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A B S T R A C T

The European Union relies on imports to meet the protein requirements of its livestock. Regions specialized in livestock production suffer even more from a deficit in protein self-sufficiency. Legumes represent an interesting source of plant protein. However, despite public policies promoting legume production, their use in animal feed remains limited. The aim of this study was to define levers to increase protein self-sufficiency in western France with a view to reducing negative environmental impacts of agricultural production. A regional foresight was performed to define innovative levers for legume production, which could improve protein self-sufficiency. Then, a modeling framework was developed to assess economic and environmental impacts of different levers. It combines a Computable Generable Equilibrium model and the regional model SYNERGY, which simulates local exchanges of crops between farms. Results showed that an increase in coupled support for legumes leads to an increase in legume production but has no influence on protein self-sufficiency or other indicators, since legumes are not used in greater amounts in feed. When the demand for GMO-free animal products increases, the production of legumes, including multispecies grassland, increases substantially, and most livestock are fed legumes. However, on pig farms, protein self-sufficiency decreases because legume production does not meet the quantity needed by pig rations. Local exchange of crops between farms was limited. Regional profit increases, but environmental indicators do not improve, in part due to the increase in legume imports from outside western France. In such a highly specialized region, improvement in protein self-sufficiency seems relatively limited, and a decrease in livestock production should be considered to meet this objective and improve environmental results.

1. Introduction

The European Union (EU) relies on imports to feed its livestock due to a deficit in protein-rich feed, containing more than 15% protein (European Commission, 2018). The self-sufficiency in protein for feed, defined as the ratio of protein produced to total protein consumed, reaches 79% in the EU, but the self-sufficiency in protein-rich feed reaches only 45% (European Commission, 2019). Of the EU's total imports of protein-rich feed, 81% is soybean meal, most of it genetically modified (European Commission, 2019; ISAAA, 2018). This situation raises questions about the EU security of supply (Gale et al., 2014) and consumer expectations for GMO-free products (e.g., milk, pork), which are associated with greater food safety and quality (Boecker et al., 2008; Dolgopolova and Roosen, 2018). In addition, the recent concept of "imported deforestation" highlights environmental damages of soybean production in certain countries (Pendrill et al., 2019).

In this context, an interesting lever to improve protein self-sufficiency in the EU, while limiting environmental impacts, would be to develop domestic production of legumes (such as faba bean, pea, soybean). The main interest of legumes lies in their ability to fix atmospheric nitrogen (N), which provides joint production of N-rich crops used for feed and food, and N as an input for subsequent crops (Peoples et al., 2009). To increase legume production, the EU established several policies, such as voluntary coupled support for legumes (Zander et al., 2016). As a consequence, the areas of sole-crop legumes increased by 88% from 2013 to 2018, reaching 4% of Europe's utilized agricultural area (Eurostat, 2017). Nonetheless, EU self-sufficiency in protein-rich feed

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increased by only 4 percentage points during the same period.

Indeed, legumes for feed suffer from a double issue of economic attractiveness in the EU. On the supply side, their lower profitability in the short term than that of other crops limits their introduction on farms, even though their opportunity costs at the rotation scale can be zero or negative (Jouan et al., 2019; Preissel et al., 2015). On the demand side, their high substitutability with other protein-rich feeds, such as imported soybean meal, limits their incorporation into rations (Meynard et al., 2018). At the junction of supply and demand, legumes also have high transaction costs and experience a lock-in situation, favoring the development of a few main crops (e.g., wheat, maize, rapeseed) (Jouan et al., 2019; Magrini et al., 2016). Innovative solutions that improve the attractiveness of legumes must be developed to increase their use in animal feed in the EU and thus reduce reliance on imported protein-rich feed.

Foresights are systematic, participatory and multi-disciplinary approaches to explore futures and drivers of change through the use of scenarios (FTP, 2014). Consequently, foresights can identify assets and constraints related to innovative solutions. Recent foresights on agriculture have considered legume production (Uthayakumar et al., 2019), and some have also been associated with models to quantify the changes defined (Le Mouël et al., 2018; Poux and Aubert, 2019; van Vliet and Verburg, 2012). However, these models, usually based on biomass balances, fail to consider the diversity of production techniques and the specific characteristics of agricultural regions in the EU. For example, western France (i.e., Brittany and Pays de la Loire regions) has a high density of animal production; due to the large number of animals compared to the regional utilized agricultural area that can provide feed, the issue of protein self-sufficiency is even more critical there.

The aim of this study was to define levers to increase protein self-sufficiency in western France with a view to reducing negative environmental impacts of agricultural production. Local production of legumes, and their use in feed, is seen as one promising tool. A regional foresight called “TERUnic foresight” was performed to define innovative levers for legume production, which could improve protein self-sufficiency. It brings together many stakeholders from the many types of agricultural production of the region (e.g., farmers, cooperative managers). Then, a modeling framework was developed to estimate economic and environmental impacts of levers identified during the foresight analysis. This modeling framework combines a Computable Generable Equilibrium model (hereafter, “macro-model”) (Gohin et al., 2016) with the detailed regional-supply bio-economic model SYNERGY (Jouan et al., 2020). In this way, the macro-economic effects calculated by the macro-model are used in SYNERGY, which performs detailed assessment at the regional scale (western France).

2. Method

2.1. Regional foresight

Foresights aim to open the field of possibilities by developing scenarios, without prejudging their probable or desirable nature (Sebillotte et al., 2003). In the French approach, foresight is a participative and volunteer approach that relies on a group of experts to combine their diverse skills (Jouvenel, 2004). The TERUnic foresight is based on a method commonly used for foresights in the agricultural sector in France: the SYSPAHMM method (Sebillotte and Sebillotte, 2010). However, we reorganized the four steps of the original method into three steps, as detailed below. This three-step approach of the SYSPAHMM method, already implemented in a recent foresight (Aigrain et al., 2019), makes it possible to study contrasting scenarios that represent different evolutions of protein self-sufficiency.

2.1.1. Definition of study boundaries and representation of the system

The first step consisted of setting boundaries to the study, the time horizon and the structural trends (i.e., slow changes, observable over a long period and subject to strong inertia (Gaudin, 2005)). The study of self-sufficiency in protein was restricted to dairy, beef, pig, and poultry sectors, under conventional and organic farming, in western France. Crop production was also included, with a focus on legumes. The time horizon chosen −2040 − was a compromise reached by the stakeholders: it represented a middle ground between a long-term horizon (e.g. 2050), which would have too many uncertainties, and the near future (e.g. 2030), in which current events, such as the reform of the EU’s common agricultural policy or pre-existing innovations, would have too much influence. The structural trends defined were climate change, an increase in human population, an increase in fossil fuel prices and stricter regulation of pesticides. Based on these elements, we defined the boundaries of the system (Fig. 1) and set up the panel of 30 stakeholders Appendix A.

2.1.2. Definition of final states and hypothesis through a participatory approach

The second step consisted of defining the final states and formulating hypotheses (i.e., a short sentence that expresses an action likely to influence the trajectory of the system considered and whose inverse can also be expressed (FranceAgriMer, 2018)). To this end, a first focus group was organized for half a day with most stakeholders on the panel. During this focus group, three distinct final states out of four that we had proposed were chosen. The three final states chosen were then defined using keywords (3 keywords per stakeholder). Then, for two months after this focus group, individual semi-structured interviews were held with a larger group of stakeholders to encompass the diversity of production types, sectors and stakeholders in the region (Appendix). Interview responses enabled us to identify the main obstacles and levers for protein self-sufficiency and to define hypotheses. After these interviews, we collected a pool of 64 hypotheses and classified them in three dimensions that correspond to three types of determinants influencing protein self-sufficiency: (i) agro-technical innovations, (ii) markets and public policies, and (iii) organization of the sectors and consumers’ behavior.

2.1.3. Design of scenarios

The third step consisted of analyzing and connecting the hypotheses to shape different paths and design scenarios. To this end, a second focus group was organized with most stakeholders from the first one. The stakeholders were grouped in several roundtable discussions to bring together experts from different agricultural production types and organizations. In each roundtable discussion, one scenario had to be designed based on the pool of hypotheses classified in the three dimensions. Then, based on this work, we defined the final version of scenarios (Fig. 2). These consistent combinations make it possible to explain the multiple steps leading to different final states of the system considered in 2040.

2.2. The modeling framework

2.2.1. Overview of the macro-model used

The macro-model is based on the standard global trade analysis project (GTAP)-Agr model, containing social accounting matrices (i.e., matrices representing flows of economic transactions between economic agents) for many countries (Keeney and Hertel, 2005). It was first adapted to analyze the agricultural and agro-food sector in France (Gohin et al., 2016). The macro-model represents firms’ behavior in terms of supply of products, demand for inputs and use

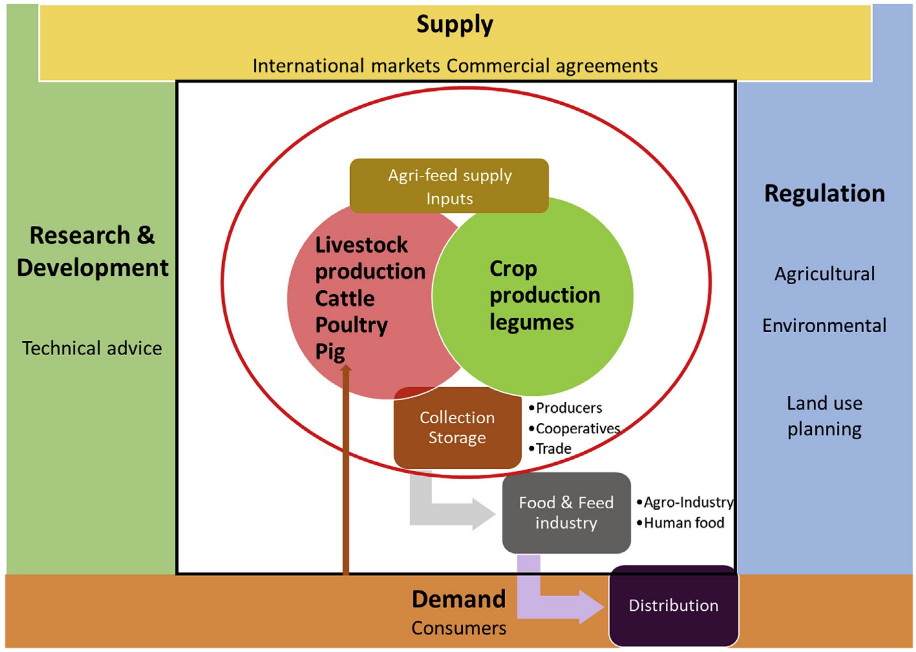

Fig. 1. Boundaries of the system in the TERUnic foresight.

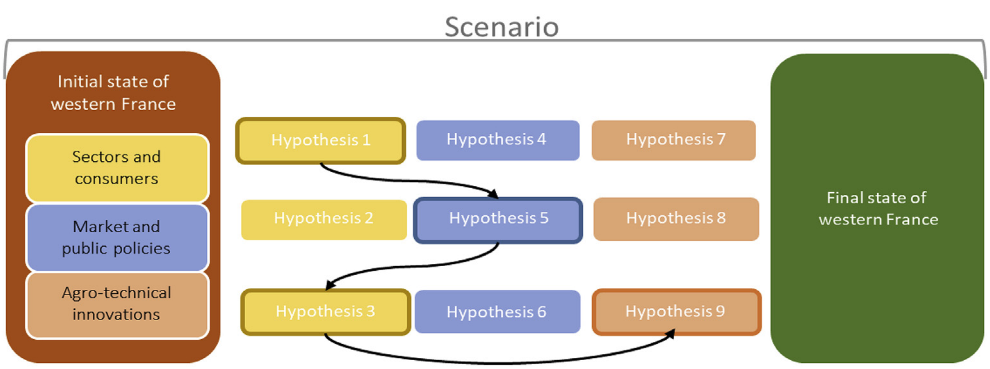

Fig. 2. General principle of scenario design in TERUnic Foresight.

of factors (i.e., capital, labor or land for the agriculture sector) and household behavior in terms of final consumption of products and investment in enterprises. These behaviors depend on prices, technical and budgetary constraints, regulatory constraints and taxes or subsidies. Producers maximize their profits under the constraint of a production function, while consumers maximize their utility under budgetary constraints.

For this study, an updated social accounting matrix was built for the French economy, based on the method of Gohin et al. (2016). This matrix describes 26 agricultural products and 19 products from the agro-food industry. In particular, it was improved and specifically detailed by making the distinction between a GMO or non-GMO origin for certain products in agriculture and agro-food activities, whether they are produced, traded or consumed domestically. Since few data on products from animals fed with or without GMOs were available, the study of Tillie and Rodríguez-Cerezo (2015) was used to fill the social accounting matrix and to make assumptions about the quantities and prices of GMO-free products. The potential substitution between legumes and animal products to supply protein in food is not considered. Exchanges between western France and the "rest of the world" are made through export and import demand functions. Price elasticities are obtained from both the social accounting matrix and previous studies (e.g., Gohin (2009); Gohin et al. (2015)). The model is calibrated to reproduce the initial situation observed in 2011, which is the most recent year with complete data.

The macro-model assessed four types of impacts: (i) those on crop and livestock production (ii) those on intermediate and final consumption of crop and animal products by firms and households, (iii) those on imports and exports of France and (iv) macroeconomic impacts such as labor demand and added-value. In addition, the macro-model also provides equilibrium prices for agricultural and agro-food products; these endogenous prices vary depending on the simulation.

2.2.2. Overview of the SYNERGY model used

The bio-economic model SYNERGY is a static non-linear programming model (Jouan et al., 2020). It represents the supply of agricultural products focused on three specialized farm types (dairy cow, pig and crop) in western France. This region is divided into several sectors, corresponding to administrative departments, to consider the variety of soil and climate conditions. In each sector, the total area allocated to each farm type may change, as may animal numbers and land use within each farm type. 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 for manure or intra-region for crops). In addition to this local market, exchanges can occur with the rest of the world (i.e., rest of France and other countries) at exogenous prices (see section 5.2 for a description of the data sample). However, although exogenous, these selling and buying prices can vary depending on the simulation of the macro-model (see section 6.2.2.3).

To the previous version of SYNERGY (Jouan et al., 2020), a new crop, and its corresponding rotations and rations, was added: multispecies grassland (i.e., temporary grassland with 30% clover by cover). SYNERGY now includes 60 rotations and 12 crops. In addition, another feed was added: GMO-free soybean meal. Thus, two soybean meals are now available: a GMO-free version, produced in the rest of France, and a conventional version, imported from the rest of the world. It is assumed that soybean is not produced in western France, since only very early varieties are adapted to the hottest parts of this region (Terres Inovia, 2017). GMO-free soybean meal is assumed to cost 80 €.t^{-1} more than conventional soybean meal (Feedsim Avenir, 2019). Overall, GMO-free animal products come from animals fed rations containing GMO-free (i) soybean meal or (ii) other legumes (i.e., peas, faba beans, dehydrated alfalfa or multispecies grassland) (hereafter called "legume-based rations"). SYNERGY now includes 25 potential rations for dairy production and two potential rations for pig production.

The model is calibrated to reproduce the mean of observed crop areas and animal numbers in western France for the period 2013–2017. The initial area of each legume (i.e., alfalfa, faba bean and peas) was arbitrarily set at 0.5% of the area of each farm in each sector, thus covering a total of 1.5% of the area of each farm in each sector. Multispecies grassland was set at 15% of the total area of temporary grassland on dairy farms.

SYNERGY generates four types of indicators: (i) structural (e.g., crop areas, numbers of animals) (ii) economic (e.g., regional profit, farm profit, level of farm-to-farm exchanges), (iii) technical (e.g., protein self-sufficiency, application of N fertilizers), and (iv) environmental. SyNE (range = 0–1) assesses the efficiency with which agricultural systems transform N inputs into desired agricultural products and SyNB (kg N.ha^{-1}) reflects potential N losses from agricultural systems, including those during production of inputs (Godinot et al., 2014). All indicators are provided for each farm type at the sector scale and at the regional scale (average weighted by area), as well as at the regional scale, all types of farms combined (average weighted by area).

Finally, one innovative feature of SYNERGY is to calculate protein self-sufficiency at the regional scale. Indeed, increased protein self-sufficiency at the farm scale can be low due to high numbers of animals relative to the available farm area. However, since SYNERGY can represent farm-to-farm exchanges, livestock farms can buy crops, such as legumes, from crop farms. In this case, protein self-sufficiency at the farm scale is constant, but that at the regional scale increases since less protein-rich feed is bought from the rest of the world.

2.2.3. Coupling the macro-model and SYNERGY

As mentioned, the macro-model provides endogenous prices for agricultural and agro-food products, which vary depending on the simulation. SYNERGY then uses these variations in prices: selling prices of outputs (e.g., milk) and buying prices of inputs (e.g., GMO-free soybean meal) (Fig. 3). In addition, since the macro-model considers investment cost and labor demand, while SYNERGY does not, it was decided to limit the increase in livestock production in SYNERGY to the same range of variation as that observed in the macro-model.

3. Results

3.1. Results of the TERUnic foresight

3.1.1. Description of the three scenarios

The three scenarios defined by the stakeholders are the following:

- Scenario 1 ("Regional specialization and economies of scale") considers a decrease in protein self-sufficiency in western France by 2040. Consumption of non-labeled products has not developed. Specialization in livestock production and international competition has increased. Plant breeding of legume crops is limited, and the level of technical lock-in in legume storage and processing remains high.
- Scenario 2 ("Development of local agro-food chain") considers a moderate increase in protein self-sufficiency in western France by 2040. Consumers prefer products from labeled agro-food chains. Plant breeding of legume crops is strengthened, and cooperatives develop storage tools for them. Current European incentives such as voluntary coupled support are maintained and adapted to local contexts.
- Scenario 3 ("Environment, complementarity and economies of scope") considers a huge increase in protein self-sufficiency in western France by 2040. Consumers prefer products from labeled agro-food chains that protect the environment. Agricultural policy is driven by environmental goals. Strict regulations on the environment and animal welfare are implemented. Farms are less specialized, and the number of animals raised within the region decreases substantially. Agro-technical innovations have increased the use of legumes.

A detailed description of the three scenarios is available in the study of Caraes (2018).

3.1.2. From scenarios to levers: modeling choices

Each scenario includes multiple levers, and simulating all of them simultaneously can make the results of economic models complex and confusing. Thus, we simulated only the main lever of scenarios 2 and 3, in which protein self-sufficiency increases: the demand for products from labeled agro-food chains. We chose to examine this lever by focusing on GMO-free animal products, since "GMO-free" was one of the main labels identified by stakeholders. Thus, the lever called "Le_GMO" is represented as an increase in demand for GMO-free animal products (by 50% for pork and 25% for milk and beef compared to the baseline situation (BASE)). This increase is introduced in the macro-model, which predicts variations in prices of inputs and outputs that are then used in SYNERGY (Table 1). The increase in livestock production was limited to the same variation as that in the macro-model: +2.5% for milk production and +1% for pig production.

In addition, we studied another lever ("Le_SU"), which is represented as an increase in coupled support for legumes. Coupled support is set at 200 €.ha^{-1} for grain legumes (i.e., peas and faba beans), which is twice its minimum current value and corresponds to a 46% increase in the value of coupled support already set in BASE. A similar increase is set for alfalfa, leading to a coupled support of 182 €.ha^{-1} for this crop. In a first step, only this increase in coupled support is used in the macro-model, which decreases the price of legumes by 2%. In a second step, both this variation in price and the change in coupled support are used in SYNERGY.

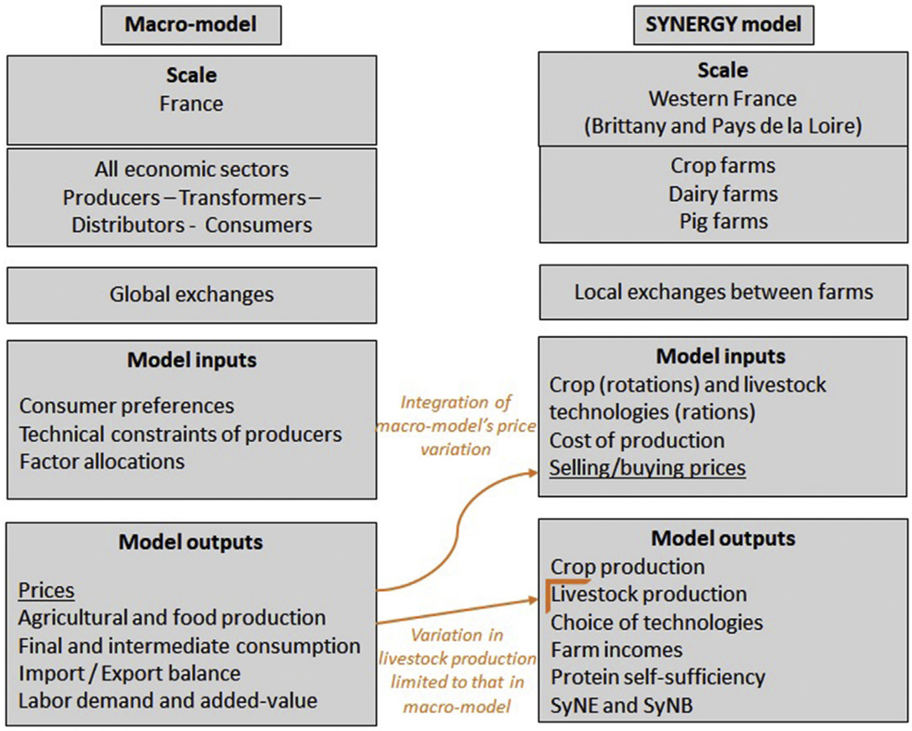

Fig. 3. Summary of macro-and SYNERGY models and their connections.

Table 1
Increase in demand for GMO-free animal products in in the macro-model and the corresponding simulated variations in prices in the SYNERGY model.

	Macro-model	SYNERGY model
Product	Increase in demand	Variation in prices
GMO-free milk	+50%	7%
GMO-free beef	+50%	0%
GMO-free pork	+100%	7%
Conventional milk		−5%
Conventional beef		−3%
Conventional pork		0%
GMO-free soybean meal		16%
Conventional soybean meal		−1%

3.2. Results of the modeling framework

3.2.1. Baseline situation (BASE)

Dairy farms cover 73% of the regional area (Table 2). Legumes as sole crops (alfalfa, faba bean, pea) cover 1.5% of the area of each farm in each sector, and multispecies grassland covers 15% of temporary grasslands of dairy farms. When multispecies grassland is recorded as “legume”, the total percentage of legumes in the region reaches 5.1%. In addition, the percentage of multispecies grassland is higher in sectors where temporary grassland areas are higher, which corresponds to the northwestern part of the region (sectors s22, s29, s35, s44 and s56; Fig. 4). Temporary pure grasslands, permanent grasslands and forage maize cover 50% of the regional area, while wheat covers 21% of the regional area.

The percentage of legume-based rations is low on pig farms (0.4% of pigs are fed legumes) but much larger on dairy farms (20.6% of dairy cows) because of rations based on multispecies grasslands. This percentage of legume-based rations is similar among dairy farms, except for the dairy farm in sector 72 (“Dairy72”), where it is substantially lower (9.2%) due to less area of temporary grassland set after calibration, and thus less area of multispecies grassland. Protein self-sufficiency at the regional scale reaches 59%, with huge differences among farm types: on average, 74% for dairy farms and 24% for pig farms. In 8 of the 9 sectors, pig farms export their manure, mainly to dairy farms. There are no local exchanges of crops. Dairy farms generate 65% of regional profit, even though the profit per ha is higher on pig farms (3342 €.ha^{-1}).

At the regional scale, for all farms, potential N losses (SyNB indicator) reach 127 kg N.ha^{-1}, and N efficiency (SyNE indicator) reaches 0.41 points, on average. For dairy farms, potential N losses differ greatly (53 kg N.ha^{-1}) between Dairy35 (84 kg N.ha^{-1}) and Dairy29 (137 kg N.ha^{-1}) due lower input of N fertilizer and N-efficient dairy cow rations on the former (Table 2).

3.2.2. Lever “coupled support for legumes” (Le_SU)

In “Le_SU”, when coupled support for legumes is set at 200 €.ha^{-1} for faba beans and peas and 182 €.ha^{-1} for alfalfa, the total area of these legumes increases, particularly on crop farms (+33%, on average), and reaches an increase of 13% at the regional scale, compared to BASE (Table 2). However, this substantial increase does not lead to a high percentage of legumes in the regional area (only 1.7%) because the initial legume area in the region was small in BASE (i.e., only 1.5% of the regional utilized agricultural area). In addition, when multispecies grassland is recorded as “legume”, the overall increase in legumes is more moderate (+3%): since the multispecies grassland is not subsidized, its area decreases by 1%, and the total percentage of legumes including multispecies grassland remains constant. There are no substantial impacts on livestock production, since the percentage of animals fed legumes does not change. The other indicators remain constant.

3.2.3. Lever “increased demand for GMO-free animal products” (Le_GMO)

When this lever is applied, the area of sole-crop legumes increases by 14% at the regional scale, compared to BASE (Table 2). This increase is particularly high on dairy farms (+17% more area, on average). Like for the previous lever, legumes cover only 1.7% of the regional area. However, the increase in multispecies grassland

Table 2
Results for the main indicators of the SYNERGY model, under the two levers tested, Le_SU and Le_GMO, compared to the baseline situation (BASE).

Indicator	BASE	Le_SU	Le_GMO
Legume percentage	5.1%	5.2%	12.3%
Sole-crop legumes	1.5%	1.7%	1.8%
Multispecies grassland	3.6%	3.6%	10.5%
Area of farms (ha)			
- Dairy farms	1,128,399	1,130,106	1,093,793
- Pig farms	188,735	189,277	185,236
- Crop farms	239,242	236,993	277,347
Milk production (hL)	741,807	741,17	760,353[a]
Pig production (thousands of head)	12,178	12,178	12,299[a]
Percentage of legume-based rations			
- Dairy farms	20.6%	20.5%	94.0%
- Pig farms	0.4%	0.5%	100.0%
Purchases of GM soybean meal (t N)	50,909	50,919	0[b]
Local exchanges of crops (t N)	–	–	985
Regional protein self-sufficiency	59%	59%	59%
Farm protein self-sufficiency			
- Dairy farms	74%	74%	74%
- Pig farms	24%	24%	20%
Purchases of synthetic N fertilizers (t N)	315,845	315,518	287,743
SyNB (System N Balance, kg N.ha^{-1})			
Dairy farms	112	112	117
- Pig farms	260	259	318
- Crop farms	90	90	92
SyNE (System N Efficiency, range = 0−1)			
- Dairy farms	0.38	0.38	0.35
- Pig farms	0.41	0.41	0.37
Crop farms	0.56	0.57	0.56
- Regional profit (M€)	2191	2293	2607
- Dairy farm income			
- *Regional total (k€)*	1,484,794	1,487,167	1,602,932
- *Per hL of milk (€.hL^{-1})*	2002	2005	2108
- Pig farm income			
- *Regional total (k€)*	630,689	631,286	802,932
- *Per pig (€.pig^{-1})*	51.8	51.8	65.3
Crop farm income			
- Regional total (k€)	175.987	174,536	199,987
- Per ha (€.ha^{-1})	736	736	721

BASE: baseline. Le_SU: coupled support for legume increased to 200€.ha^{-1} for peas and faba beans and 184 €.ha^{-1} for alfalfa. Le_GMO: demand for GMO-free animal products is increased in the macro-model, leading to several price variations. [a] the increase in milk and pig production is limited to that observed in the macro-model. [b] GMO-free soybean is purchased (1327 t N).

is substantially higher (+194% more area), and the percentage of legumes, including multispecies grassland, reaches 12% of the regional area. Thus, the incentive to produce legumes for feed is an effective lever to increase production of multispecies grassland used in feed.

Compared to BASE, livestock production increases at the regional scale (+2.5% more milk produced and +1% more pigs produced). The increase in pig production is similar throughout the region, and the entire pig herd is fed legume-based rations. This shift in rations leads to an increased need for legumes that is not met by legume production in the region. Therefore, protein self-sufficiency decreases by 4 percentage points on pig farms, on average. The decrease in protein self-sufficiency is particularly high on Pig85 (−16 percentage points) due to a decrease in farm area (−42%) and an increase in pig production (+2%); thus, the stocking rate increases, as do feed purchases.

The increase in milk production varies more among sectors than the increase in pig production: milk production increases in the northwestern part of the region (particularly on Dairy35, with 10% more milk production) but decreases in the southern and eastern parts (particularly on Dairy72, with 19% less milk production). On dairy farms, the shift toward legume-based rations also varies more: 94% of cows are fed legumes, mainly multispecies grassland (48%) and alfalfa (33%). However, the remaining 6% of cows that are not fed legume-based rations are located on only three farms (Dairy44, Dairy53 and Dairy85) and are fed GMO-free soybean meal. Protein self-sufficiency on dairy farms remains constant on average, but substantial differences exist among farms. For example, when feed is based mainly on multispecies grassland and stocking rate decreases, protein self-sufficiency increases on Dairy22 and Dairy49 (by +9 and + 8 percentage points, respectively). In contrast, when feed is based mainly on alfalfa, protein self-sufficiency decreases on Dairy35 (by −11 percentage points) because the farm produces less alfalfa than that needed for dairy cow rations.

Finally, due to the shift in rations that leads to an increased need for legumes on dairy and pig farms, imports of legumes from outside the region increase by a factor of 18, and genetically modified soybean meal is no longer imported into the region. Also, local exchanges of crops appear, in particular of peas, faba beans and rapeseed (Fig. 4). However, these exchanges represent only 1% of the quantities of these crops consumed in the region. Thus, exchanges of crops do not influence the protein self-sufficiency of the region.

Compared to BASE, the environmental results worsen slightly at the regional scale, despite the 9% decrease in synthetic N consumption. Indeed, SyNB increases by 10 kg N.ha^{-1}, and SyNE decreases by 0.02 points. These small decreases hide larger changes at the farm scale that offset each other (Fig. 5). On pig farms, SyNB increases by 58 kg N.ha^{-1}, on average, mainly due to the increase in the stocking rate, which is not compensated by the increased exports of manure. SyNE also worsens (by −0.04 points, on average) due to legume-based rations for pigs that contain less N. These large decreases are partly compensated by smaller decreases on dairy farms, which cover a larger percentage of the regional area. On dairy farms, SyNB increases by only 5 kg N.ha^{-1}, and SyNE decreases by 0.03 points, on average. However, the results on dairy farms are very heterogeneous. Three of nine dairy farms (Dairy53, Dairy72 and Dairy85) have improved SyNB and SyNE due to an increase in the legume percentage that decreases purchases of N-rich inputs for fertilization (e.g., manure, synthetic N fertilizer) and feed (e.g., imported legumes). However, although high use of multispecies grassland increases protein self-sufficiency of farms, SyNE worsens because the feed ration is less efficient in N (i.e., more N is needed to produce the same quantity of outputs such as milk or meat). Otherwise, SyNB worsens on farms on which protein self-sufficiency decreases, due to an increase in feed purchases (e.g., alfalfa purchases on Dairy35). Environmental indicators on crop farms change little.

Compared to BASE, economic indicators improve: profit increases by 14% at the regional scale, with differences among farms. On pig farms, income per pig increases by 26% on average, with particularly high increases on Pig44 and Pig53 (+30%). On dairy farms, income per L of milk increases by 5% on average, with a particularly high increase on Dairy72 (+17%). Thus, it is possible to increase the profitability of milk production while improving protein self-sufficiency and environmental indicators. However, the trade-off between economic and environmental benefits does not always go in the same direction: on Dairy35, the increase in profitability goes along with a decrease in protein self-sufficiency and worsening of environmental indicators. Finally, on crop farms, income per ha decreases by 2% on average, with substantial differences among crop farms, from −6% on Crop29 to +3% on Crop22.

4. Discussion

This study is the first one to focus on the issue of protein self-

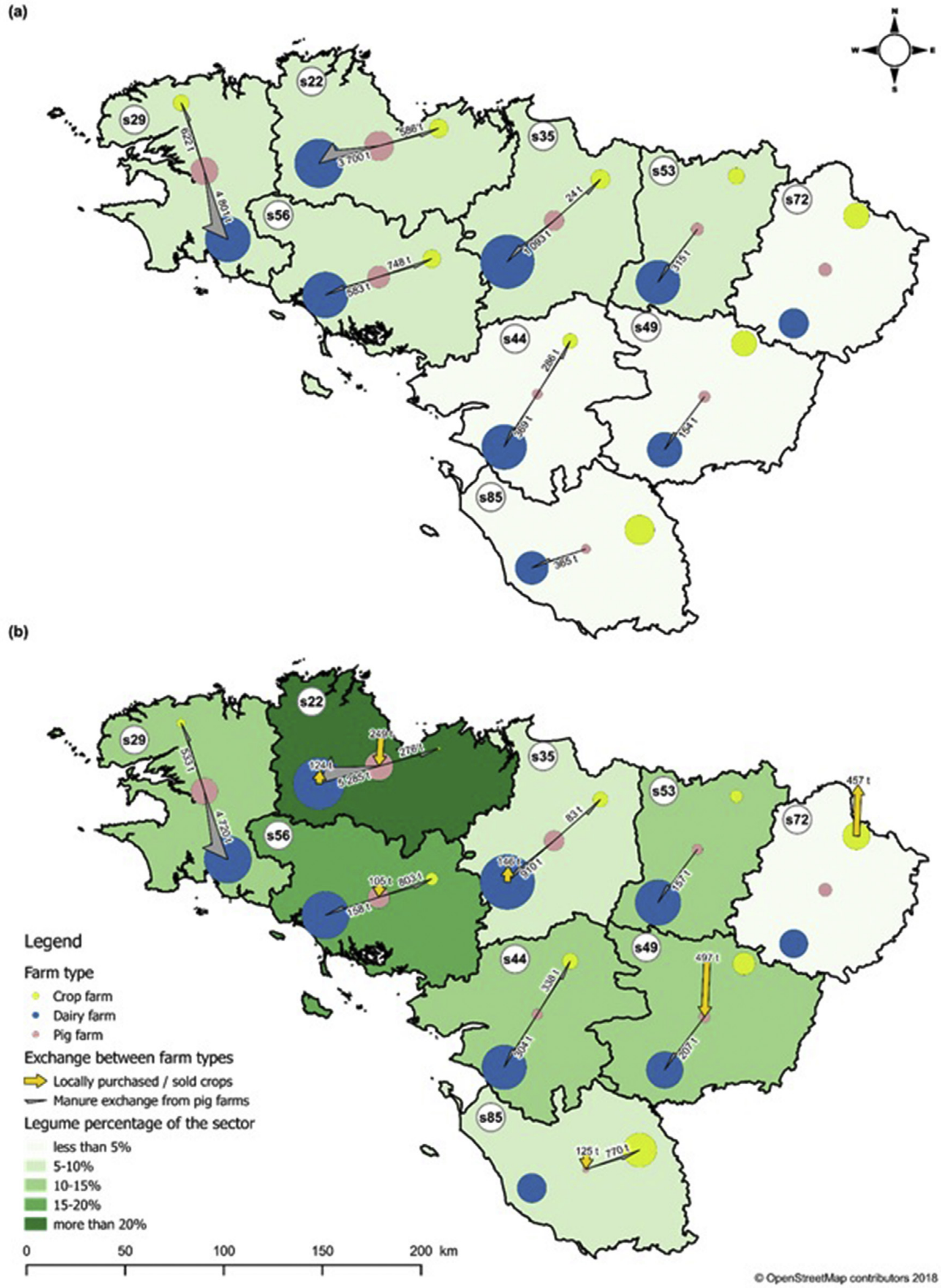

Fig. 4. Legume production and farm-to-farm exchanges of crops and manure in western France in (a) the baseline situation and (b) under increased demand for GMO-free animal products (Le_GMO) Legume percentage includes sole-crop legumes (peas, faba beans and alfalfa) and multispecies grassland. Circles are proportional to the area of each farm type in each sector. Crop exchanges of less than 80 t of N are not represented.

sufficiency at the regional scale through a modeling framework. Two levers related to the production or use of legumes in feed were tested to increase protein self-sufficiency in western France while reducing negative environmental impacts: a policy-oriented lever (i.e., increase in coupled support for legumes) and a demand-oriented lever. Regarding the first lever, when coupled support increased, only crop production was impacted. Production of subsidized legumes (i.e., peas, faba beans and alfalfa) increased by 13% at the regional scale, in particular on crop farms. However, feed rations did not change, and impacts on economic and

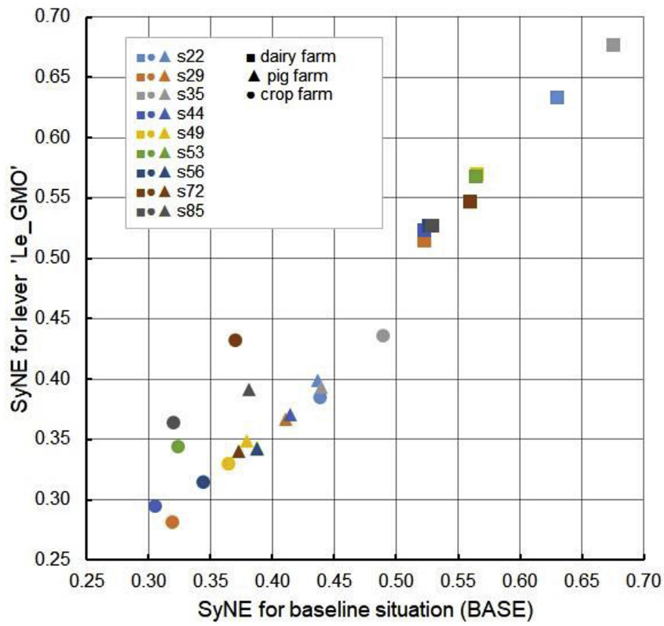

Fig. 5. N efficiency (SyNE indicators) between the baseline situation (BASE) and under an increased demand for GMO-free animal products (Le_GMO), among farms and sectors.

environmental indicators were low. This result differs from the study of Helming et al. (2014), who estimated a 4% increase in the use of legumes in feed when coupled support for grain legumes is provided. However, the level of this coupled support (at least 282€.ha^{-1}) is higher than that in our study, which may explain the difference. In addition, the increase in legume production, and its use in feed, could have been higher if multispecies grassland had also been subsidized.

Regarding the second lever, when demand for GMO-free animal products increased, production of sole-crop legumes increased by the same degree as that with the policy-oriented lever, particularly on livestock farms. However, the use of legumes in feed increased greatly, with rations almost completely legume-based. On dairy farms, this shift went along with a stable protein self-sufficiency, on average, while it decreased on pig farms because legume production did not meet the quantity needed by pig rations. Specific support for locally produced legumes would thus be necessary, as proposed in the foresight scenarios. However, the economic situation of livestock farms improved, particularly on pig farms, because the selling price of non-GMO pigs increased more than their production cost. Unfortunately, environmental results were not as good: N efficiency and potential N losses worsened, on average. In addition, an increase in protein self-sufficiency, as on dairy farms that used feed based on forage maize and multispecies grassland, was generally related to a decrease in N efficiency. Nonetheless, it is difficult to compare these results since, to the best of our knowledge, no study has considered an increase in GMO-free animal products as a lever to increase production of legumes used in feed. In addition, beyond protein self-sufficiency at the farm scale, regional protein self-sufficiency did not increase, since farm-to-farm exchanges of crops remained low (ca. 1% of the crops used in feed). The differential in price between local and global purchases seems to be too low to foster local exchanges. Again, it is impossible for us to compare these results to those of other studies. Finally, contrary to expectations, local exchanges occurred more from the northwestern part of the region, oriented mainly toward livestock production, to the southeastern part of the region, oriented more toward crop production. Indeed, certain farms in the northwestern part produced more livestock than those in the southeastern part, but did so less intensively (i.e., fewer animals per ha). Thus, these northwestern farms can export feed, while the southeastern ones need to import it.

The main originality of this study is the identification of the close relation between the demand for animal products and effects on feed choice and crop production. The GMO-free label was chosen as a lever to increase protein self-sufficiency because of collaborative work: the TERUnic foresight. This foresight relied on an original method whose initial steps defined final states (i.e., the level of protein self-sufficiency), allowing participants to look to futures that differ substantially from current trends. In addition, the TERUnic foresight had the advantage of including a variety of experts from different types of livestock production, which differ in their constraints in the use of legumes for feed. However, this foresight was performed in less time (i.e., 6 months) than other foresights, which limited the complexity of scenarios.

Another originality of this study is the modeling framework that uses a macro-model to simulate market effects and then transfers these effects to the bio-economic model SYNERGY. The SYNERGY model has three main advantages. First, by simulating farm-to-farm exchanges, protein self-sufficiency can be studied not only at the farm scale but also the regional scale. To our knowledge, this is the first regional model to do so. Second, trade-offs between economic impacts, environmental impacts and protein self-sufficiency are highlighted. Third, by considering the region's heterogeneity, SYNERGY can differentiate development opportunities of protein self-sufficiency constrained by local characteristics, such as local crop yields and the level of livestock production. It is particularly relevant for dairy farms, on which forages (e.g., multispecies grassland), as self-produced feed, depend on local characteristics. However, this modeling framework had some limitations. In particular, the price differential between locally and globally purchased crops was set at a realistic value of 10%, according to data from a professional journal (Jouan et al., 2020). Changing this value may lead to different results. Similarly, due to a lack of data, multispecies grassland was assumed to cover 15% of temporary grassland on dairy farms. This strong assumption should be validated by future studies, and sensitivity analyses should be performed. Finally, the macro-model and SYNERGY model do not use the same reference year due to the former's lack of data availability. However, coupling the two models provides a real added value. For example, had the increase in price of GM-free soybean meal simulated by the macro-model not been used in SYNERGY, the use of this meal would have been much higher, limiting the development of legumes.

The main conclusions of this study raise questions about the relevance of such high livestock production in light of environmental impacts and protein self-sufficiency. Even when using legume-based feed, protein self-sufficiency did not improve greatly, nor did environmental results. Indeed, due to the high livestock production, the ability to use feed based on legumes produced in the region is low compared to the need for N-rich feed, in particular for pig production. Thus, one way to improve protein self-sufficiency and environmental results could be to decrease the number of animals that need to be fed. To explore this option, we simulated a halving of dairy and pig production. Initial results showed an increase in regional protein self-sufficiency by 12 percentage points, with a 34% increase in local exchanges of crops. Regional profit decreased by 18%, but environmental results improved substantially, with a decrease in potential N losses of 28 kg N.ha^{-1} at the regional scale and, on average, 108 kg N.ha^{-1} on pig farms. Such encouraging environmental results raise the question of whether the agricultural sector of western France, which is oriented mainly to exports, should change drastically.

Further analysis could also be performed by targeting a certain level of protein self-sufficiency, as Gaudino et al. (2018) did. Finally, regarding dairy production, multispecies grassland seems a promising lever to increase protein self-sufficiency. Future studies should be performed to determine an adequate public policy that would foster its production.

5. Conclusions

The EU relies on imports to feed its livestock due to a deficit in protein-rich feed. The aim of this study was to define levers to increase protein self-sufficiency in western France with a view to reducing negative environmental impacts of agricultural production. To do it, an original method was implemented combining a foresight and a modeling framework to test levers identified in the foresight: increased coupled support for legumes and increased demand for GMO-free animal products. The modeling framework being based on a macro-model coupled with a regional model, our study is the first one to assess the impacts of a GMO-free certification at the regional scale, highlighting the close relation between the demand for animal products and effects on feed choice and crop production. Results showed that an increase in coupled support for legumes leads to an increase in legume production but has no influence on protein self-sufficiency or other indicators, since legumes are not used in greater amounts in feed. When the demand for GMO-free animal products increases, legume production increases substantially, and most livestock are fed legumes. However, local exchange of crops between farms is limited, and protein self-sufficiency decreases on pig farms. Environmental indicators do not improve, mainly due to low N efficiency of legume-based rations and an increase in legume imports from outside the region.

These results raise questions about the relevance of such high livestock production in western France. At this scale, the only way to improve substantially environmental impacts and protein self-sufficiency seems to decrease animal production, even though multispecies grassland can represent a promising lever regarding protein self-sufficiency of dairy production. However, the issue of protein self-sufficiency must be addressed not only at the regional scale, but also at the national scale. In particular, it would be interesting to study exchanges of crops with regions oriented more toward crop production. Enhancing complementarities between regions could thus be an interesting lever to increase protein self-sufficiency at the national scale.

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CRediT authorship contribution statement

Julia Jouan: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft. **Aude Ridier:** Conceptualization, Methodology, Validation, Resources, Supervision, Funding acquisition, Project administration, Writing - review & editing. **Matthieu Carof:** Conceptualization, Methodology, Validation, Supervision, Writing - review & editing.

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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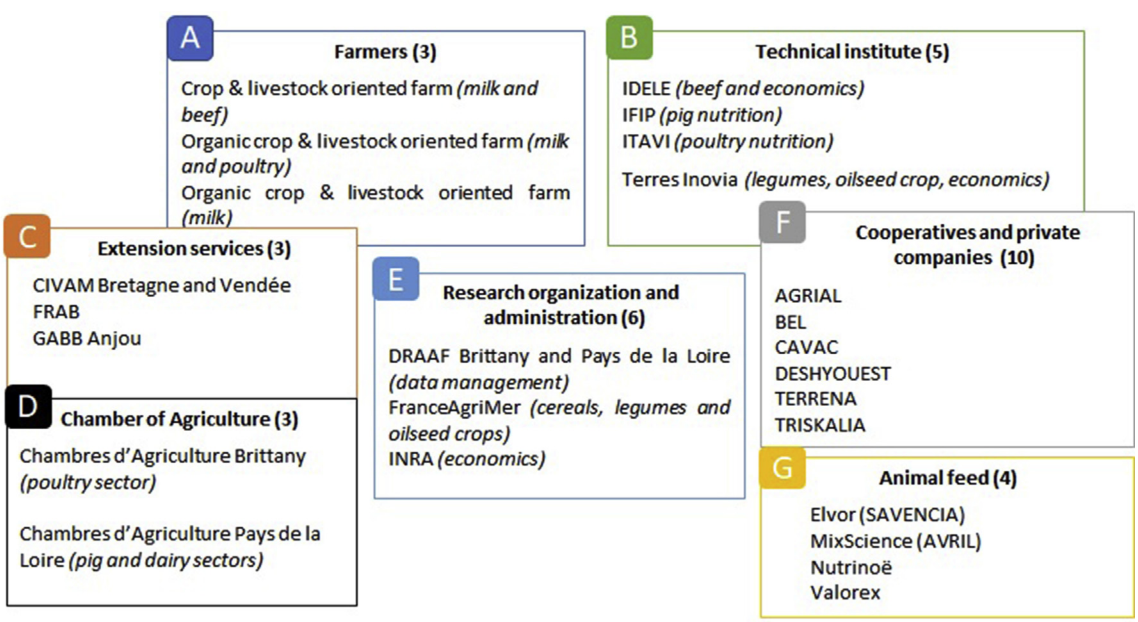
Appendix



Appendix A. Panel of stakeholders contributing to the TERUnic foresight.

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