# Protein Deficit in France – A Prospective Analysis

## Alexandre Gohin* and Alice Issanchou*

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**Abstract** – France's deficit in protein-rich products dates back nearly 50 years. Many protein plans aimed at boosting the supply of legumes have succeeded one another without managing to solve the issue. Does it mean that French agriculture is economically tied to grain production using imports of synthetic fertilisers and to off-farm livestock production using soya imports? The novelty of our quantitative analysis is to take into account the role of French consumers' potential demand for products that are free from genetically modified organisms (GMOs). Our prospective simulations show that, while this demand is a far more powerful driver for reducing imports of GMO soya cake than traditional subsidies for legumes, it is unlikely to lead to a significant improvement in protein self-sufficiency, as net imports of other protein-rich products are increasing. In contrast, substantial progress could be made by improving the productivity of forage land.

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Since the 1973 embargo on US soya exports following a major local drought, France has implemented various protein plans to promote its own production and limit the import of plant-based protein-rich products (PRPs), including soya beans and soya cake, high-protein peas, faba beans, rapeseed cake, lentils and chickpeas. Though initially motivated by purely economic considerations, recent protein plans increasingly emphasise the direct environmental benefits of these crops. Due to their ability to fix atmospheric nitrogen in the soil, legumes reduce the need for synthetic fertilisers on cultivated land, thereby reducing direct greenhouse gas (GHG) emissions.

Despite nearly 50 years of public support for this sector, France remains largely dependent on imports of PRPs, particularly soya cake for animal feed. The degree of public support and the raw material price ratios have so far had little impact on the decisions of French producers and users in terms of favouring domestic PRP production. The evolutions in recent years are due more to the growth of the first-generation biofuel sector, the consumption of which has been capped, than to French protein plans. Moreover, the expansion of legume crops does not always appear to be the best solution for mitigating GHG emissions from agriculture (Pellerin *et al.*, 2017). Strong public support for legumes as part of the fight against climate change is therefore unlikely to be achieved in the near future. Finally, while PRP trade policies are managed at the EU level, many Member States that are even more dependent on imports from third countries than France consider that specialisation and international trade based on comparative advantages could lead to potential improvements in standards of living (Mahé, 2005). As third countries have comparative advantages in terms of protein production (especially soya), they find imports preferable to local supply. This is reflected, for example, in attitudes towards free trade treaties with Canada and the Mercosur countries.

Is France set to remain heavily dependent on PRP imports for the foreseeable future? In other words, is French agriculture economically tied to grain production facilitated by imports of synthetic fertilisers and to off-farm livestock production facilitated by PRP imports, thereby generating excess nitrogen polluting our air, soil and water (Magrini *et al.*, 2015)? Will the new national plant-based protein plan announced in December 2020 deliver only modest results like its predecessors?

This article aims to make a quantitative contribution to the complex and perennial debate on plant-based protein by incorporating a new dimension, which is increasingly being discussed but has not been extensively measured to date: French consumer demand for local food products without genetically modified organisms (GMOs). Imported PRPs, especially soya, are largely derived from genetically modified crops. Consumer leverage could therefore be used to help reduce French protein dependence by reducing the amounts of these GMO-based products imported. Several surveys indicate a potential demand from French consumers for GMO-free food products and locally produced foods in general (FranceAgriMer, 2018). Agri-food industry stakeholders are increasingly moving to meet this potential demand, as detailed at the *États Généraux de l'Alimentation* (French National Food Conference) (Terres Univia, 2017).

This potential demand from French consumers concerns dried legumes and processed foods (meat and dairy products). A methodology that takes into account the different products and players in the food sector is essential to quantify this new driver of consumer demand and to compare it with the more conventional drivers of public support. We therefore develop an original computable general equilibrium (CGE) model that separates the non-GMO sectors from "conventional" sectors. CGE models are widely used for the *ex ante* assessment of the impact of public policies (such as free trade agreements and agricultural policies), whether in terms of production, trade, demand, price and market impacts in general. Our static model allows for the quantification of a wide range of consequences of different prospective scenarios, e.g. involving the acreage dedicated to legume crops or the dependence on GMO soya imports, including potential reductions in grain and/or animal product exports. It therefore allows us to determine whether gains in protein self-sufficiency might come at the expense of a loss of self-sufficiency in other sectors and, ultimately, the risk of a loss of agri-food trade surplus. It also measures the impact on revenue generated by agricultural and agri-food activities, enabling us to assess possible conflicts between protein self-sufficiency and the economic returns of the sectors. Our approach therefore provides a unified and coherent quantification of the various issues surrounding the broad topic of plant-based protein. However, our static model does not cover all the issues at stake, such as transient and long-term effects on biodiversity or net GHG emissions, which is why no normative analysis of the objective of reducing France's protein deficit has been conducted.

Our prospective simulations show that, while this potential consumer demand is a far more powerful driver for the reduction of GM soya cake imports than traditional subsidies for legumes, it is unlikely to lead to a significant improvement in protein self-sufficiency, as net imports of other PRPs are increasing. In contrast, substantial progress could be made by improving the productivity of forage land. Changes in consumer demand have a greater positive impact on French agricultural and agri-food revenue than public subsidies.

The rest of the article is organised as follows: the first section provides a more detailed description of the issue under study; the second summarises the main findings of the available literature; the third is devoted to the model developed, with emphasis on the original elements introduced, and describes the scenarios tested; the fourth reviews the outcomes of these scenarios and includes a sensitivity analysis. The conclusion summarises the main findings and suggests possible extensions to this empirical study.

## 1. The Context: French and European Protein Self-Sufficiency

### 1.1. What Is It All About?

Both plant and animal proteins are made up of amino acids. The nutritional value of a protein is dependent on its ability to provide the amino acids essential for the growth of the organism concerned and to replenish the proteins in its body. Not all proteins contain the same amino acids. When it comes to human nutritional needs, sources of animal proteins are more balanced in terms of amino acids than plant proteins, something that can be corrected for by combining different sources of plant protein (e.g. grains and legumes).[1]

The rest of this article focuses on animal proteins and plant proteins used for animal feed. Due to the lack of macroeconomic data, sources of plant proteins used directly in human food have been omitted from the analysis. According to microeconomic data collected by Agrosynergie (2018), these mainly include dried legumes (lentils, chickpeas, beans, etc.) and soya beans. They represent a niche but growing market driven largely by the increasing popularity of vegetarian and vegan diets. These proteins enjoy a positive image in terms of health and environmental benefits, but a negative one in terms of digestibility and convenience (preparation time). The prospects of these markets depend largely on the public research strategy in this area and on the actions of the processing industry (Magrini *et al.*, 2018).

On average, it takes about 4.9 kg of plant protein to produce 1 kg of animal protein (weighted according to the weights of the different animal species) (Guéguen *et al.*, 2016). Indeed, livestock have specific protein requirements for growth and maintenance, which are covered by coarse fodder (grazed/harvested grass, maize/fodder beet, etc.) and single or mixed concentrate feed. The latter are made from different raw materials, and those containing more than 15% protein are considered PRPs. For example, grains are composed mainly of starch, a source of energy, and are therefore not classified as PRPs, even though they do contain protein. Oilseed (especially soya) cakes on the other hand are protein-rich products. Dry pulses (peas and faba beans) have a medium starch and protein content.

Figures I and II below show how the production and use of PRPs in animal feed in France and Europe have changed since 1973. While their use increased sharply at the beginning of the study period, since 2000, it has grown only marginally in Europe and even declined in France, due to a more modest increase in livestock production volumes and increased productivity in these sectors. Soya cake is the most widely consumed PRP, followed by other oilseed cakes (rapeseed and sunflower). PRP production also increased significantly at the beginning of the study period, with more modest increases since the early 2000s. Production of rapeseed and sunflower cake has increased considerably, partly due to the expansion of the biofuel industry. In contrast, production of legumes decreased substantially over the same period. The French PRP deficit has always been less pronounced than the European deficit, partly due to the available agricultural land, the scale of livestock production and national policies.

### 1.2. Impact of Public Policies

The French and European deficits in PRP for animal feed are partly explained by a an agreement adopted in the 1960s between Europe and the US, which allowed the European Union (EU) to implement a price support policy for its cereals in exchange for duty-free access to the EU for

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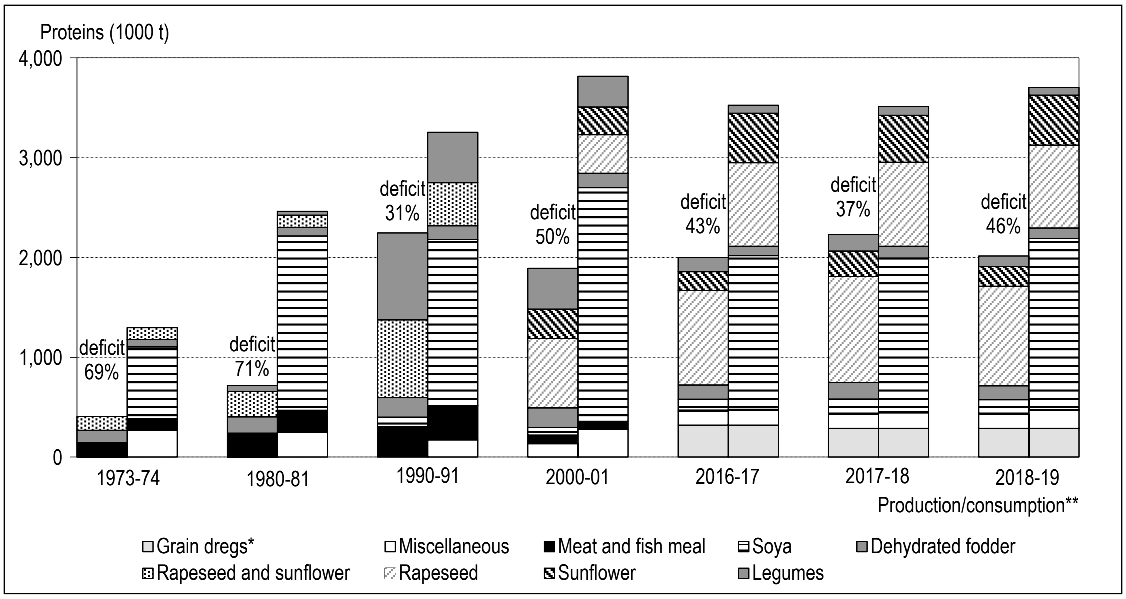
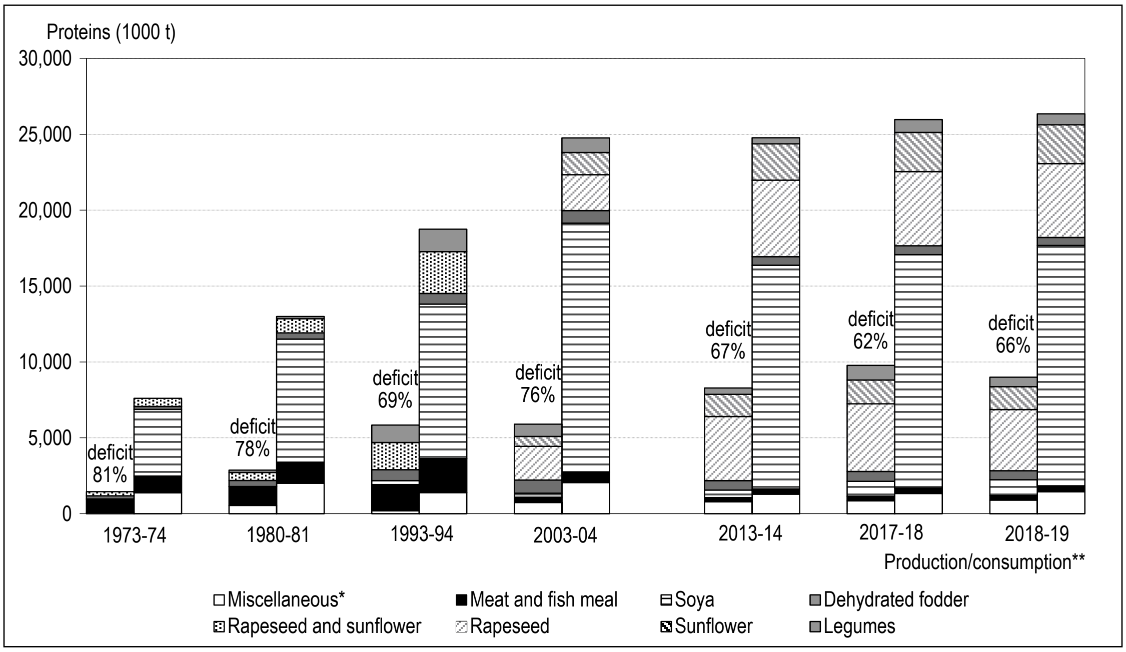
[1] *See also in Agrosynergie (2018) a more comprehensive overview of the topic.*

Figure I – **Changes in the French balance of protein-rich products (PRPs) for animal feed**



*Estimated data not available before 2009-10.
**For each period, the first bar corresponds to production, the second to consumption.
Sources: Terres Univia (estimate).

Figure II – **Changes in the European PRP balance for animal feed**



*Excluding grain dregs (data not available).
**For each period, the first bar corresponds to production, the second to consumption.
Sources: Terres Univia (estimate).

US oilseed imports (Hache, 2015). Therefore, the EU and France came to depend on soya bean and soya cake imports from the US, Argentina and Brazil. In a highly concentrated global soya market, such a dependence was a weakness for the European animal production sector (in 1973, the United States reduced its soya exports due to a severe drought). As a result, Europe implemented various protein plans to boost European legume production, the first of which dates back to 1975 and the latest to 2020.

Support for legume and soya bean acreage and production has been a recurrent feature of these protein plans.[2] Since 1992 and the MacSharry reform of the Common Agricultural

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[2] *For details, see: https://draaf.nouvelle-aquitaine.agriculture.gouv.fr/IMG/pdf/AgresteNA_AR_67_proteagineux-lien_cle8119fc.pdf*

Policy (CAP), support for the cultivation of legumes and soya beans (on a per-hectare basis) has decreased overall, but less so than for other crops competing for agricultural land. However, combined changes in support, crop prices, yields and variable production costs led to a decline in margins per hectare of land dedicated to legume crops between 1992 and 2008 relative to the margins per hectare of competing crops (Ramanantsoa & Villien, 2012). This contributed to a sharp decline in French land allocated to legume crops.[3] The CAP Health Check in 2008 brought an increase in relative support for legume acreage, leading to an increase in the amount of land dedicated to growing these crops.

The latest plan (period 2014-2020) falls within the framework of the post-2013 CAP, with combined support for land dedicated to legume crops, including fodder crops, in amounts ranging from €100 to €200/ha. These crops are now also indirectly supported by the eligibility criteria for direct payments under the first pillar of the CAP, which encompass the bulk of agricultural budget support. These criteria, known as “greening”, require the maintenance of minimum areas of ecological interest, which include protein acreage. The agri-environmental and climate measures under the second pillar of the CAP are another public instrument promoting legume crops and recognising their positive environmental impacts (input reduction through longer rotations). However, restrictions/bans on plant protection products (e.g. against faba bean seed beetle) have made these crops less attractive to farmers. During that period, the acreage devoted to legumes in France increased only marginally. In contrast, the acreage devoted to soya increased significantly, partly due to new seed varieties that were better suited to different geographical areas and to the implementation of a French soya charter involving the various stakeholders in the industry in order to meet the French demand for non-GMO soya. Despite this increase, legumes still accounted for only a modest share (4%) of French arable land surface area, which was largely dominated by grains.

The health crisis that emerged at the beginning of 2020 brought the issue of French sovereignty to the fore, not only in terms of medical equipment (masks) but also in relation to food supply. Jaravel & Méjean (2021) begin by demonstrating that, in terms of vulnerability, the French agri-food supply is just behind the chemical sector. They then propose three measures aimed at building a realistic and effective resilience strategy without resorting to excessive protectionism: greater diversification of supplies, expansion of storage capacity for low value-added products and, finally, increased innovation for vulnerable inputs at the technological frontier. However, the government-led France Relance recovery plan includes further measures intended to boost French production, including the supply of plant proteins. This new plan aims to double the acreage devoted to legumes by 2030, to 8% of the available agricultural land. In concrete terms, this plan, initially endowed with 100 million euros, provides public funds to help structure supply chains (inspired in part by the example of the soya sector) and encourage investment in agricultural holdings (the initial budget of 20 million euros was used up in the first year and a new budget for the same amount was approved in 2021). These amounts remain well below the combined subsidies for acreage dedicated to legume crops (under the national low-carbon strategy, the budget announced for 2027 alone amounts to 236 million euros). Like previous plans, it includes actions to promote human consumption of legumes (not explicitly covered in this article) and support varietal research.

In this respect, GMO seed crops have been banned in France since 2008 (only one crop – maize – is allowed in Europe, which is mainly grown in Spain); however, about a hundred GMO crops and their by-products are authorised for import and use in food and feed. This includes soya beans and by-products such as soya oil and soya cake. These authorised GMO products are subject to traceability and labelling obligations, with an exemption threshold to account for possible cases of accidental presence (e.g. in the management of raw material transport). These obligations do not apply to products (dairy, meat) from animals that may be fed GMO raw materials. Operators in these sectors can choose to declare that their livestock have been fed “GMO-free”, at extra cost to themselves and/or to consumers.

GMO farming began in the mid-1990s and has grown steadily since then, recently approaching 190 million hectares, i.e. more than 10% of the world’s arable land, concentrated in three countries: the United States, Brazil and Argentina (75, 50 and 24 million hectares, respectively).

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[3] *Other factors contributed to this decline, including greater volatility in the yields of these crops and blocking of supply chains (Zander* et al.*, 2016; Magrini* et al.*, 2016). To our knowledge, there is no econometric quantification of the relative contributions of these different factors to changes in PRP acreage/production/balance sheets.*

They mainly consist of soya, maize, cotton and rapeseed, with almost 96, 60, 25 and 10 million hectares, respectively. As a result, almost 80% of the soya grown worldwide is GMO, making it increasingly difficult to supply certified non-GMO soya in France and Europe.

This expansion of GMO crops is partly due to the ever-increasing numbers of new GMO seeds being authorised (Nes *et al.*, 2021). Resistance to herbicides (especially the controversial glyphosate) and insects are still the dominant traits of GMO crops. New GMO seeds target other characteristics, such as increased resistance to climatic hazards or changes in the nutritional composition of products. Moreover, while GMOs are organisms whose genetic material has been detectably altered, this is not the case for seeds produced through new technologies, generally grouped together under the term “genome editing”, which were introduced in laboratories in the mid-2000s. These technologies, also used in gene therapy (Parisi & Rodriguez-Cerezo, 2021), do not insert one or more genes from another organism into the genome of an organism: rather, they selectively modify a genetic sequence within an organism by means of different processes, such as gene mutation, activation or silencing. The products created using these new technologies can also be obtained by conventional (natural) plant breeding techniques. A major advantage of these new technologies is their lower procurement cost in research and development (only 5% of the cost of conventional technology – Bullock *et al.*, 2021). The cultivation of these new seeds has recently begun in the United States (Gotch *et al.*, 2021).

European countries have debated at length the legal status of the products created using these new technologies. In July 2018, the EU Court of Justice temporarily settled the debate on the grounds that they should be governed by the rules applied to GMO products. However, in the spring of 2021, following a request from the European Council, the European Commission published a report that was more favourable to these new technologies and derivatives, stressing on the one hand that they can contribute to more sustainable food systems and therefore to the objectives of the Green Deal, and on the other hand that the current EU legislation on GMOs, adopted in 2001, is no longer appropriate. The debate on these technologies and the resulting products, as well as their possible contributions to protein self-sufficiency, are therefore being reopened in Europe and France (see for example Le Déaut, 2021).

## 2. Literature Review

French and European protein independence is a long-standing issue that has given rise to numerous research projects. This article is limited to a summary of recent studies that include economic computations.

In terms of supply, many studies consider the size of the agricultural holding, the field crop farm and/or the mixed crop-livestock farm. These studies mainly analyse the potential trade-offs between economic and environmental objectives where levels of legume/PRP production/use vary. They include prospective and *ex post* comparative analyses, but make no attempt to statistically explain farmers’ choices in terms of levels of production of PRPs. Summarising the findings of the various French studies conducted to date, Magrini *et al.* (2015; 2016) conclude that there is no trade-off for French farms: the expansion of legume crops is beneficial in the long term, within the framework of appropriate rotations, from both an environmental and economic point of view. These results are not consistently observed in other production regions. As an example, Reckling *et al.* (2016) evaluate the same trade-offs between the economic and environmental effects of the integration of legumes in five European regions. These authors find that, while the introduction of legumes led to significant reductions in nitrous oxide emissions and nitrogen fertiliser use, it also led to a decrease in gross margins in three out of five regions. More recently, Cortignani & Dono (2020) show that the expansion of legume crops promoted by the greening measures of the CAP improved the environmental balance of Italian farms as expected, but to the detriment of economic (income) and social (salaried and non-salaried work) impacts. Lastly, using a micro-econometric model that takes into account the heterogeneity of French agricultural holdings, Koutchadé *et al.* (2021) quantify the impact of coupled subsidies on extensive margins, i.e. on decisions to include legumes in crop rotation. They also show that these subsidies have much more limited impacts on intensive margins, i.e. the number of hectares cultivated once the crop is integrated into the crop rotation.

Some macroeconomic analyses have examined the supply of legumes at national level in France. The latest to our knowledge was provided by Ramanantsoa & Villien (2012), who simulated the impacts of different public support schemes for legume and soya bean production at national level using the MAGALI supply model.

They showed that the price changes considered would have a greater impact on PRP land use and production than direct subsidies. They also pointed out that the cost of reducing GHG emissions is high in relation to the carbon price.

Other studies have focused specifically on the French demand for PRPs, in particular by French animal feed companies. Le Cadre *et al.* (2015) therefore investigated the possible use of locally produced, certified non-GMO soya cake, showing major raw material substitutions and once again the importance of relative prices.

Europe-wide studies covering all aspects of legume/PRP markets are more numerous (recent examples include Henseler *et al.*, 2013; Kalaitzandonakes *et al.*, 2014; Kuhlman *et al.*, 2017; Deppermann *et al.*, 2018; Jensen *et al.*, 2021; Gotch *et al.*, 2021). Using the CAPRI model, Kuhlman *et al.* (2017) test six scenarios, finding that those in which foreign GMO products were rejected (captured by a reduction in imports) in Europe and the introduction of a carbon tax were the most effective for promoting legume production. The scenario combining a tax on meat consumption and a subsidy for the consumption of vegetables has a neutral effect on the acreage devoted to legume crops, due to the decrease in the land used for soya as a result of the decrease in meat production. Deppermann *et al.* (2018) use the Globiom model to simulate the impacts of restricting animal feed to using only local raw materials until 2050; it resulted in a decrease in milk and meat production, as well as in the acreage used for grain production (replaced by legumes). The authors found that the gain in protein independence came at the expense of self-sufficiency for animal products and grains. Jensen *et al.* (2021) use the Aglink-Cosimo model developed by OECD and FAO to quantify the impact of three scenarios on European protein autonomy: a subsidy coupled to land used for legume production, an increase in pea and soya yields and finally a halt in palm oil imports for biodiesel production. *A priori*, the latter scenario should stimulate European rapeseed oil production (to replace palm oil) and simultaneously European rapeseed cake production, thereby reducing the need to import soya cake. The authors find that only the second scenario (increased yields) leads to a significant improvement in European protein self-sufficiency. Lastly, Gotch *et al.* (2021) examine the economic issues related to the legal status of crops derived from new genome editing technologies. For these authors, the economic and environmental impacts are negative, considerable and quite similar to those calculated by Deppermann *et al.* (2018) if the EU keeps these products in the GMO category.

In all the above-mentioned studies, the methods applied do not explicitly differentiate between the GMO and non-GMO sectors, mainly because of the lack of data to measure them, but more theoretical studies have investigated the impacts of the introduction of GMO technologies and their regulation. For example, Moschini *et al.* (2005) concluded that the introduction of GMO food products would have a negative impact on the European economy due to the high costs of traceability and segregation. This is also due to the resistance of European consumers to taking up these products/technologies, as recently measured by Marette *et al.* (2021).

## 3. Modelling and Definition of Scenarios

Compared to the various macroeconomic models mentioned above, our CGE model makes it possible to simultaneously consider consumers, producers and the entire sector, with two major original elements: the database constructed and the specification of the behaviour of economic agents. Indeed, this model describes the French agricultural and agri-food sectors in great detail, distinguishing between sectors described as certified non-GMO and other sectors ("conventional"). Clearly, this separation in two of the diversity of French agricultural sectors is reductive, as it, for instance, places the organic sector and others that use plant protection products in the former group, but it is still an improvement on existing models, which generally consider a single market/technology for each product. Moreover, the specification of producer/consumer behaviour is more complex than conventional CES production/utility functions, in order to better capture the economic trade-offs of these agents between the two sectors.

Our CGE model is otherwise traditional in its general principles: it is a static model, allowing the analysis of steady states and not the dynamics between these states; it presupposes pure and perfect competition in all product markets, with the price balancing supply and demand. It is a single-country model centred on France; trade with other countries is specified with the traditional Armington specification. The economic behaviours of agents in the "Rest of the World" are specified through export and import demand functions.

For the macroeconomic closure, we assumed that investment is determined by savings, which is itself determined by an exogenous savings rate for French households. Public consumption of goods and subsidy/tax rates on the various cash flows are also fixed. The balance of the State budget is ensured by a variation in net levies on households. Finally, the trade balance is fixed and the real exchange rate endogenous. Kilkenny & Robinson (1990) showed that none of these macroeconomic assumptions had any substantial bearing on the market impacts that we measure and constitute the aim of this article. In the same vein, Gohin & Moschini (2006) showed that for agricultural policy reform scenarios, the impacts on markets measured by a CGE model were very similar to a partial equilibrium (PE) model defined on the same sectors of interest. In this article, we opted for the use of the full CGE model, which poses no additional difficulties in terms of data resolution and acquisition; CGE modelling, which satisfies Walras' law, ensures the economic consistency of the findings.

The database of our CGE model is a Social Accounting Matrix (SAM) representing the macroeconomic accounts of the French socio-economic system; its structure is detailed in the Box below. The remainder of this section sets out the main specifications of economic behaviour and the three scenarios tested.

### Box – **The Social Accounting Matrix**

The basic SAM at the French level was constructed based on the tables of the National Accounts (INSEE): Input-Output Table (IOT) and Table of Integrated Economic Accounts (TIEA), in the version that includes 17 activities. At this stage, there is only one aggregate sector for agriculture, forestry and fisheries. Agricultural production was then differentiated from forestry and fishing, and the products of the French agricultural sector were differentiated using different data sources from INSEE and Agreste: Resource-Use Balances (RUB), supply balances, agricultural accounts and price or quote data. A distinction was also made between the various agri-food sectors and their energy consumption based on ESANE, a system used for the compilation of INSEE's annual company statistics, FranceAgriMer's statistical data, Agreste's *Enquêtes triennales sur l'alimentation animale* (three-yearly surveys on animal feed) and INSEE's *Enquête annuelle sur les consommations d'énergie dans l'industrie* (annual survey on industrial energy consumption – EACEI).

Next, a distinction was made between farms in Brittany and the Loire region, which are particularly active in livestock production, and the rest of France using data derived mainly from regional agricultural accounts, the *Tables de l'Agriculture Bretonne* (TAB) and the memento of agricultural statistics of Pays de la Loire.

The main originality of our SAM lies in the distinction between conventional and certified non-GMO goods for a number of products from agriculture and the agri-food industries, whether produced, traded or consumed on the French market. Only limited data are available on animal products fed with or without GMOs. We used the study by Tillie & Rodríguez-Cerezo (2015) whose data date back to 2012 and concern the European markets for certified non-GMO soya and its by-products (see table below). Market data were collected for 14 EU countries, including France, for three types of soya-derived products: soya beans, soya cake and soya-containing compound feed for livestock. We used these data to make assumptions about the quantities and prices of various certified GMO-free products (including concentrate feed, milk, meat).

Table – **Characteristics of non-GMO markets**

| Data | % non-GMO (quantity) | Premium/additional cost (%) |
|---|---|---|
| Soya bean imports | 10 | +15.65 |
| Soya cake imports | 10 | +20.10 |
| Production of concentrate feed for poultry | 10 | |
| Production of concentrate feed for cattle | 19 | |
| Production of concentrate feed for swine | 7 | |
| Concentrate feed | | +18.85 |
| Cost of broiler chicken production | | +19.50 |
| Cost of milk production | | +7.50 |
| Cost of pork production | | +14.50 |
| Consumer price of poultry meat | | +16.20 |
| Consumer price of eggs | | +16.40 |
| Consumer price of milk | | +12.70 |
| Consumer price of pork | | +14.00 |

Sources: Tillie & Rodriguez-Cerezo (2015)

We had access to the quantities of non-GMO certified and conventional soya and soya cake imports and the quantities of non-GMO certified compound feed produced in France for poultry, cattle and swine. Based on operator surveys, Tillie & Rodrìguez-Cerezo (2015) also provided the additional costs of non-GMO certified soya, soya cake or concentrate feed according to regulatory tolerance thresholds. The authors also estimated the increase in production costs for one kilogram of chicken, milk and pork from certified non-GMO fed animals and the difference in retail prices for animal products labelled as being derived from non-GMO fed animals.

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Box – *(contd.)*

We assumed that certified non-GMO or standard concentrate feeds have the same nutritional value and the same yield. Next, we estimated the number of animals fed with certified non-GMO feed in relation to certified non-GMO concentrate feed produced in France. In order to determine the value of the certified non-GMO production of the various animal products, we applied marked-up producer prices, assuming that these producer prices reflected the increase in production costs estimated in Tillie & Rodrìguez-Cerezo (2015). For the agri-food sector, we assumed that the production of products from non-GMO fed animals is proportional to the domestic production of non-GMO fed animals and that the increase in production costs at the farmer level is passed on along the chain.

For household consumption, we assumed that the proportion of certified non-GMO goods is the same as that of certified non-GMO goods produced in France. We applied the premium paid by consumers for certified non-GMO products as estimated in the report by Tillie & Rodriguez-Cerez (2015) and reported in the table to the values obtained.

Overall, our analysis distinguished between 26 agricultural products(i) and 19 products from the agri-food industry.(ii)

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*(i) For crop production, we distinguished between soft wheat, barley, maize, rapeseed, non-GMO soya, conventional soya, sunflower, peas, faba beans and other oilseeds, fodder, fruit and vegetables and beet. For animal production, we distinguished between cattle, calves, swine, milk, poultry and eggs, and for each of these products, we determined the proportion of non-GMO products. The remainder of these values is classified as “other agricultural products”.*

*(ii) For agri-food products, we distinguished between beef (conventional and non-GMO), pork (conventional and non-GMO), poultry meat (conventional and non-GMO), other meats, dairy products (conventional and non-GMO), soya oil, other oils, soya cake (conventional and non-GMO), other oil cakes, compound feed (conventional and non-GMO), sugar, beverages and tobacco, and finally a residual “other agri-food products”.*

## 3.1. Main Characteristics of the Computable General Equilibrium Model

SAM data are fed into a CGE model that simulates the behaviour of firms in terms of product supply, input demand and use of factors (capital, labour or land for the agricultural sector) and the behaviour of households in terms of final consumption of products and savings. These behaviours depend not only on prices, technical and budgetary constraints, but also on regulatory constraints and taxes or subsidies that can be modelled. We assume here that producers maximise their profits under the constraint of a production function and consumers maximise their utility under a budget constraint.

### *3.1.1. The Behaviour of Agricultural Producers*

This section focuses on representative regional multi-output farms. Three farms are included in our model: one representative of the agricultural sector in Pays de la Loire, one representative of Brittany and one representative of the rest of France. We only distinguish between the two main French regions for livestock production in terms of agricultural production due to availability of the data. Each farm maximises its profits under technical constraints. The decision variables are the inputs specific to each output, acreage allocated to the different crops, numbers of animals, non-attributable intermediate consumption (such as insurance services) and salaried jobs. The maximisation programme depends on input and output prices, fixed factors (material and building capital, total agricultural surface area and self-employed labour) and technological possibilities. For the latter, we follow Koutchadé *et al.* (2021) and model crop yields using a quadratic function specific to each crop, dependent on the quantities of inputs used (fertilisers and plant protection products). However, these yields do not depend on the number of hectares cultivated. Gross margins are derived per hectare for each crop, assuming that producers determine the optimal crop rotations that maximise the sum of these margins multiplied by the acreage allocated to these crops, minus a concave cost function dependent on acreage. We proceed in the same way for each animal activity: the yields per animal are then quadratic functions of feed intake (concentrates and fodder for herbivores), and the optimal numbers of animals maximise the sum of margins minus a concave cost function which depends on the number of animals.

Technologies in multi-product sectors are traditionally specified with CES functions. The results are then used to model land use trade-offs and came under significant criticism due to the non-additivity of quantities. Gohin (2020) solved the problem by developing a quadratic approach. However, it is parameter-intensive. To reduce the number of parameters, the logistic functions are specified as in Koutchadé *et al.* (2021).

### *3.1.2. French Consumer Behaviour*

We assume that consumers make a series of choices: firstly, they choose between the consumption of food and non-food goods according to a linear expenditure system (LES) function. It is therefore assumed that a minimum necessary amount is allocated to food and non-food goods. This expenditure system makes it possible to capture non-homothetic income effects, which are regularly estimated in econometric studies conducted on both microeconomic and macroeconomic data. The choice between food and non-food goods is made according to a Cobb-Douglas function, which is not critically important in our analysis, as prices of other goods vary little in the simulated scenarios.

Within food goods, consumers then make a choice between meat, dairy products, eggs, cooking oils and other food goods, again using a LES function. The choice between other food goods (fruit, beverages, etc.) is made according to a Cobb-Douglas function, again without prejudice, as the prices of these goods vary little in our scenarios. A choice is also made between different meats (beef, pork, poultry and other meats) according to a new LES function. The final level of decision-making is between certified non-GMO and conventional products and concerns eggs, dairy products and different meats. This last level of trade-off is specified by a CES-LES function. This function, which is used in the MIRAGE model, is parsimonious, regular and more flexible than the LES function in taking into account price effects, the latter restricting goods to the status of gross complements. This allows for greater relevance in the analysis of a change in French consumer demand for GMO-free food products.

### *3.1.3. Calibration*

The parameters of the production and utility functions are calibrated using SAM data and price or expenditure elasticity. For agricultural supply, the parameters are determined on the basis of the econometric findings of Koutchadé *et al.* (2021). For example, the price elasticity of wheat production is 0.55, broken down into a surface area effect (0.50) and yield effect (0.05). For (non-GMO) soya produced in France, these elasticities are respectively 0.80, 0.54 and 0.26. For final household demand, we rely mainly on the econometric findings of Caillavet *et al.* (2016), and for the distinction between non-GMO and conventional food goods on the recent econometric estimates on organic dairy products by Lindström (2021). For trade, we assume that France is a small country on the world markets for agricultural and agri-food products. The same values were therefore adopted for the price elasticities of export demand (to the nearest whole number), import supply and Armington substitution elasticities. Fontagné *et al.* (2022), who have estimated these elasticities econometrically, find values close to 10 for animal products. This value is therefore used for conventional food products. However, to reflect the preferences of French households for local and certified non-GMO products, we retain a value of 0.1 for the own-price elasticity of import supply in order to take account of the fact that foreign producers may also want to offer certified non-GMO food products, competing with those produced in France, especially for French households located near land borders (with Germany for example). Similarly, the own price elasticity of export demand is set at −0.1. This means that foreign consumers also tend to favour domestic non-GMO production. These two elasticities are not supported at all by the econometric estimation, so we conduct a sensitivity analysis of the results obtained with these elasticities.

## 3.2. Definition of Scenarios

A number of proposals have been made to improve protein self-sufficiency, at the national and/or European level (see literature review). Here, we consider three contrasting scenarios in terms of protein independence strategies, all tested on our model calibrated for the year 2011, for two reasons: on the one hand, this avoids the need to establish a reference scenario (e.g. for 2030), which is a tricky exercise: for example, there is a lack of information to quantify the trend in certified non-GMO sectors in France over the last ten years. On the other hand, the main economic variables have shown little change over the last ten years, the main exceptions being the steady decline in the number of farms, the rise of soya and the decline in the price of sugar (which was high in 2011 compared to the average of the last ten years). Conversely, the levels of production and prices of the main agricultural commodities observed in 2011 are in line with the average of the last ten years. The results presented here should therefore be understood as the effects that would have occurred in 2011 had these scenarios been implemented, economic stakeholders had adapted to them (according to the elasticities mentioned above) and markets had reached a new steady state.

The *first scenario* (“*Coupled subsidies*”) is a conventional one that appears in all protein plans and is regularly tested in analyses. It concerns the increase in coupled aid for the cultivation of soya and legumes authorised by the new CAP and already planned in France as part of its national low carbon strategy. It simulates an amount of coupled aid of €200/ha for soya, pea and faba bean crops (compared to €0/ha for soya in 2011 and €155/ha for peas and faba beans), which is close to the maximum amount of coupled aid paid for the last 10 years for a legume crop.

The *second scenario* ("*Technical progress*") simulates a varietal improvement that would compensate for the productivity gap between legumes and wheat (Magrini *et al.* 2016) through investment in research, at least initially driven by public authorities. As pointed out by Alston & Pardey (2021), it is not easy to determine the research and development expenditure needed to obtain a given varietal improvement; therefore, the costs associated with this scenario are omitted from our computations and, as mentioned in the introduction, no normative analysis is conducted. We assume that this varietal improvement would lead, all else being equal, to an increase in yield per hectare of 25% for peas/faba beans/soya and 12.5% for fodder. Note that Jensen *et al.* (2021) made more conservative assumptions (8% for the former, 0% for the latter), consistent for these latter crops with almost zero efforts in recent years in terms of varietal selection for grassland forage species (ACTA, 2021). These conservative assumptions are also consistent with the vision of lock-in described in Magrini *et al.* (2016), where research efforts focused primarily on "main" plants. As a counterpoint, new genome editing technologies no longer focus exclusively on these plants; some are applied to protein and fodder crops (alfalfa, ryegrass) (Parisi & Rodriguez-Cerezo, 2021). It is impossible to predict whether these new technologies will be authorised in France and in Europe in the short-to-medium or long term. Our aim here is just to test a breaking scenario.

The *third scenario* ("*Demand*") simulates an increase in consumer demand for French and certified non-GMO products. We then assume a doubling of the demand for eggs, poultry and pork, all else being equal. Initially these demands represent 10%, 10% and 7% of total demand for these products by French households in terms of volume. For certified non-GMO beef and dairy products, the initial levels of demand are higher (20%) and a 50% increase is assumed. Correspondingly, demand for conventional products decline such that initial budgets are unchanged. As the prices of certified non-GMO products are higher than those of conventional products, these assumptions imply a decrease in the overall quantities consumed. These assumed trends (all else being equal) are based on increases in the consumption of organic products in recent years and on the health, environmental and societal concerns of households. Therefore, according to CRÉDOC surveys summarised in FranceAgriMer (2018), the "Made in France" criterion has become the main criterion for choice, ahead of price and food safety. This third scenario is in line with a trend identified in Soler & Thomas (2020) of French households preferring to consume smaller quantities of better quality food. It is also consistent with recent analyses quantifying the effects of a reduction in red meat consumption motivated by health and environmental considerations (Cavaillet *et al.*, 2016; Bonnet *et al.*, 2018). Finally, the scale of our shocks (leading to market shares for non-GMO products ranging from 20% to 30%) is consistent with the objective set out in the European Green Pact to reach 25% organic products by 2030.

## 4. Results

In this section, we describe and comment on the findings obtained for the three scenarios. Table 1 provides a summary of those findings.

### 4.1. Coupled Subsidies Scenario

Unsurprisingly, the first scenario involving increased coupled subsidies to soya, pea and faba bean acreage leads to an increase in planted acreage (e.g. 8.6% for soya). The percentage increase is higher for soya than for the other two crops as the increase in the coupled subsidy is also higher. However, these increases remain modest and far from the stated objectives of doubling production. Consider the example of soya. In this scenario, the coupled subsidy is increased from €0/ha to €200/ha, which represents an equivalent price increase of 17.1% based on the initial soya yield. All else being equal, and in particular before modification of the equilibrium prices, this stimulates an increase in soya acreage of 9.2% (given the elasticity of 0.54 reported previously) and therefore in production of the same level. Smaller increases are obtained of 8.6% for acreage and 8.1% for production (Table 1-A). Indeed, the additional production leads to a fall in the price of certified non-GMO soya beans (Table 1-B) of around 1.8%, which reduces the initial effect of the subsidy on both planted acreage and yields (a decrease of 0.5%, consistent with the own price elasticity of the soya yield). Another, more limited effect, leading to a modest increase in French soya bean production, stems from the increase in the acreage planted with high-protein peas and faba beans.

Table 1 – **Simulation findings by scenario: variation in level and % from baseline**

| | Baseline value | Scenario 1 “Coupled subsidies” | | Scenario 2 “Technical progress” | | Scenario 3 “Demand” | |
|---|---|---|---|---|---|---|---|
| | | Level | (%) | Level | (%) | Level | (%) |
| A – **Impacts on French crop production (acreage in thousands of hectares, production in thousands of tonnes)** | | | | | | | |
| Wheat acreage | 4,990 | −1.70 | −0.03 | −4.95 | −0.10 | 9.55 | 0.19 |
| Wheat production | 36,236 | −12.15 | −0.03 | −37.97 | −0.10 | 69.86 | 0.19 |
| Rapeseed acreage | 1,560 | −0.55 | −0.04 | −1.38 | −0.09 | 2.49 | 0.16 |
| Rapeseed production | 4,812 | −1.60 | −0.03 | −5.85 | −0.12 | 8.23 | 0.17 |
| Soya acreage | 40 | 3.45 | 8.62 | 3.22 | 8.05 | 2.80 | 7.00 |
| Soya production | 137 | 11.06 | 8.07 | 44.12 | 32.20 | 13.63 | 9.95 |
| Pea acreage | 180 | 3.02 | 1.68 | 11.89 | 6.60 | 0.31 | 0.17 |
| Pea production | 1,070 | 15.69 | 1.47 | 318.54 | 29.77 | 2.00 | 0.19 |
| B – **Impacts on prices (€/tonne)** | | | | | | | |
| Conventional soya | 354 | −0.13 | −0.04 | −1.03 | −0.29 | −1.00 | −0.28 |
| Non-GMO soya | 403 | −7.34 | −1.82 | −34.62 | −8.59 | 48.92 | 12.14 |
| Conv. soya cake | 300 | 0.16 | 0.05 | −1.50 | −0.50 | −1.92 | −0.64 |
| Non-GMO soya cake | 340 | −5.29 | −1.55 | −28.88 | −8.49 | 55.41 | 16.30 |
| Conv. poultry | 1,880 | 0.02 | 0.00 | 4.17 | 0.22 | −5.36 | −0.28 |
| Non-GMO poultry | 2,120 | −2.12 | −0.10 | −12.13 | −0.57 | 214.93 | 10.14 |
| Soft wheat | 183 | 0.02 | 0.01 | −0.26 | −0.14 | 0.14 | 0.08 |
| C – **Impacts on demand for raw materials for animal feed (thousands of tonnes)** | | | | | | | |
| Wheat | 11,328 | 1.05 | 0.01 | −146.56 | −1.29 | 67.70 | 0.60 |
| Conv. soya cake | 3,416 | −1.30 | −0.04 | −151.92 | −4.45 | −149.94 | −4.39 |
| Other oil cakes | 4,134 | −3.73 | −0.09 | −145.33 | −3.52 | 74.09 | 1.79 |
| Non-GMO soya cake | 452 | 8.34 | 1.84 | 31.57 | 6.99 | 17.26 | 3.82 |
| D – **Impacts on livestock production (thousands of tonnes)** | | | | | | | |
| Conv. pork | 1,895 | 0.00 | 0.00 | −1.65 | −0.09 | −94.29 | −4.98 |
| Non-GMO pork | 148 | 0.01 | 0.01 | 0.09 | 0.06 | 110.12 | 74.41 |
| Conv. poultry meat | 1,678 | −0.03 | 0.00 | −2.70 | −0.16 | −111.68 | −6.66 |
| Non-GMO poultry meat | 186 | 0.09 | 0.05 | 0.67 | 0.36 | 117.96 | 63.42 |
| Conv. cow’s milk. | 19,226 | −0.55 | 0.00 | 416.40 | 2.17 | −1,414.47 | −7.36 |
| Non-GMO cow’s milk | 5,880 | 0.07 | 0.00 | −1.07 | −0.02 | 2,136.26 | 36.33 |
| E – **Impacts on trade** | | | | | | | |
| Wheat (000t) | 18,267 | −11.00 | −0.06 | 124.58 | 0.68 | −85.16 | −0.47 |
| Conv. soya cake (000t) | 3,061 | 0.11 | 0.00 | −141.03 | −4.61 | −142.48 | −4.65 |
| Conv. pork meat (€M) | −13 | 0.05 | −0.36 | −11.81 | 90.87 | 183.52 | −1,411.72 |
| Conv. poultry meat (€M) | 396 | 0.01 | 0.00 | −9.95 | −2.51 | 124.75 | 31.50 |
| Conv. dairy products (€M) | 2,344 | −0.53 | −0.02 | 388.70 | 16.58 | 988.64 | 42.18 |
| PRP (€M) | −897 | 6.21 | −0.69 | 174.37 | −19.44 | 10.46 | −1.17 |
| Agri/agro balance (€M) | 10,843 | −12.90 | −0.12 | 873.58 | 8.06 | 1,570.69 | 14.49 |
| F – **Impacts on business income and employment** | | | | | | | |
| Farm income (€M) | 38,114 | 10.93 | 0.03 | 643.16 | 1.69 | 336.34 | 0.88 |
| AFI income (€M) | 29,814 | 0.04 | 0.00 | 74.10 | 0.25 | 590.48 | 1.98 |
| Agricultural salaried employment | 230,674 | −8.03 | 0.00 | 4,449.33 | 1.93 | 2,743.49 | 1.19 |
| Agri-food salaried employment | 534,661 | 6.37 | 0.00 | 1,142.40 | 0.21 | 9,197.38 | 1.72 |

For meat, the unit of measurement is the tonne of carcass equivalent (see https://www.franceagrimer.fr/FAQ/VIANDES/Viandes-Que-signifie-T.E.C).
Sources: Authors’ calculations.

This supplement of non-GMO French soya beans goes mainly to the French vegetable fat industry, with little change in trade (imports and exports). The 8.4% increase in French production of certified non-GMO soya cake is therefore entirely absorbed by animal feed. However, this represents an increase of only 1.8% of this tonnage as a large proportion (almost 80%) is originally imported (Table 1-C). The consequences are somewhat different for peas and faba beans, as a high percentage (around 30%) is exported. Production supplements are therefore also partly exported, which contributes to a smaller fall in prices (0.4% compared to 1.8% for soya beans).

These PRP supplements used in animal feed modestly displace the use of conventional soya cake and other oil cakes (especially rapeseed cake), by less than 0.1%. The use of soft wheat in animal feed even increases slightly, complementing the rations fed to poultry. The increases in certified non-GMO granivore and herbivore production (Table 1-D) are actually very limited, the most significant in percentage being poultry production, which is more reliant on soya cake than other animal production.

In terms of trade in products (Table 1-E), net exports of soft wheat fall slightly, mainly due to a slight decrease in allocated production and acreage. More surprising is the near stagnation of imports of conventional soya cake, while their use in animal feed falls slightly. This is due to the fact that the French fat sector uses its crushing plants more frequently for the crushing of certified non-GMO soya beans than for that of conventional soya beans, resulting in a decrease in French production of conventional soya cake. However, imports of conventional soya beans decrease, causing the French PRP balance to improve by 6.4 million euro. Protein self-sufficiency improves, but only marginally. In contrast, the French agricultural and agri-food trade balance deteriorates by around 12.8 million euro, mainly due to the decline in grain exports.

While this scenario improves farm incomes by almost 11 million euro for an additional budgetary expenditure of 21 million euro, i.e. a transfer efficiency of 0.5 (Table 1-F), this does not lead to an increase in paid labour in agriculture, but rather to an increase in the rental value of agricultural land. This scenario benefits vegetable production, which is relatively less labour-intensive and more land-intensive. The impacts on the agri-food industries are negligible.

In general, for this scenario, the main results of our simulation are consistent with those obtained in the literature (e.g. Jensen *et al*., 2021), which emphasise the modest impacts of acreage-based subsidies on the markets. Our main contribution is to show the differentiated impacts between the conventional and certified non-GMO sectors. This first scenario also gives credibility to our modelling choices.

### 4.2. Technological Progress Scenario

Some of the mechanisms identified above are also at work in our second scenario. Indeed, all else being equal, an increase in yields leads to an increase in margins per hectare, which encourages a change in crop rotation in favour of seed and forage legumes. This results in an increase of 8% in the French acreage of non-GMO soya beans (Table 1-A). In contrast to the previous scenario, the increases are higher in terms of percentage of production (close to 32% for soya beans) due to the exogenous increase in yields. In fact, the increase in production once again leads to price reductions (exceeding 8% for non-GMO soya beans, Table 1-B), which limit the increase in yields and ultimately production. The increase in legume acreage is at the expense of all other arable crops; forage acreages are also down slightly because yield growth is assumed to be lower.

In terms of animal feed (Table 1-C), we again see an increase in the use of certified non-GMO soya cake, which is more competitive in price. By contrast, reductions in the use of other PRPs are significant, especially conventional soya cake (of the order of −150,000 tonnes) and even grains (by a similar tonnage for wheat). This is explained by the increase in the production of fodder for own consumption. In fact, production of herbivores increases (Table 1-D), with total milk production increasing by 1.6%, i.e. by over 400 million litres.

This scenario leads to an increase in certified non-GMO granivore production, to the detriment of conventional granivore production, as the cost of certified non-GMO feed is reduced. Conversely, conventional milk production increases and milk production from non-GMO fed cows stagnates. This is due to the greater weight of fodder in the production costs of conventional milk than in those of certified non-GMO milk. Indeed, all fodder produced in France is non-GMO and can therefore be used in both sectors. However, the non-GMO sectors are subject to additional traceability and labelling costs (cf. section 3.1 for sizing).

In terms of trade (Table 1-E), this scenario leads to a significant decrease in imports of conventional soya cake (nearly 150,000 tonnes) and, at the same time, an almost equivalent increase in net exports of wheat, mainly due to the above-mentioned effects on animal feed. Although net exports of white meats decline, net exports of dairy products increase very strongly, also contributing to the improvement of the French agricultural and agri-food trade balance: this gain approaches one billion euro.

This scenario is also positive in terms of agricultural and agri-food income as well as salaried employment in both sectors (Table 1-F). In particular, the increase in salaried agricultural employment is significant because livestock activities (especially dairy) are labour intensive. Employment increases comparatively more slowly in the agri-food industries, as the positive effects obtained in the meat and dairy industries are partially mitigated by a decline in employment in the compound feed industry.

Once again, the main results for this scenario are qualitatively in line with those obtained in the literature (e.g. Jensen *et al.*, 2021), which emphasise the importance of technological progress. Our results appear stronger, mainly because we assumed an increase in forage yields of 12.5%. In fact they are critically dependent on this assumption. If, conversely, we assume no increase in forage yields, the impacts are once again modest, as in the first scenario. Fodder is rarely studied in global macroeconomic approaches (Gohin, 2020), usually due to the lack of available data, but our analysis illustrates the importance of taking it into account in agri-environmental issues.

## 4.3. Consumer Demand Scenario

The logic of the counterpart of this third scenario is different. The shift in demand towards French certified non-GMO products leads to an increase in the prices of the relevant products (Table 1-B). Conversely, it leads to price decreases for conventional products. For example, the increase is 10.1% for certified non-GMO poultry meat with a decrease of 0.3% for the conventional counterpart. These price changes are necessary to stimulate a shift in supply from French farmers and agri-food companies. Demand for certified non-GMO raw materials for animal feed is increasing, justifying a price increase of more than 16% for certified non-GMO soya cake. The increase in the price of certified non-GMO soya beans, however, is slightly less (12%) because, in our scenario, the soya oil extracted from them is not more valuable to French consumers.

Unsurprisingly, this scenario also leads to an increase in legume and soya bean acreage (Table 1-A) and, on the other hand, to an increase in grain and oilseed acreage. At the end of the simulation, only fodder acreage decreased. The main explanation is that the increase in demand for certified non-GMO white meat is higher than that for livestock products (red meat and dairy products). However, white meat production does not require fodder, only simple and compound concentrated feed.

This scenario too leads to a significant decline in the use of conventional soya cake in animal feed (150,000 tonnes, Table 1-C). This decline is partly offset by certified non-GMO soya cake and partly by the consumption of other oilseeds, particularly rapeseed produced in France, i.e. non-GMO. There is also an increase in the use of soft wheat for animal feed for the same reasons.

Total animal production (certified non-GMO and conventional) increases (Table 1-D) even though total French demand for these products decreases. For example, French pork production increases by 16,000 tonnes. This is due to terms of trade effects: conventional French production becomes more competitive in price. Indeed, agri-food companies make better margins on certified non-GMO products sold on the domestic market, which allows them to reduce their margins on conventional production.

This scenario leads to a considerable increase, of more than 1.5 billion euro, in the French trade surplus in agricultural and agri-food products (Table 1-E), mainly due to animal products. In contrast, the PRP deficit is barely reduced (by only 10 million euro). In fact, the decline in imports of conventional soya cake is offset primarily by an increase in imports of other oilseed cakes and to a lesser extent by a decline in exports of peas and faba beans.

This scenario is favourable to agricultural and agri-food incomes, as well as to salaried employment in these sectors (Table 1-F). The percentage effects are strong for agri-food industries, especially the dairy and meat industries, which are the target of new French consumer demands. Unlike the previous two, this scenario does not lead to an increase in the rental value of agricultural land, so the increase in agricultural incomes primarily benefits active farmers.

## 4.4. Robustness

The findings presented above obviously depend on many modelling assumptions and choices with regard to the calibration of behavioural parameters. As noted in section 3.1, the choice of many parameters was based on econometric studies. The notable exception concerns the parameters governing trade in non-GMO products. So far, we have assumed low own-price elasticities of export demand and import supply for these products (−0.1 and 0.1) compared to conventional products (−10 and 10). In this sensitivity analysis, the latter values are assumed for both product types (i.e. −10 and 10). This is an extreme calibration as it implies that French households no longer favour local products, and similarly foreign consumers no longer favour their local production.

This alternative calibration only marginally affects the results of the first coupled subsidy scenario, as the price impacts are small with the standard version. For example, the price of non-GMO soya beans falls by 1.2%, compared to 1.8% with the central calibration.

The results of the second crop improvement scenario change more significantly. For example, the fall in the prices of non-GMO soya beans and soya cake amounts to 5%, compared with 8.5% with the central calibration. This is because it becomes easier for French producers to export their additional production of non-GMO soya beans and soya cake on the world market, which limits the price drop. However, this does not lead to a significant change in the French protein deficit, which is reduced by 181 million euro, compared to 174 million euro with the central calibration. That is because at the same time, net trade in conventional oil cakes improves less, as these are still used in animal feed due to price effects. The effects on agricultural and agri-food incomes are unchanged.

The results of the demand change scenario also change perceptibly. The price increase for non-GMO poultry is only 6.6%, compared to 10.1% with the central calibration. Again, this does not lead to a significant change in the French protein deficit: the balance improves by 24 million euro, compared to 10 million euro with the central calibration. Again, this results from a substitution between GMO soya cake and other oil cakes. Finally, it is worth noting that, in this scenario, farm incomes do not improve with the alternative calibration, whereas they increase by 336 million euro with the central calibration. This is due to lower animal production (especially milk), which generates more value added than crop production.

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French protein independence is a nearly 50-year-old antiphon, which endures to this day, in the face of economic pressures. Will the new context – characterised by the health crisis that emerged in 2020, the increasingly perceptible changes in societal demands in favour of the environment and localism, and the emergence of new plant breeding technologies – allow these economic pressures to be overcome? This article provides some answers to this question through the development of an original economic model and the quantification of three contrasting scenarios.

The results of our simulations show that changes in French consumer demand for products derived from non-GMO fed animals is a much more powerful driver for reducing soya cake imports than traditional coupled subsidies for legume crops. However, this demand scenario does not lead to a significant improvement in protein self-sufficiency, as imports of other oil cakes increase. The trade balance of agricultural and agri-food products improves significantly, mainly due to the increase in net exports of dairy products. Moreover, this demand scenario increases the income of agri-food activities, slightly less so those of agricultural activities, stimulating their net job creation.

The scenario of coupled support for legume acreage, which is the preferred scenario in all the protein plans that have succeeded one another over the past 30 years, has little effect on the markets for plant-based products and no effect on the markets for animal products. French legume production grows less than the dedicated acreage, as coupled subsidies do not provide an incentive to increase yields. As a result, the effects on agricultural and agri-food incomes are barely noticeable.

In contrast, the scenario of crop improvement for fodder and seed legumes logically leads, by extending the scope of possibilities, to an improvement in protein self-sufficiency, in the agricultural and agri-food trade balance, as well as in agricultural and agri-food revenues. French households enjoy an additional supply of white meat from non-GMO-fed animals. However, the growth of fodder has a negative impact on the compound feed sector.

In short, this quantitative study shows that several drivers are necessary to reduce the French protein deficit and that this reduction cannot depend solely on public action but also on citizens in their consumer behaviour and acceptance or not of new technologies.

As in any empirical study, many hypotheses were put forward to obtain the above findings, which require further exploration. In particular, a more detailed representation of the agricultural sectors beyond that used in this article with the original separation of the certified non-GMO sectors in France (distinction of the organic sectors or pulses used directly in human food) would help to improve robustness. ☐

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