SYNERGY: a bio economic model assessing the economic and environmental impacts of increased regional protein self-sufficiency

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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. The purpose of this paper is to assess the impacts of increased protein self-sufficiency through legume development at the regional level. To do so, the SYNERGY bio-economic model is set up. This model accounts for (i) different scales, (ii) different types of farm, (iii) different pedological and climatic conditions and (iv) possible exchanges of organic fertilizers and crops 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 exchanges between farms, as long as locally purchased crops are at least 10% cheaper than world purchased ones. This price differential can represent the saving in terms of transport and transaction costs. When local exchanges are possible and a GMO-free certification is set up, legume-based rations are dominant in livestock farms, and the protein self-sufficiency is even more enhanced. In both situations, the economic consequences are positive as incomes increase at the regional level. However, the impacts in term of nitrogen management are more reserved.

Keywords:

Legumes, bio-economic model, farm complementarity

1. Introduction

The European Union (EU) relies on imports to feed farm animals. In particular, protein self-sufficiency[1] in EU for feed is not reached. Thus, 58% of protein rich materials[2] used in animal feed are imported, and consist at 88% of soybean meals (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]. In order to enhance legume production, EU set up several types of area subsidies such as coupled support, agri-environmental measures or green

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[1] The protein self-sufficiency in EU defined as the ratio of proteins produced and consumed in EU by animals to total protein consumed by animals

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

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

payments, which assimilate legumes as ecological focus areas. Following this reform, the area of grain legumes has 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 advantage 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 assessing the impacts of increased protein self-sufficiency through crops exchanges between farms. Economic and environmental impacts will be assessed. Mathematical programming models offer a prospective 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 permits 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 agent-based models (Happe et al., 2011) or mathematical programming models with supply and demand either explicitly or endogenously described (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.

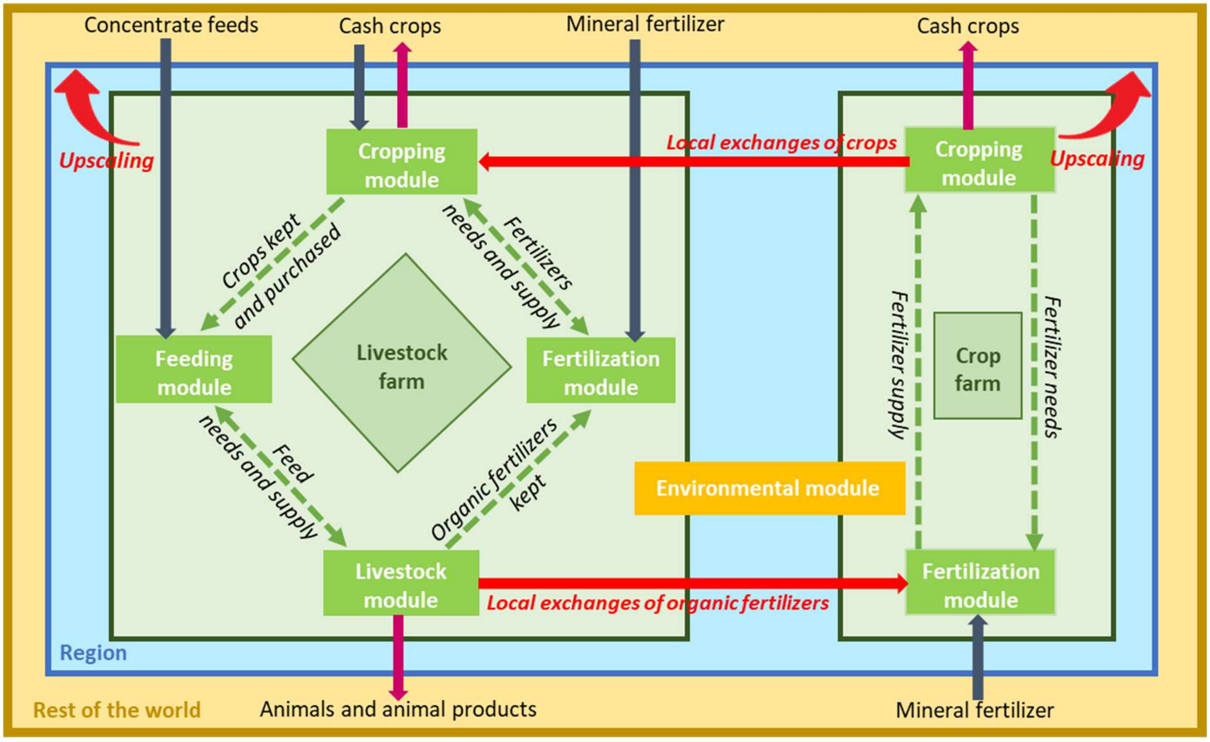
2. Method

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. It optimizes the sum of farms' expected income 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). 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 its 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. Farmers can also buy commodities they cannot produce (e.g., mineral fertilizer, concentrate feeds[4]).

Figure 1
Explanatory scheme the SYNERGY model, adapted from Jouan et al., (2017)



Continuous arrows represent exchanges on local and world markets, dashed arrows represent fertilization and feeding balances inside farms

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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".

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 though incomes computation. Third, an environmental assessment is performed thanks to the environmental module that balances 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.

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 is the sum of expected incomes $\mathrm{R}_{f,\mathrm{s}}$ 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).

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

The income $\mathrm{R}_{f,\mathrm{s}}$ 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 section 2.2.). The model also introduces the possibility to add a price differential between locally and world bought commodities, which reflects the potentials lower costs of transport and transaction for local commodities.

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

2.2. SYNERGY modules

- *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.

- *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 depend 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. 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". 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.

- *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 environmental constraints, which restrict the amount of animal manure spread on the field.

- *The feeding module*

The feeding module balances feed needs with feed resources. It does not generate profit or cost as feeding cost are including in the cropping and animal modules. Feed needs are described by different animal rations, which are composed of crops and concentrates feeds. These rations differ according to the type of animals, and the type of farm. 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 come 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.

- *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 the two NUTS 2 regions FR51 and FR52 (Pays de la Loire and Brittany), located in western France. In this region, animal productions are significant: the region represents 13.5% of French utilized agricultural land but concentrates 68% of pig production and 38% milk production of France[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 (id.). 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 types were implemented in order to take into account the diversity of farms, and in particular the diversity of animal productions.

3.2. Diversity of farms

In the region, seven farm types were considered: one type of crop farm, one type of hog farm and five types of dairy farm (Table 1). These dairy farms were built based on the Inosys-Réseaux d'élevage[6] reference. 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. A unique type of hog farm was built, as feed systems in hog farms are far less dependent of farm structural characteristics.

Table 3
Main characteristics of farm types implemented in SYNERGY

Farm type	Production	Average production/animal	% forage corn in main fodder area
DA51_corn	dairy cows and crops	8 600 - 8 100 L /cow	x ≥30%
DA51_mixed	dairy cows and crops	7 017 - 6 517 L /cow	10%< x <30%
DA52_corn	dairy cows and crops	9 000 - 8 500 L /cow	x ≥30%
DA52_mixed	dairy cows and crops	7 092 – 6 592 L /cow	10%< x <30%
DA_grass	dairy cows and crops	6 205 – 5 705 L /cow	10% ≤ x
HO	growing-finishing pigs and crops	118 kg of live weight/pig	no constraints
CR	crops	-	no constraints

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

[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

3.3 Diversity of technologies

Concerning animal production, in order to address the technological change induced by the challenge of increasing protein self-sufficiency, we considered both standard and alternative feed rations, which differ according to the livestock farm type they belong. In dairy farms, the rations were built by using the software Inration. Five 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 either rapeseed meal, or pea, or faba bean, or dehydrated alfalfa, or pasture associated with forage legumes. If it was not possible to replace all soybean meal by legumes due to nutritional constraints, rapeseed meal was added. Sixty dairy rations were inserted into the model, thirty for dairy cows and thirty for heifers (we suppose that calves eat only milk). In hog farms, the rations were built by using the software Porfal© 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). Two alternative rations of hog farms were built by substituting soybean meal by either rapeseed meal, or a set of grain legumes (i.e., pea and faba bean). Six hog rations were inserted into the model, three for growing-finishing pigs, and three 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.

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). A second kind of scenarios was implemented where local exchanges between farms are possible: farmers can sell and buy crops and exchange organic fertilizers to other farmers inside the region. These scenarios differ by setting various price differentials between crops bought on local or world market, from 0% to 25%: these scenarios are called SC_E0, SC_E05, SC_E10, SC_E15, SC_E20, SC_E25. The price differential reflects the potential lower costs of transport and transaction for locally exchanged commodities. A last scenario, called SC_GMO, was implemented: a GMO-free certification is set up, in addition to local exchanges without a price differentiation. This certification applies to animal commodities produced with legumes or rapeseed, instead of soybean meal, which is mostly genetically modified. Prices of certified GMO-free milk and meat are put 6% higher than standard products, as for emerging GMO-free milk sectors in the case study.

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 by econometric method or positive mathematical programming is disputable in the present situation because of lack of data (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 milk production in each district remains between 70% and 130% of the observed levels. Indeed, although the quotas have disappeared, the dairy farms still hold a multi-year contract with their dairy, ordering a stable production. 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 satisfying, as the PRD of only 2 out of 10 commodity are above 15%: ones of grain corn and pastures. (Table 2). It can be explained by the high variability of grassland and corn yields in the region, which may not sufficiently be reflected in the model.

Table 2:

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
barley	4%	12%	-	1%
legumes	1%	5%	-	-3%
forage corn	17%	20%	-	-5%
grain corn	8%	2%	-	-20%
pastures	47%	40%	-	18%
rapeseed	3%	4%		-1%
wheat	19%	26%	-	9%
dairy cows	1 280 206	1 260 3046	2%	-
growing-finishing pig	15 534 301	14 756 683	7%	-
milk (hl)	91 861 815	102 405 482	-11%	

4.2 Analysis of scenarios

- *Comparison of "baseline" scenario and scenario "with local exchanges"*

In the baseline scenario (B), pure legume cultures represent 3% of the agricultural area in the region, with mainly alfalfa an associated pastures are represent 5%. Standard rations (i.e., with soybean meal) are used for feeding 56% of dairy cows and 36% of pigs. We implemented a scenario where local exchanges of crops and organic fertilizers are possible (SCE_0). In this scenario, the surfaces of legumes and associated pasture in the region decrease by 4%, replaced by barley and grain corn (Table 3). This is linked to an increase of pig production, which rises by 30% whereas milk production decreases by 4%. An explanation is that hog farms are now exporting organic fertilizers, which allows the development of pig production, which is, in the model, more profitable per hectare than dairy production. It is interesting to notice that there is a change in dairy farm types: corn-based dairy farms decrease for the benefit of mixed dairy farms (i.e., corn and grass based). Thus, dairy farms become less intensive. Similar to the previous explanation, dairy farms are now exporting organic fertilizers, which allows them to use rations that produce more nitrogen such as mixed rations. Concerning rations, the proportions of each type of ration in hog farms do not change. However, in dairy farms, legume-based rations are slightly less implemented (-1%). Exchanges of cereals and corn happens between livestock farms and crop farms but do not increase the protein self-sufficiency of the region. At the contrary, the protein self-sufficiency slightly decreases at the regional level 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 incomes per hectares of hog farms rise by 33%, but the incomes of dairy farms decrease by 4%. These changes make sense as milk production becomes less intensive and pig production more intensive. Overall, the income at the regional level rises by 10%. 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. At the regional level, SyNE slightly increases (+0.02). If we look closer, SyNE increases in dairy and crop farms but decreases in hog farms. The SyNB (System N Balance) indicator reflects the potential for total N losses from agricultural systems. At the regional level, SyBN slightly increases (+1), in particular in hog farms. These results are due to the increase of hog production, enhancing the production of organic fertilizers, which is not completely compensated by exports to crop farms. Finally, with local exchanges, the hog production rises, economic results are improved, but environmental and self-sufficiency indicators are slightly worsened.

- *Comparison of "baseline" scenario and scenario "with local exchanges and price differentiation"*

We implemented different scenarios when local exchanges are possible and prices of locally purchased crops are from 5% to 25% cheaper than those of world purchased crops. The legume area starts to increase by 20% from the scenario SC_E10, when the price differential is 10%. In this scenario, milk production decreases by 8%, whereas pig production rises by 58%, compared to the baseline scenario. Thus, the livestock production changes in proportion slightly higher than the scenario without price differential (SC_E0). Concerning rations, the proportions of each type of ration in hog farms do not change. However, in dairy farms, legume-based rations are slightly less implemented (-1%). As before, corn-based dairy farms decrease but for the benefit of grass-based dairy farms. Thus, dairy farms become even less intensive than in the scenario without price differential. It is interesting to notice that exchanges of crops are multiplied by 439% between this scenario and the scenario without price differential. In particular, hog farms buy locally some legumes (29% of the total pure legumes produced) to crops farms. As a result, the protein self-sufficiency slightly increases (+2%) compared to the baseline scenario, because even though the pig production rises. Concerning the economic assessment, the incomes per hectare of hog farms rise by 15%, but the incomes of dairy farms decrease by 5%, compared to the baseline scenario. These changes make sense as milk production become less intensive and pig production more intensive. Overall, the income at the regional level rises by 10%, just as in the scenario without price differential. Concerning the environmental assessment, SyNE remains constant at the regional level compared to the baseline scenario. However, if we look closer, SyNE rises in dairy and hog farms, and decreases in crop farms. Thus, dairy and hog farms become more efficient whereas crop farms become less efficient. In the same way, SyNB just slightly decreases at the regional level compared to the baseline scenario, but it decreases in hog farms and increases in crop farms. These results can be explained by the high amount of organic fertilizers exported from hog farms. In return, crop farms use more organic fertilizers, but these organic fertilizers are less valued than chemical ones. Finally, with local exchanges and price differential, the hog production increases even more, economic and self-sufficiency indicators are improved but environmental results are slightly worsened.

- *Comparison of "baseline" scenario and scenario "with local exchanges, price differentiation of 10% and GMO-free certification"*

We implemented a scenario where local exchanges are possible, with a price differentiation at 10%, and a GMO-free certification. This certification is set up to animal commodities produced with legumes instead of soybean meal: prices of such commodities are 6% higher. In this scenario, the legume area rises by 192%, mainly thanks to the increase of pea and associated pasture. Milk production decreases by 2% whereas pig production rises by 58%. Thus, the livestock production changes in the same proportion than the scenario with only price differential (SC_E10). Concerning rations, the proportions of each type of ration in hog farms do not change. However, in dairy farms, legume-based rations represent now 92% of rations. Unlike in other scenarios, grass-based dairy farms decrease, for the benefit of corn-based and mixed-dairy farms. Thus, dairy farms become more intensive. It is interesting to notice that exchanges of crops increased by 497% compared to the (SC_E0). In particular, hog farms and dairy farms no longer buy crops only from crop farms, but also buy them from one another. As a result, the protein self-sufficiency rises by 5% compared to the baseline scenario even though the pig production rises. Concerning the economic assessment, the incomes of dairy farms increase by 1%, those of hog farms by 17%, compared to the baseline scenario. These changes make sense as milk and pig productions become more intensive. Overall, the income at the regional level rises by 16%, which is better than the two other scenarios studied. Concerning the environmental assessment, SyNE decreases by 0.03 points, and SyNB increases by 3 points at the regional level, compared to the baseline scenario. However, if we look closer, these indicators are improved significantly in hog farms. Thus, the same trends are observed as in scenario SC_E10, with high amount of organic fertilizer exported from hog farms. Finally, with GMO-certification, the animal production rises, economic and self-sufficiency indicators are improved, but environmental results are slightly worsened.

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

	B	SC_E0	SC_E10	SC_GMO
Legume area	140 495 ha	-4%	+20%	+192%
Milk produced	102 405 482 hl	-4%	-8%	-2%
Pig produced	14 756 681	+30%	+58%	+58%
Protein self-sufficiency	59%	-2%	+2%	+5%
Incomes	1690 €/ha	+10%	+10%	+16%
crop farms	*734 €/ha*	*+1%*	*+0%*	*+0%*
dairy farms	*1612 €/ha*	*-4%*	*-5%*	*+1%*
hog farms	*3243 €/ha*	*+33%*	*+15%*	*+17%*
SyNB	42	+1	-1	+3
SyNE	0.71	+0.02	+0	-0.03

B: baseline scenario; SC_EO: scenario with local exchanges; SC_E10: scenario with local exchanges and price differentiation; SC_GMO: scenario with local exchange and GMO-free certification; SyNB and SyNE: nitrogen-related indicators based on Godinot et al. (2014).

5 Discussion & conclusion

The SYNERGY model aims at assessing the impacts of an increased of protein self-sufficiency at the regional level, by taking into account exchanges of crops and organic fertilizers between farms. It simulates different types of farms, feed rations and crop rotations. The SYNERGY model reproduces the main characteristics of agricultural productions studied in the case study region. When local exchanges are possible, and a price differential of at least 10% between locally and world purchased crops is observed, the protein self-sufficiency is slightly enhanced. The price differential can reflect the potential lower costs of transport and transaction for locally exchanged crops. When a GMO-free certification is added to the second scenario, legume-based rations are more used in livestock farms and the protein self-sufficiency rises even more. In both situations, the economic consequences are positive as incomes increase at the regional level. However, the impacts in term of nitrogen management are more reserved.

These results are highlight different issues. First, it shows that local exchanges of organic fertilizers represent an important lever to enhance animal production without degrading environmental conditions. Second, a GMO-free certification makes the animal production with legume-based rations more profitable, in particular for dairy production, but farmers still buy most of grain legumes on world market. An explanation is that yield of grain legumes are far lower than those on cereals in Europe. Magrini et al. (2016) have studied the socio-economic reasons for this situation. They show that legumes face a technological lock-in situation because agriculture and agri-food sector have focused for years on the development of other crops. One of the action identified to promote legume production is developing innovative market outlets. Thus, a certification of local feed network may be a solution. Third, the model shows that local exchanges of crops can help enhancing legumes production, and so protein self-sufficiency, provided that costs of transaction and transport are lower on local markets than on world market. This condition could be met if appropriate vertical relationships existed between farmers and cooperatives. Indeed, it is unlikely that such exchanges take place 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 terms of animal feed through technical processes (toasting, extrusion, etc.).

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 region. Besides, it would be interesting 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 greenhouse gas emissions and pesticides. Despite these limitations, the SYNERGY model is the first model to analyze the economic and environmental impacts of increased protein self-sufficiency through complementarity between livestock and crop farms.

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