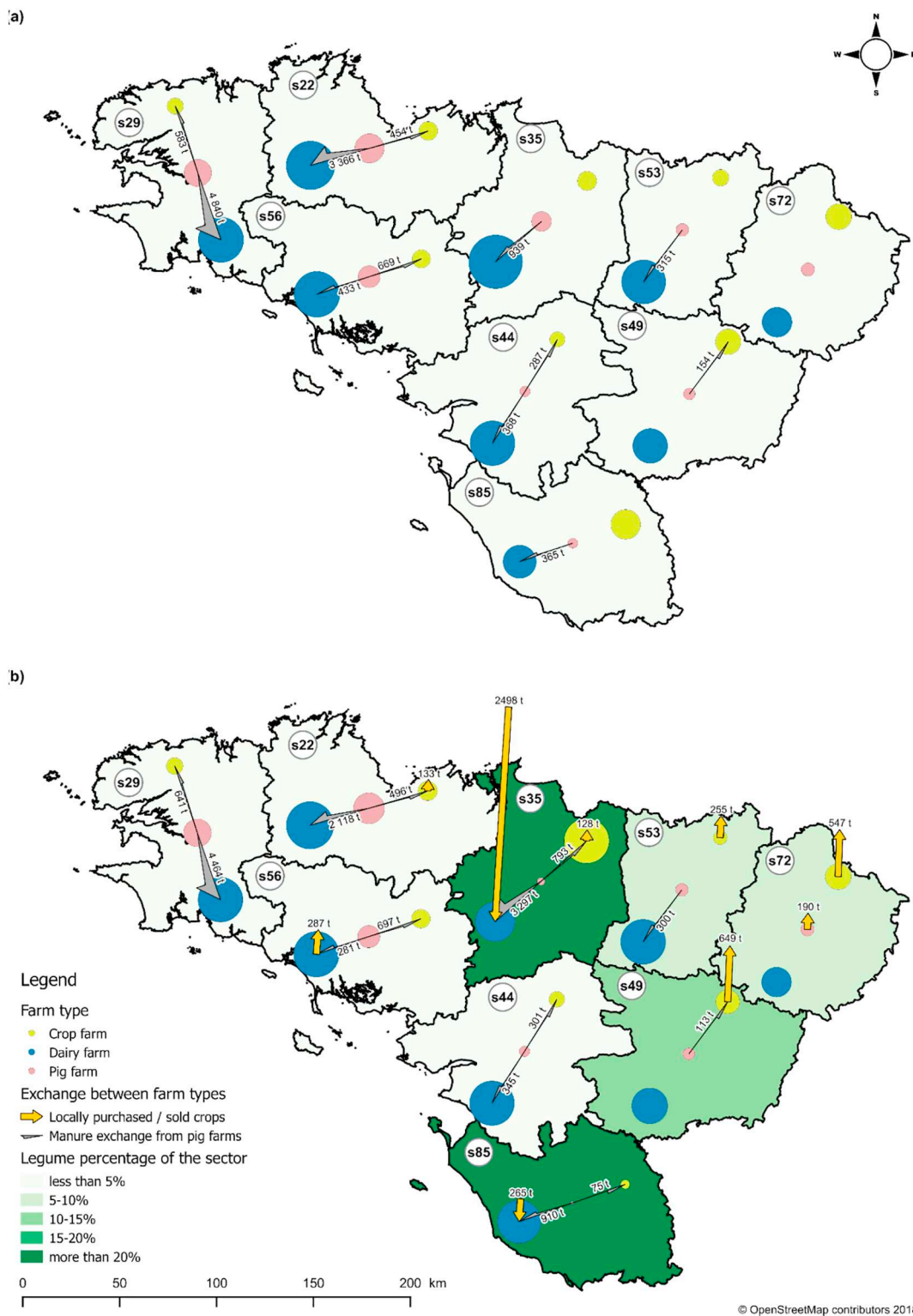


Fig. 3. Exchanges of manure between farms by sector (administrative department) in western France in (a) the baseline scenario and (b) the scenario LEG10+MaC (initial legume area = 10%, and local exchanges of crops are available in addition to manure exchanges). Circles are proportional to the area of each farm type in each sector. Arrows representing crop exchanges (in t N) are proportional to the absolute value of the balance “Purchases – Sales”: only balances ≥ 125 t N are represented.

4.2. LEG10 scenario

In the LEG10 scenario, legume area is set at 10% of the regional area, and the total amount of manure exchanged at the regional level is capped at the total amount predicted for BASE. Under these constraints, legume area is allocated among farms and sections: legume share is

particularly high in the eastern and southern sections, because it increases more on crop farms, which are mainly located in these sections (Table 2). However, since local exchanges of crops between farms are impossible, 75% of legumes produced in the region are exported and are not used as feed. Linked with the increase in the legume share (and so, with the advantages of legumes regarding N), purchase of synthetic

N fertilizers decreases by 7% (Table 2).

It is interesting to notice that the production, and use, of alfalfa increase substantially in Dairy35 because the PMP constraints integrate that there is a dehydration factory of alfalfa in the related sector. Regarding dairy production in the overall region, it decreases by 11%, and 20% of cows are now fed with legumes, mainly alfalfa. However, the need in legumes exceeds the regional production. Thus, most legumes used in feed are imported and the protein self-sufficiency is not increased. Regarding pig production, it decreases by 2% and the share of pigs fed with legumes only reaches 1.7%. This low use of legume is due to a lower profitability of legume-based rations, and to the need to keep spreadable areas on most pig farms, linked with high densities of pigs per ha.

Compared to BASE, profit decreases by 4% at the regional level, with variability among farms. Incomes of crop farms increase by a mean of 12% due to larger areas but their incomes per ha decrease by 6%, reflecting a loss of crop profitability: with a legume share of 22%, crop farms lose a mean of 43 €.ha⁻¹ compared to BASE. Incomes of dairy farms decrease by a mean of 8% but their incomes per L of milk increase when legume-based rations represent > 10% of the rations used (i.e., for Dairy35, Dairy49, Dairy72 and Dairy85), which must be linked with a higher self-sufficiency, except for Dairy35. Incomes of pig farms decrease by a mean of 2%, mainly due to the decrease in pig production, and a lower efficiency of the legume-based ration (more feed is needed to produce the same number of pigs).

However, compared to BASE, environmental indicators are not substantially improved due to heterogeneous changes among farms that offset one another. High shares of legumes on dairy and crop farms lead to improve N efficiency and N losses due to lower synthetic N fertilization. However, this improvement is compensated by a deterioration of these indicators on dairy and pigs farms importing more N-rich feed (e.g., Dairy35 importing more alfalfa) or increasing stocking rates of animals.

4.3. LEG10 + Ma scenario

In the LEG10 + Ma scenario, legume share is also set at 10% of the regional area, but the total amount of manure exchanged at the regional level can freely increase. Two farms, Pig35 and Pig85, increase their manure exports. Since these farms export a large share of their manure (ca. 60%), they are not anymore constrained by spreading area and the shares of legumes increase on these farms. However, contrary to expected, they also produce more pigs per hectare, which offsets the regional decrease observed in LEG10. This intensification leads to a decrease in the protein self-sufficiency of these farms. In addition, the increase in manure exports from Pig35 and Pig85 leads to lower application of synthetic N fertilizers per ha on crop farms and on dairy farms that import their manure in the corresponding sectors. However, these decreases are offset by higher purchases of synthetic N fertilizers from Pig35, which exports too much manure compare to its crop needs.

The increase in pig production does not lead to a better profitability: incomes per pig decrease by 35% and 27%, respectively on Pig35 and Pig85, due to the increases in feed expenses and manure exports, which represent additional costs for pig farms. Nevertheless, for crop farms, income per ha increases by a mean of 13 €.ha⁻¹ because of decreased use of synthetic N fertilizers, but it remains 18 €.ha⁻¹ below the income predicted in BASE. Compared to LEG10, the environmental indicators are stable at the regional level but are worsened for Pig35 and Pig85, mainly due to an intensification of pig production (more pigs produced per ha) and higher N fertilization.

4.4. LEG10 + MaC scenario

In the LEG10 + MaC scenario, farm-to-farm exchanges of crops (including legumes) become possible. Alfalfa is exchanged locally between farms: 33% of alfalfa produced in the region is sold by several crop farms and pig farms to Dairy35 (Fig. 2). Consequently, purchases of alfalfa on the world market decrease by a mean of 24% compared to LEG10 + Ma.

Table 2

Results of the SYNERGY model for the main indicators, by scenario. BASE: baseline. LEG10: Legume area set to 10% of the regional area, and manure exchanges are capped at the regional level. LEG10 + Ma: Legume area remains 10%, and manure exchanges can increase. LEG10 + MaC: Legume area remains 10%, and local exchanges of crops are available in addition to exchanges of manure that can increase.

	Baseline	LEG10	LEG10 + Ma	LEG10 + MaC
Legume share (input data)	1.5%	10.0%	10.0%	10.0%
Area of farms (ha)				
■ Dairy farms	1,128,399	1,085,642	1,087,053	1,084,768
■ Pig farms	188,735	185,847	174,325	175,030
■ Crop farms	239,242	284,887	294,998	296,579
Milk production (hL)	736,110	656,015	660,548	660,003
Pig production (thousands of head)	12,178	11,915	12,108	12,104
Share of legume-based rations				
■ Dairy farms	4.8%	20.3%	20.6%	20.5%
■ Pig farms	0.4%	1.7%	1.5%	1.4%
Purchases of synthetic N fertilizers (t N)	121,033	112,720	113,141	112,338
Local exchanges of manure (t N)	12,775	12,199	14,909	14,831
Local exchanges of crops (t N)	–	–	–	2907
Regional protein self-sufficiency	57.8%	56.2%	55.4%	56.6%
Farm protein self-sufficiency				
■ Dairy farms	72.4%	72.1%	71.8%	71.8%
■ Pig farms	23.7%	23.6%	21.9%	21.9%
Regional profit (M€)	2188	2090	2098	2099
Dairy farm income				
■ Regional total (k€)	1,410,698	1,304,664	1,314,742	1,314,083
■ Per hL of milk (€.hL ⁻¹)	1916	1989	1990	1991
Pig farm income				
■ Regional total (k€)	612,234	601,138	588,821	589,237
■ Per pig (€.pig ⁻¹)	50	50	49	49
Crop farm income				
■ Regional total (k€)	164,747	184,064	194,268	195,295
■ Per ha (€.ha ⁻¹)	689	646	659	658
SyNB (System N Balance, kg N.ha ⁻¹)				
■ Dairy farms	122	116	118	117
■ Pig farms	267	270	285	284
■ Crop farms	93	91	92	93
SyNE (System N Efficiency, range = 0–1)				
■ Dairy farms	0.35	0.37	0.37	0.37
■ Pig farms	0.41	0.40	0.40	0.40
■ Crop farms	0.55	0.58	0.58	0.57

Some wheat, maize and rapeseed are also exchanged, but to a lesser extent. Unfortunately, farm-to-farm exchanges are not large enough to influence the other indicators greatly: areas and herd sizes remain nearly the same, as do economic and environmental indicators (Table 2).

5. Discussion & conclusion

SYNERGY was used to study interactions between specialized farms to highlight potential benefits of complementarities among them at the regional level. We focused on legume production and how farm-to-farm exchanges of crops and manure can improve environmental and economic results. SYNERGY was applied to western France, a region that specializes in animal production but has a large amount of crop production in the south.

When the legume share is set to 10%, legume production increases more on crop farms than on livestock farms and only 25% of the legumes produced are kept to feed livestock. Thus, legumes are more profitable as a final product than as an intermediate one. These results

are different from the study of [Schläfke et al. \(2014\)](#), which showed that grain legumes have more economic potential on dairy farms as on-farm feed than as cash crops. This difference is due to two factors that are specific to our model. First, the rotational constraints in SYNERGY limit the legume share on dairy farms: since forages represent a large share of area on dairy farms, legumes have to be included in long rotations with forages, which restrict their share. Indeed, if the rotational constraints are removed, the legume share on dairy farms becomes the same as that on crop farms. Second, application of the Nitrates Directive limits the legume share on pig farms: since spreading manure on legumes is prohibited, increasing the legume share decreases the potential manure-spreading area, which is an issue on pig farms because they produce large quantities of manure.

Due to the limited increase in legume production on livestock farms, animals fed with legumes are still in minority. When manure exports increase, it does lead to an increase in legume production on the farms concerned by these increases. However, contrary to what was expected, it also leads to an increase in the number of pig produced per ha, without a rise of legume-based rations. This intensification of pig production worsened environmental indicators, in particular N potential losses: a rebound effect is thus observed ([Figge and Thorpe, 2019](#)). This is consistent with results of [Regan et al. \(2017\)](#), who analyzed case studies of coupling dairy and crop production and observed intensification of production. However, the extreme intensification predicted by SYNERGY is not likely to happen, since high stocking rates on livestock farms require authorization in France, and it is unlikely that such rates would be allowed.

This negative environmental impact of pig production offsets the slight improvements on crop and dairy farms linked to decreases in synthetic N fertilizers. Substantial improvements take place only when legume shares reach high levels, at least 28%, or when stocking rates of animals decrease. Nevertheless, it is difficult to compare these results to those of another study since no study has analyzed such changes at the regional level. Results for potential N losses are consistent with those of [Reckling et al. \(2016\)](#) at the cropping-system level, even though the decrease in synthetic N fertilizer they estimated is greater than that in our study. N efficiency improves less in our study than in that of [Plaza-Bonilla et al. \(2017\)](#), partly because SYNERGY does not consider the potential increase in crop yield following a legume. This omission may also explain why SYNERGY predicts a decrease in regional profit and in income per ha for crop farms, while studies at the rotation level show that legumes are usually as profitable as other crops ([Preissel et al., 2015](#)). Overall, regarding economic results, the regional profit is stable because the loss of profitability due to the development of legume production, characterized by positive opportunity costs, is offset by the increase in pig production.

Finally, adding local exchanges of crops has little influence on results. One dairy farm in particular purchases alfalfa from other farms in the region, but doing so does not lead to large technical changes. The lower purchase price on the local market is a mechanism that is insufficient to promote legume-based rations in the region.

In brief, the two levers studied to enhanced crop-livestock complementarities at the regional level, namely legume production and local exchanges of N-rich inputs, are insufficient to improve economic and environmental outcomes. Legumes are not sufficiently produced and used on livestock farms, and the limited local exchanges of crops do not increase this use. This can be explained by the extent of livestock production in the case-study region, implying high feed requirements, which it is not profitable to meet from local resources. Thus, our study highlights that substantial changes in term of crop production, and exchanges of N-rich materials, are not sufficient to improve the sustainability in a region that includes a large livestock production.

SYNERGY's main contribution is to address the issue of reconnecting crop and livestock production beyond the farm level to highlight possible complementarities between farms. These complementarities are represented through different types of farms in a region, but the region we studied remains too specialized in livestock production for

complementarities to become apparent. Therefore, it would be interesting to apply SYNERGY to regions that are more specialized in crop production and have a larger N deficit. Methodologically, SYNERGY is generalizable and transferable to other geographic levels and other contexts by changing data for farms, crop activities and animal activities. The PMP calibration introduced in SYNERGY leads to smooth results, which implicitly take into account costs that are not accounted for here (e.g., investment costs). However, due to its short-term feature, it also limits structural changes such as a substantial decrease in livestock production in long term.

Besides, sustainable crop rotations are designed in SYNERGY by integrating a minimum return period and by differentiating N supply according to the crop need, the pre-crop effect, and the soil type (to include mineralization). However, we did not consider multispecies grassland (e.g., temporary grassland with clovers), even though they may be a useful tool to increase protein self-sufficiency of dairy farms. We also considered only conventional production technology for crops. Interesting results may emerge by adding organic production, which prohibits the use of synthetic N fertilizers, or by implementing a GMO-free labelling for animal products, which may increase the profitability of legume-based rations. Going further, extreme scenarios, such as a substantial decrease in animal production, could be assessed by SYNERGY. Another improvement of the model would be to add other environmental indicators. In particular, it would be more relevant to study nitrous oxide (N₂O), which is emitted in part by the use of synthetic N fertilizers and has a global-warming effect nearly 300 times as large as that of CO₂. Thus, decreasing synthetic N fertilizer use could dramatically reduce agriculture's impact on climate change. Finally, we did not use SYNERGY to test scenarios with different prices or public policies, but it could easily be used to do so. Thus, we did not question how a region could reach a legume share of 10%, but further studies should address it.

Multiple issues are highlighted by SYNERGY in this study. First, it shows that increasing legume production does not lead to substantial improvements of environmental indicators since the main impacts are due to livestock production in the region studied. Improving crop-livestock complementarities through exchanges of manure has also no positive impact because it leads to an intensification of livestock production. Nonetheless, intensive animal production is increasingly questionable from a societal perspective. It would be interesting to study a scenario in which animal production cannot increase or even decreases, which would correspond to an external "shock" in consumer preferences. In this case, manure exchanges could represent a promising mechanism to improve environmental indicators. Second, even with large legume share in the region, soybean-based rations remain dominant; thus, it is still more profitable to produce milk and meat with soybean meal. However, the emerging market of GMO-free food may represent an opportunity for use of legumes in feed: it could create added value for milk and meat produced from animals fed locally with produced legumes instead of imported soybean meal. However, the booming demand for vegetarian food strongly competes for the use of legumes. Indeed, legumes for human consumption often have a higher economic value than those for feed, which further limits the use of legumes in feed. Finally, the small improvements in environmental indicators raise questions about the utility of closing the N cycle by reconnecting animal production and feed production geographically. Feeding livestock with locally produced crops may be less N efficient, but relying on ultra-optimized rations with imported feed (e.g., soybean meal produced in South America) may support deforestation. This dilemma reflects the many paths that agriculture can follow between agroecology and agro-industry.

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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.

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Appendix A. Sources of the input data used in the SYNERGY model for the western France case study

Module	Data	Source
Selling price Animal	FranceAgriMer, IDELE ^a	Selling price
	Milk and meat yields and qualities	INOSYS Réseaux d'élevage ^b , IFIP ^c
Cropping	Breeding costs (insemination, vet)	INOSYS Réseaux d'élevage, IFIP
	Crop yields	FranceAgriMer
	Production costs (seeds, pesticides)	Regional extension services, PEREL ^d
	Purchase price	IFIP
Feeding	Selling price	FranceAgriMer
	Standard and alternative dairy feed rations	IDELE, INRAtion software
Fertilization	Standard and alternative pig feed rations	IFIP, Porfal© software
	Need for fertilization (nitrogen)	COMIFER
	Quantity of nitrogen produced by animals	RMT livestock and environment (CORPEN)
	Calculation of nitrogen balance	COMIFER

^a IDELE is the French Livestock Institute.

^b Inosys-Réseaux d'élevage, associated with IDELE, produces reference data for herbivore breeding systems and builds case-studies of livestock management systems.

^c IFIP is the French Pig Research Institute.

^d PEREL is a tool to foster forage self-sufficiency.

Appendix B. Example of ration compositions used in the SYNERGY model. Dairy cow rations are based on forage maize; synthetic amino acids in rations are not included

Ration	Forage	Crops (except legumes)	Legumes	Concentrate feeds
dairy cow_soybean	76%	10%	0%	14% ^a
dairy cow_faba	62%	9%	29%	0%
dairy cow_pea	60%	9%	28%	4% ^b
dairy cow_alfalfa	56%	10%	33%	1% ^b
Pig_soybean	0%	91%	0%	8% ^a
Pig_pea&faba	0%	82%	15%	3% ^b

^a Soybean meal.

^b Rapeseed meal.

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