# SYNERGY: a bioeconomic model to assess the impacts of increased protein self-sufficiency through farm-to-farm exchanges

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## Abstract

The European Union (EU) relies on imports to meet the protein requirements of livestock. The Common Agricultural Policy aims at improving EU protein self-sufficiency by developing the production of protein-rich crops such as legumes. However, the production of legumes can be limited in livestock farm due to regulatory constraints. The purpose of this paper is to implement a model assessing the impacts of increased protein self-sufficiency through farm-to-farm exchanges of crops (whom legumes) and organic fertilizers. To do so, the SYNERGY bio-economic model is set up and implemented in a region of western France. This model accounts for (i) different scales, (ii) different types of farm, (iii) different pedological and climatic conditions and (iv) possible exchanges of crops and organic fertilizers between farms. It analyzes both economic and environmental impacts, in terms of revenues and use of nitrogen. The main assumption is that the complementarity between specialized crop farms and livestock farms can increase protein self-sufficiency while having positive economic and environmental impacts at the regional level. The results show that protein self-sufficiency can be slightly enhanced thanks to local exchanges of crops between farms. However, when local exchanges of organic fertilizers happen, the protein self-sufficiency slightly decreases due to a rise of pig production. When exchange of crops and organic fertilizers happen simultaneously, the protein self-sufficiency slightly increases even though the pig production increases. In this case, incomes rise at the regional level but the impacts in term of nitrogen management are more reserved.

Keywords:
Legumes, Organic fertilizers, Nitrogen, Farm complementarity, Alternative feed

JEL classification: C67, Q12, Q16

## 1. Introduction

The European Union (EU) relies on imports to feed livestock. In particular, protein self-sufficiency[1] in EU for feed is far to be reached. Thus, 60% of protein rich materials[2] used in animal feed are imported, and consist of soybean meals at 82% (European Commission, 2017). It raises questions in terms of deforestation in countries where soybean is grown (Karstensen et al., 2013), consumer expectations for GMO-free products (Bullock and Desquilbet, 2002) and security of supply (Gale et al., 2014). In this context, the 2014 Common Agricultural Policy (CAP) aims at improving EU's self-sufficiency in proteins for feed by developing legume productions. Legumes, including both grain legumes (e.g., faba bean, field pea, lupin, soybean) and fodder legumes (e.g., field pea, alfalfa, white clover), are high-protein crops that can be introduced into feed rations in the form of grains and forages in order to meet animal protein requirements (Bues et al., 2013). Grain legumes, including soybean, cover only 1.87% of European arable land, against 21% in USA[3] for the years 2010 to 2014. In order to enhance legume production, EU set up several types of area subsidies such as coupled support, agri-environmental measures or green payments, which assimilate legumes as ecological focus areas. Following this reform, the areas of grain legumes, mainly soybean, have increased of 30% between 2014 and 2016[3].

Nevertheless, the development of legumes still faces economic and environmental challenges. From an economic point of view, farmers may not be interested in substituting their current crops by legumes. As far as annual gross margin per hectare is concerned, legumes are usually less profitable than main crops (e.g., winter wheat) and their yields are seen as more variable by farmers, even though quantitative studies are contradictory (Cernay et al., 2015; Peltonen-Sainio and Niemi, 2012). From an environmental point of view, legumes have several advantages thanks to the production of ecosystem services such as nitrogen (N) provision (Nemecek et al., 2008; Preissel et al., 2015). However, regulatory constraints such as regional action programs of the nitrate directive can discourage livestock farmers to produce legumes: in some areas in France, the spreading of animal manure is prohibited on most legumes in order to prevent nitrate losses (Decree (FR) No 2011-1257).

In this paper, we address the issue of implementing a model to assess the impacts of increased protein self-sufficiency through crops and organic fertilizers farm-to-farm exchanges. Economic and environmental impacts will be assessed. Mathematical programming models offer a prospective

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[1] The protein self-sufficiency is defined as the ratio of proteins produced and consumed by livestock to total protein consumed by livestock, in the same area.

[2] Protein rich materials raw materials are containing more than 15% of proteins

[3] Authors 'calculations from Eurostat, FAOstat & World Bank data

analysis by optimizing a utility function, which represents the economic rationality of farmers (Delmotte et al., 2013). Thus, changes of agricultural practices can be assessed even though they have not been introduced at large scale yet. Among mathematical programming models, bio-economic models permit to assess both economic and environmental impacts as they aim at identifying the possible trade-off between economic and environmental considerations (Janssen and van Ittersum, 2007). In the case of legume production, several bio-economic models have been conducted, at the field scale (Reckling et al., 2016) and at the farm scale (Schläfke et al., 2014). Such models are relevant because decision-making process takes place at the farm scale and because they help appraising farm's sustainability (Reidsma et al., 2018). However, they fail aggregate impacts at higher scales (e.g., region, country), while this may be useful to policy makers. Hybrid models address this issue by aggregating results from the farm to higher scales (Britz et al., 2012). Hybrid bio-economic models have been mainly developed to study policy changes that impact agricultural production (Chopin et al., 2015; Gocht et al., 2017). These models usually take into account the diversity of farms (e.g., crop farms, livestock farms) and technologies but none of them focuses on legume production. Besides, one of the levers to increase the production of legumes has been very little studied: crop-livestock integration beyond the farm level (Martin et al., 2016). On the one hand, livestock farms can export organic fertilizers to crop farms, which are deficient in nitrogen for crop fertilization. On the other hand, crop farms can produce legumes and sell them to feed animals in livestock farms. Such interactions can be either studied qualitatively (Regan et al., 2017), or simulated through either agent-based models (Happe et al., 2011) or mathematical programming models with supply and demand either explicitly or endogenously described (Helming and Reinhard, 2009; Spreen, 2006). Our hypothesis is that the complementarity between specialized crop farms and livestock farms can increase protein self-sufficiency while having positive economic and environmental impacts at the regional level. This complementarity between farms would thus correspond to an "agroecological way of producing", which combines high productivity and limited impacts on the environment. The bio-economic model SYNERGY proposed in this paper is in direct line with these considerations. First, it is a hybrid model implemented at farm scale and then, aggregated at the regional level. Second, it takes into account various types of farms, pedological and climatic conditions and technologies inside the region in order to minimize aggregation bias. Third, the complementarity of farms is highlighted by accounting for exchanges of crops and organic fertilizers between farms.

The paper is structured as follows. The second section presents our methodological approach. The area under study and the applied model are described in the third section. The fourth section presents the results. The fifth section is devoted to discussions and conclusion.

## 2. Method

### *2.1. Overview of the bio-economic model SYNERGY*

The bio-economic model SYNERGY (cross-Scale model using complementaritY betweeN livEstock and cRop farms to enhance reGional protein self-sufficiencY) is a hybrid static programming model, which is implemented at farm scale and then, aggregated at the regional level. SYNERGY simulates farms types including livestock farms and crop farms located in a same region (in the model, a livestock farm is defined as a farm where animals such as bovines, hogs are raised). SYNERGY model consists of several modules, which detail crop and livestock management systems (i.e., farm activities) (Fig. 1). Crop management systems (here defined as the way to produce a specific crop, including different levels of inputs used, associated with different yields) are described in cropping and fertilization modules. Livestock management systems (here defined as the way to raise a specific animal, including different feed rations associated with different milk and meat yields) are described in livestock and feeding modules. Finally, the environmental module describes impact of farm activities on the environment (in the current state of the model, only nitrogen impact is taken into account).

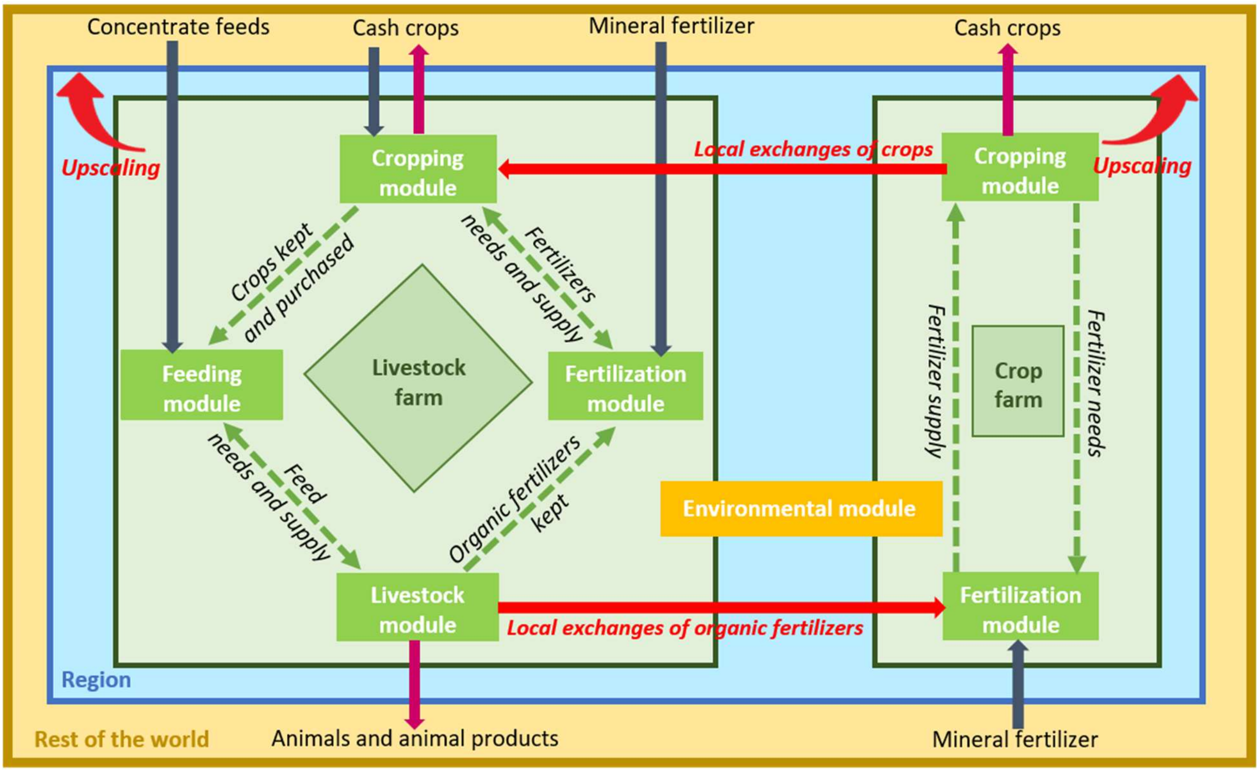

**Fig. 1.** Presentation of SYNERGY model adapted from Jouan et al. (2017).

Thanks to farm activities, farmers produce commodities (i) to self-supply needs for their management systems (e.g., a livestock farmer can use crops grown on his farm to feed his animals) and, (ii) to sell them on markets. Depending on the commodity, commodities can be exchanged on either local markets, world market (i.e., “Rest of the world” in Figure 1), or both markets (Table 1). Farmers can also buy commodities they cannot produce (e.g., mineral fertilizer, concentrate feeds[4]). Exchanges occur at exogenous prices, as we assume that the region meets the characteristics of a small country compared to the rest of the world. For crops, they are purchased at a higher price than the selling price to take into account transport and transaction costs. Regarding organic fertilizers, their price corresponds to a cost of transport, borne by the seller. Due to high cost of transport, organic fertilizers can be exported only inside a limited area, which corresponds to a French district.

**Table 1**
Possible outlets of commodities produced in farms

| Module | Commodity | Exchanged on local market | Exchanged on world market | Kept on farm |
|---|---|---|---|---|
| Cropping | Corn silage | X | | X |
| | Grain | X | X | X |
| | Other silages, hay and grass | | | X |
| Fertilization | Organic fertilizers | X | | X |
| Livestock | Meat | | X | |
| | Milk | | X | |

SYNERGY generates three types of outputs. First, an assessment of protein self-sufficiency in animal feed is performed from results on land use, and crop and herd management systems. Second, a farm economic performance assessment is performed through incomes computation. Third, an environmental assessment is performed thanks to the environmental module that calculates different nitrogen-related indicators. All these assessments are made at the farm scale for each farm type, in each territory, and at the regional level through a scaling process.

## *2.2. The objective function and the principles of commodity balance*

The objective function is a Markovitz-Freund mean-variance one. It implements an optimal land allocation between activities of each farm and between the areas of farm in the region. This optimal allocation is obtained from the maximization at the regional level of the expected utility, *E(U),* which

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[4] In the model, concentrate feeds are manufactured concentrate feeds such as oilcakes (e.g., soybean meal) and milling by-products (e.g., bran). Row concentrate feeds such as cereals and legumes are referenced as “crops”.

is the sum of expected incomes $R_{f,s}$ of farm *f*, in territory $s$, balanced with the sum of positive and negative variations of these incomes, respectively $Z^{+}_{f,s}$ and $Z^{-}_{f,s}$, multiplied by a risk-aversion coefficient $\Phi_{f,s}$ for farm *f*, in territory $s$ (Eq. 1).

$$\text{MAX E(U)}= \sum_{f}\sum_{s}\text{E}(\text{R}_{f,s}) - \Phi_{f,s}\sum_{f}\sum_{s}(Z^{+}_{f,s} + Z^{-}_{f,s})\,, \tag{1}$$

The income $R_{f,s}$ is the sum of $Profit_{m,f,s}$ of each modules $m$ of farm *f*, in territory $s$, plus $Subsidies_{f,s}$. This profit comes from commodities sold on local markets $SL_{c,f,s}$ and on world market $SW_{c,f,s}$ at a selling price $Ps_c$, minus commodities purchased on local market $BL_{c,f,s}$ and on world market $BW_{c,f,s}$ at a buying price $Pb_c$ and minus cost of production $COST_c$ multiplied by the quantities of commodity produced $Q_{c,f,s}$ (Eq. 2). This generic equation (Eq. 2) is adapted to the specificities of each module (as described in the next section.).

$$Profit_{f,m,s} = \sum_{c}\left[(SL_{c,f,s} + SW_{c,f,s})Ps_c - (BL_{c,f,s} + BW_{c,f,s})Pb_c - COST_c Q_{c,f,s}\right]\,, \tag{2}$$

## *2.3. SYNERGY modules*

### *2.3.1. The cropping module*

The cropping module sets the quantity of each crop within a farm, and its outlet: kept on farm in order to meet feed requirements, or sold on local or world markets. Crop activities are implemented through a combination of crop/rotations and take into account the precedent effect. As SYNERGY is a static model, rotations correspond to a combination of different crops with constraints of crop share corresponding to the crop minimum return period. The cropping module's profit accounts for both exchanges of crops and costs of production (i.e., cost of seeds and costs of pesticides). In livestock farms, cropping module's profit also accounts for a part of the feeding costs through crops kept in the farm and crops purchased on markets in order to feed animals.

### *2.3.2. The animal module*

The animal module sets the quantity of meat and milk (if any) produced by each animal category within a farm (e.g., cow, growing-finishing pig) and sold on world markets. The quantity of meat and milk produced per farm depends on animal numbers and productivity, which depends on livestock management systems (technology). The animal module's profit accounts for sales of meat and milk (if any), minus costs of breeding and the last part of feeding costs including purchases of concentrate feeds. As far as milk production is concerned, a contract between the dairy farm and its cooperative is implemented which prevents milk production from exceeding the quantity of milk negotiated in the contract. These contracts are not exchangeable between farms.

### *2.3.3. The fertilization module*

The fertilization module sets the quantity of animal manure produced in each farm, and its outlet: kept on farm in order to meet crop organic nitrogen requirements or sold on local market. The quantity of animal manure produced depends on the number of animals and the quantity of animal manure produced per animal, which depends on livestock management systems. The fertilization module's profit is always negative as it includes the costs of exporting organic fertilizers (if any) on local markets and purchases of mineral fertilizers on world markets. The fertilization module also balances crop nitrogen requirements with main nitrogen resources, based on the French Comifer's method. The model takes into account different sources of nitrogen: nitrogen fixed by the different legumes, produced in animal manure, bought in mineral fertilizers and mineralized by soil through humus, crop residues and grassland overturning. Crop fertilization is also limited by regulatory constraints, which restrict the amount of organic fertilizers spread on the field.

### *2.3.4. The feeding module*

The feeding module balances feed needs with feed resources. It does not generate profit or cost as feeding cost are included in both cropping and animal modules. Feed needs are described by rations, which are composed of two categories: crops and concentrates feeds. These rations differ according to the type of animals, the NUTS 2 region, but also according to the more or less intensive technologies set up in the case of dairy farms. Feed resources are (i) crops produced on farm, (ii) crops bought on local and world market, and (iii) concentrate feeds bought on world markets. The protein self-sufficiency is computed in the feeding module. It is the ratio between locally produced and consumed total nitrogenous matter (TNM) and all TNM consumed. At the farm scale, locally produced TNM comes from proteins in crops kept on farm. At the regional level, locally produced TNM comes from proteins in crops kept on farms and bought on local market. All TNM consumed includes proteins in crops kept on farm, and bought on local and world market.

### *2.3.5. The environmental module*

The environmental module implements two indicators based on Godinot et al. (2014). The SyNE (System Nitrogen Efficiency) indicator assesses efficiency of agricultural systems in transforming N inputs into desired agricultural products. The indicator SyNB (System N Balance) reflects the potential for total N losses from agricultural systems. Both SyNE and SyNB take into account all sources of N, including indirect losses i.e., those occurring during the production and transport of inputs. It also includes the annual change in N stock in the soil. The N efficiencies and N balances of different representative farms can be compared. Different assumptions were made in order to adapt SyNE and SyNB to SYNERGY: each ration is associated with a unique type of animal housing; the only mineral fertilizer used is ammonitrate; all seeds are bought, no animal is bought to renew the herd; no milk powder is bought; cows and heifers graze day and night.

## 3 The case study

### *3.1 Overview of the case study*

SYNERGY was implemented in a region corresponding to both NUTS 1 regions Pays de la Loire and Brittany (FRG and FRH), located in western France. In these regions, animal productions are significant: the whole region represents 13.5% of French utilized agricultural land but concentrates 68% of pig production and 38% of the French milk production[5]. Concerning legumes, the area of grain legumes has more than doubled between 2013 and 2017 in the whole region, but it represented only 1% arable land in 2017[5]. Nevertheless, the region is not homogeneous as most of these animal productions are gathered in the Northern part, the crop production being more in the Southern part. The heterogeneity of the region was taken into account in two ways. First, the region was divided into nine territories corresponding to French districts in order to consider the diversity of crop production: which crops can be grown and at what yields, depending on soil and climatic conditions. Second, seven farm types were implemented in order to take into account the diversity of farms, and in particular the diversity of animal productions. Data sources of the different technical coefficient implemented in the model are described in Table 2.

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[5] Authors calculations, from Agreste, http://agreste.agriculture.gouv.fr/page-d-accueil/article/agreste-donnees-en-ligne

**Table 2**
Data sources of the SYNERGY model's technical coefficients implemented in the case study region

| Module | Data | Source |
|---|---|---|
| Animal module | Milk and meat yields | INOSYS Réseaux d'élevage, IFIP |
| | Operating costs (insemination, vet) | INOSYS Réseaux d'élevage, IFIP |
| | Selling price | FranceAgriMer, IDELE |
| Cropping module | Crop yields | FranceAgriMer |
| | Operating costs (seeds, pesticides) | Regional extension services, PEREL |
| | Buying price | IFIP |
| | Selling price | FranceAgriMer |
| Feeding module | Standard and alternative bovine feed rations | IDELE, INRAtion software |
| | Standard and alternative hog feed rations | IFIP, Porfal© software |
| Fertilization module | Need of fertilization (nitrogen) | Comifer |
| | Quantity of nitrogen produced by animals | RMT livestock and environment (CORPEN) |
| | Calculation of nitrogen balance | Comifer |

### *3.2. Diversity of farms*

In the region, seven farm types were considered: one crop farm type, one hog farm type and five dairy farm types (Table 1). These dairy farms were built based on the Inosys-Réseaux d'élevage[6] references. They differ according to the NUTS 2 region, but also according to the degree of intensification of agricultural production, in the case of bovine farms. This intensification is represented by the share of forage corn in the main fodder area of the farm and by the level of milk productivity. A unique type of hog farm was built, as feed systems in hog farms are far less dependent of farm structural characteristics.

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[6] Inosys-Réseaux d'élevage aims at producing references on herbivore breeding systems and builds test cases and case studies describing different livestock management systems

**Table 3**
Main characteristics of farm types implemented in SYNERGY (standard rations)

| Farm type | Production | Average production/animal |
|---|---|---|
| DA_FRG_corn | dairy cows and crops | 8 600 L /cow |
| DA_FRG_mixed | dairy cows and crops | 7 017 L /cow |
| DA_FRH_corn | dairy cows and crops | 9 000 L /cow |
| DA_FRH_mixed | dairy cows and crops | 7 092 L /cow |
| DA_grass | dairy cows and crops | 6 205 L /cow |
| HO | growing-finishing pigs and crops | 118 kg of live weight/pig |
| CR | crops | - |

DA_FRG_corn: dairy farm type with ration based on corn of FRG sub-region; DA_FRG_mixed: dairy farm type with ration based on corn and grass of FRG sub-region; DA_FRH_corn: dairy farm type with ration based on corn of FRH sub-region; DA_FRH_mixed: dairy farm type with ration based on corn and grass of FRH sub-region; HO: hog farm type; CR: crop farm type

### *3.3 Diversity of technologies*

To cope with the technological changes needed to improve protein self-sufficiency, alternative rations have been developed for each farm type, in addition to standard rations. In dairy farms, the rations were built by using the software Inration (INRA, 2003) which permits to set up rations respecting bovine nutritional constraints. Four dairy rations for each dairy farm type were built: a standard ration with soybean meal, which is the most widespread ration, and four alternative ration built by substituting the soybean meal by legumes: either pea, or faba bean, or dehydrated alfalfa, or pasture associated with clovers. If it was not possible to replace all soybean meal by legumes due to nutritional constraints, some rapeseed meal was added. Finally, fifty dairy rations were inserted into the model, twenty-five for dairy cows and twenty-five for heifers (we suppose that calves eat only milk). In hog farms, the rations were built by using the Porfal© software, which permits to set up rations fulfilling hog nutritional constraints while minimizing the cost of the ration. The cost minimizing was based on mean prices calculated from monthly feed outlooks for the years 2013-2017 (Institut du porc, 2017). One alternative rations of hog farms were built by substituting soybean meal by a set of grain legumes (i.e., pea and faba bean). Four hog rations were inserted into the model, two for growing-finishing pigs, and two for sows (piglets are not modelled). In both dairy farms and hog farms, alternative rations are described with slightly lower yields in terms of milk or meat produced. Concerning crop production, we considered 37 rotations including 11 different crops.

**Table 4**
Example of ration compositions implemented in the SYNERGY model

| Rations | Forage | Crops (except legumes) | Legumes | Concentrate feeds |
|---|---|---|---|---|
| dairy cow_ standard | 76% | 10% | 0% | 14%[a] |
| dairy cow_ faba | 62% | 9% | 29% | 0% |
| dairy cow_ pea | 60% | 9% | 28% | 4%[b] |
| dairy cow_ alfafa | 56% | 10% | 33% | 1%[b] |
| dairy cow_ clover | 41% | 8% | 37%[c] | 13%[b] |
| GF pig_standard | 0% | 91% | 0% | 8%[a] |
| GF pig_pea&faba | 0% | 82% | 15% | 3%[b] |

Dairy cow's rations are for the DA_FRG_corn farm type; synthetic amino acids present in rations are not included in the model; GF: growing-finishing; [a] soybean meal; [b] rapeseed meal; [c] associated pasture with clovers

### *3.4 Scenarios*

Different scenarios were simulated. The first scenario is the baseline scenario (B), which should reproduce the observed data (see 3.5 Model evaluation). The second scenario (SC_Ecrop) allows for the local exchanges of crops between farms: farmers can sell and buy crops with other farmers inside the region. The third scenario (SC_Efertilizer) allows for local exchanges of organic fertilizers between farms. These two last scenarios permits to understand. These two last scenarios make it possible to understand the distinct effects of local exchanges of either crops, or organic fertilizers, on the evolution of protein self-sufficiency. Finally, the fourth scenario (SC_E) allows for local exchanges of both crops and organic fertilizers between farms. This scenario makes it possible to understand the simultaneous effects of local exchanges of crops and organic fertilizers.

### *3.5 Model evaluation*

The SYNERGY model is used here as a normative model, which aims at investigating the impacts of an innovation, i.e. the development of legumes to enhance protein self-sufficiency in animal feed. A calibration with positive mathematical programming (implementing econometric methods or not) is disputable in the present situation because of lack of data (Buysse et al., 2007; Jacquet et al., 2011): the area of legumes is very limited and no data are available yet on the protein self-sufficiency in animal feed. Nevertheless, in the baseline situation, SYNERGY model should reproduce the structural characteristics of the agricultural sector in the case study region. The model was bounded so that milk production remains between 70% and 130% of the observed levels in each district. Indeed, although dairy quotas have disappeared, dairy farms still hold a multi-year contract with their contracting industry, which leads to a fairly stable production. The surface of permanent pasture was also bounded so that these surfaces remains between 90% and 110% of the observed levels in each district. Besides, a comparison of observed data with SYNERGY outputs from the baseline scenario was implemented to validate the model. For animal production, the percentage of absolute deviation (PAD) between the observed levels of animal commodity production and the simulated levels for the baseline scenario was implemented (Hazell and Norton, 1986). For crop production, the percentage of relative deviation (PRD) was implemented, as only relative distribution of crops was available for the case-study region. Results are considered as acceptable when PAD is less than 15% at the regional level. The values implemented for base year are the mean values of 2013-2017.

## 4 Results

### *4.1 Evaluation of the model*

The calibration of SYNERGY is still in process : PAD is barely above 15% for 3 commodities out of 8 : grain and forage corns, and wheat. (Table 4).

**Table 4:**
Evaluation of SYNERGY by calculating PAD and PRD between the observed and simulated levels of commodity productions for the baseline scenario at the regional level

| | Level of commodity production | | Indicators of model deviation | |
|---|---|---|---|---|
| | Observed data | Baseline scenario | PAD | PRD |
| forage corn | 26% | 9% | - | 18% |
| grain corn | 13% | 30% | - | -17% |
| pastures | 15% | 15% | - | 0% |
| rapeseed | 5% | 2% | | 3% |
| wheat | 23% | 7% | - | 16% |
| | | | | |
| dairy cows | 867 884 | 941 717 | -9% | - |
| growing-finishing pig | 12 526 667 | 11 639 712 | 7% | - |
| milk (hl) | 62 220 267 | 60 869 695 | 2% | - |

### *4.2 Scenario analysis*

- *Scenario SC_Ecrop : Exchanges of crops are possible between farms*

When local exchanges of crops are possible between farms, the animal production or the surfaces of the different crops do not change compared to the baseline scenario (B). Nevertheless, the self-sufficiency at the regional level rises slightly by 1%. It can be explained by the local exchanges of pea between crop farms and hog farms: hog farms import less pea from the rest of the world to feed animals. Besides, local exchanges of grain corn and wheat also happen which help to rise the protein self-sufficiency as these crops also contain proteins. Concerning the economic assessment, the incomes per hectares are constant. Concerning the environmental assessment, the SyNE (System Nitrogen Efficiency) indicator assesses the efficiency of agricultural systems in transforming N inputs into desired agricultural products. The higher it is, the more efficient agricultural systems is. The SyNB (System N Balance) indicator reflects the potential for total N losses from agricultural systems. The higher it is, the more potential losses there are. At the regional level, SyNE and SyNB are constant.

- *Scenario SC_Efertilizer : Exchanges of organic fertilizers are possible between farms*

When local exchanges of organic fertilizers are possible between farms, the production of milk does not change but the number of cows decreases (-2%). Thus the production of milk becomes more intensive with more corn-based dairy systems and more standard rations increases. The production of pig also rises by 17%. An explanation is that hog farms are now exporting organic fertilizers, allowing the development of pig production, which is, in the model, more profitable per hectare than dairy production. Concerning crop production, the surfaces of legumes rise slightly by 3%, as the surfaces of cereals (+12%), whereas the surfaces of rapeseed and pasture decrease. This is linked with the changes of livestock production. Contrary to the last scenario, the protein self-sufficiency slightly decreases at the regional level (-1%) due to the rise of pig production, which is not balanced by a rise of production of protein for feed. Concerning the economic assessment, the income at the regional level rises by 14%, thanks to a rise of hog farms' incomes. Concerning environmental assessment, SyNB stays constant by SyNE increases slightly (+1), thanks to the higher efficiency of pig farms exporting organic fertilizers.

- *Scenario SC_E: Exchanges of crops and organic fertilizers are possible between farms*

When local exchanges of crops and organic fertilizers are possible between farms, the same changes in the surface of crops and animal productions are observed, as in the scenario when only exchanges of organic fertilizers are possible ("SC_Efertilizer"). Nevertheless, exchanges of crops rises by 172% compared to the scenario when only exchanges of crops are possible ("SC_Ecrop"). As the result, the protein-self sufficiency stays constant compared to the baseline scenario. Indeed, the pig production still rises but it is compensated by more proteins for feed produced and exchanged locally. Concerning economic assessment, the incomes also rises by 14% at the regional level, just as in the scenario "SC_Efertilizer". Concerning environmental assessment, at the regional level, SyNE rises by 1 point and SyNB is constant, just as in the scenario "SC_Efertilizer. Nevertheless, if we look closer, the both environmental indicators are improved for the hog farms, whereas they are worsened for the other farms.

**Table 3:**
Summary of results from the SYNERGY model applied to the case study

| | B | SC_Ecrop | SC_Efertilizer | SC_E |
|---|---|---|---|---|
| Legume area | 234 301 ha | +0% | +3% | +3% |
| Milk produced | 60 869 695 hl | +0% | -2% | -2% |
| Pig produced | 11 639 711 | +0% | +17% | +17% |
| Protein self-sufficiency | 59% | +1% | -1% | +0% |
| Incomes | 664 €/ha | +0% | +14% | +14% |
| SyNB | 73 | +0 | +0 | +0 |
| SyNE | 0.52 | +0 | +1 | +1 |

B: baseline scenario; SC_Ecrop: scenario with local exchanges of crops; SC_Efertilizer: scenario with local exchanges of organic fertilizer; SC_E: scenario with local exchanges of crops and organic fertilizers; SyNB and SyNE: nitrogen-related indicators based on Godinot et al. (2014).

## 5 Discussion & conclusion

The SYNERGY model aims at testing different scenarios influencing the protein self-sufficiency at the regional level, especially through the production of legumes and farm-to-farm exchanges of crops and organic fertilizers. It was implemented in a region on western France where animal productions are dominant. The main assumption was that the complementarity between specialized crop farms and livestock farms can increase protein self-sufficiency while having positive economic and environmental impacts at the regional level. The model reproduces the main characteristics of agricultural productions studied in the case study region. Different scenarios were implemented. First, when local exchanges of crops are possible, the protein self-sufficiency at the regional level can be slightly enhance. Second, when local exchanges of organic fertilizers happen, the protein self-sufficiency slightly decreases due to a rise of pig production. Third, when exchange of crops and organic fertilizers happen simultaneously, the protein self-sufficiency slightly increases even though the pig production increases. In this case, incomes rise at the regional level but the impacts in term of nitrogen management are more reserved.

The main contributions of the SYNERGY model are its ability to evaluate jointly two promising levers for developing protein self-sufficiency. On the one hand, crop-livestock integration beyond the farm level through the exchange of crops and organic fertilizers between specialized farms. On the other hand, the introduction of legumes into feed as an alternative to soybean meal. The design of these innovative rations was the result of a long process involving the pooling of different sources of data, the support of specialists from various fields of agricultural applied sciences as well as the handling of different specialized software. Moreover, in the current state of the model, SYNERGY is only implemented in western France. More conclusive results should be found by expanding the area studied to a larger and more diversified area. In particular, it would be interesting to include the NUTS 2 region Champagne-Ardennes (FRF2) which is a mainly cereal region where alfalfa is cultivated in crops farms in order to be dehydrated and exported in other regions. Likewise, it would be relevant to include other agricultural productions that also consume a lot of protein in feed, such as beef and poultry productions. Finally, other environmental indicators should be introduced in order to take into account other environmental issues such as greenhouse gas emissions and pesticides. Despite these limitations, one of the results from the SYNERGY model is particularly interesting: local exchanges of crops and organic fertilizers can represent an important lever to enhance animal production without degrading environmental conditions. However, is it really relevant to enhance animal production in this region when meat consumption decreases in France? The evolution of the consumer preferences have to be taken into account. For example, the demand for GMO-free animal products is emerging and can represent an important lever to increase the use of legume-based rations in feed. Finally, exchanges between farms are unlikely to happen without local intermediaries such as cooperatives. More research is thus needed to understand the vertical relationships that can exist between farmers and cooperatives in the case of a local feed system. In this perspective, it would be helpful to study the characteristics of existing and forthcoming legume production contracts, in particular when the cooperative creates added value in animal feed through technical processes and labelling.

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