Life Cycle Analyses of proposed approaches within a sample of production systems

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FEED-A-GENE

Adapting the feed, the animal and the feeding techniques to improve the efficiency and sustainability of monogastric livestock production systems

Deliverable D6.2

Life Cycle Analyses of proposed approaches within a sample of production systems

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1. Summary

Objectives

Farming systems are controversial for their impacts on the environment. Changing animal feed systems is a relevant way to reduce these impacts because the inefficient use of nutrients contributes to ecological damage. This work aims to use Life Cycle Analysis to estimate the environmental impact of two feed innovations in pig and poultry farms: (1) the use of European protein sources to replace Brazilian soybean meal, and (2) precision feeding systems to reduce the impacts associated with feed production and nutrient excretions by the animal.

Methodology

The innovations were applied by simulation to the fattening period of conventional pig production and poultry production. The environmental impacts were assessed by Life Cycle Assessment (LCA) with the SimaPro software for one kilogram of animal product at the farm gate. Five impacts were considered: non-renewable energy consumption, climate change, acidification, eutrophication, and land occupation.

Innovative feedstuffs

Four innovative feedstuffs were selected from the results of WP1: a fine fraction of rapeseed meal obtained after sieving of classical rapeseed meal (IF1); two European soybean meals with a cooking-pressing process, one of which involved a preceding dehulling of the soybean (IF2), the other was done without dehulling (IF3); and Danish protein paste extracted from a bio-refining process of green biomass (IF4). Data concerning the production processes of these ingredients and their nutritional characteristics were provided by partners of the Feed-a-Gene project (WP1). Data concerning other classical feedstuffs came from the Feed tables of INRA-AFZ-CIRAD (nutritional characteristics) and from the French database AGRIBALYSE (life cycle inventories).

For pig production, two environmental benefits associated with the innovative feedstuffs were assessed:

- Current benefit: this corresponds to the environmental results that are currently attainable. It compares the environmental impacts of animals fed with feed including innovative feedstuffs (one innovative strategy for each innovative feedstuff) to that of animals fed with classical feedstuffs (baseline). The rate of incorporation of Brazilian soybean meal in the feeds of the baseline depends on the economic context and the relative prices of protein sources. To define the incorporation rate of the innovative feedstuffs in feeds, the lowest prices during the last ten years for a reference feedstuff were applied. The simulations were applied to four economically contrasting years of the last ten years for four European countries (France, Germany, Spain, and the Netherlands).
- Potential benefit: this is the difference in environmental impacts between innovative feeding strategies, with a maximum incorporation of innovative feedstuffs, and baseline strategies with maximum incorporation of Brazilian soybean meal. To maximize the incorporation rate of innovative feedstuffs and Brazilian soybean meal in the feeds, prices of 0€ were considered for these feedstuffs. The prices of the other ingredients are based on the four previous economic contexts in France.

For poultry production, only the potential benefit was assessed. The baseline (or "control") feeds already have a relatively high proportion of Brazilian soybean meal, meaning that the incorporation of

innovative feedstuffs could already potentially replace the Brazilian soybean meal. Moreover, to maximize the incorporation rate of innovative feedstuffs, a price of 0€ was used.

Precision feeding

For pig production, two innovative precision feeding strategies were assessed: for *ad libitum* feeding and for restricted feeding. These strategies were applied to the fattening period and adjusted daily to supply nutrients to pigs according to their individual nutrient requirements. The first strategy gives the opportunity to let the pigs express their potential and to obtain data concerning their behaviour. The restricted feeding strategy represents the classical condition of pig production in France during fattening period. The restriction is used to control the growth of the pigs and their fat deposition. The environmental benefit of the innovative feeding strategies was assessed using two different approaches.

- Experimental approach. Simulations considered data obtained from experiments performed by the Feed-a-Gene partners (WP4) including feed formula, feed intake, animal performance and direct energy consumption. The LCA is performed using these data by comparing the precision feeding strategies to the baseline (biphase feeding strategies with diets with a low protein content). The environmental benefit obtained represents what could be achieved currently in commercial farms by applying a precision feeding strategy.
- Modelled approach. For both the *ad libitum* and restricted strategies, four steps of improvement were simulated using MOGADOR (Cadero et al., 2018): biphase feeding, biphase feeding using low-protein diets, multiphase feeding in groups, and individual multiphase feeding. In this approach precision feeding is modelled as if the individual animal profiles were known beforehand. The environmental benefits obtained are the maximum future benefits.

For broiler production, one precision feeding strategy was assessed. The control system used a maximum of four feeds in a multiphase feeding strategy, although the fourth feed was not actually used in our simulation as broilers were assumed to be slaughtered at day 32. The precision feeding system used the same feed as the control system during the first ten days (starter feed), then a mix of two pre-feeds was used that depended on the age of the animal, using a total of four pre-feeds during the batch. In our simulation, only three pre-feeds were actually used given the slaughter age of the broilers. Trial results were used to determine animal performance and they were considered equal for the control system and the precision feeding system. Results of the LCAs show the potential difference between a multiphase feeding strategy and a precision feeding strategy. These results should be considered with caution, as animal performance in our models is better than in commercial farms as they were based on trial results obtained in experimental facilities.

Results

Innovative feedstuffs

Per ton of ingredient, the innovative feedstuffs have an interesting impact on reducing climate change compared with Brazilian soybean meal (>50%). This is also the case for energy consumption, which is higher for Brazilian soybeans because of transport to Europe. The impact on acidification and land occupation could be higher for the innovative feedstuffs compared to Brazilian soybean meal because soybean is a legume and does not need fertilisation and there are two harvests per year in Brazil compared to only one in Europe.

For pig production, the relevance of replacing Brazilian soybean meal by innovative feedstuffs is rather limited because little Brazilian soybean meal is currently used in pig feeds (less than 5% in finishing diets). This is due to the relative prices of the different protein sources, which makes rapeseed and sunflower meals more competitive than soybean meal. In a virtual context in which Brazilian soybean meal would become the main protein source (i.e., incorporation of 13% in the finishing diet), the innovative feedstuff results in a reduction in climate change impacts (by 8-9% for the European soybean meal and by 3-4% for the protein paste and the fine fraction of rapeseed meal). As indicated before, other impacts, such as acidification and land occupation, increased.

For broiler production, innovative feedstuffs were studied at their maximum incorporation rate (zero price for innovative feedstuffs) and could replace Brazilian soybean meal in broiler and laying hen feeds. For broiler feeds, the use of European soybean meal can lead to a reduction in the use of phosphorus and non-renewable energy, climate change impacts, and acidification, but it would increase eutrophication and land occupation. The use of the fine fraction of rapeseed meal slightly increases acidification and land occupation and slightly decreases all the other impacts. The use of protein paste increases almost all impacts, although only slightly for phosphorus consumption and climate change, and decreases non-renewable energy use. These last results reflect the use of soybean oil, which is incorporated in the feeds using protein paste, and of Brazilian soybean meal, which will still be incorporated despite the use of protein paste.

For laying hen feeds, the conclusions are similar. The use of European soybean meal, per kg of feed, decreases all impacts except for eutrophication (no significant change) and land occupation (+27%). The use of protein paste increases acidification, eutrophication, and land occupation (depending on the economic context). The use of the fine fraction of rapeseed meal decreases all impacts except acidification, in relatively limited proportions.

Precision feeding

For pig production, the environmental benefits of precision feeding mainly reflect reductions in acidification and eutrophication because of the associated reduction in nitrogen excretion. In the experimental approach, the nitrogen excretion was reduced by 8% and 10% for the *ad libitum* and restricted strategies respectively, compared to biphase feeding with a low protein content diet. The resulting reductions in acidification for one kilogram of pig at the farm gate were 5.5% and 4.3%, respectively for the two strategies. For the restricted strategy, the environmental impact of precision feeding was moderated by a slight increase in the feed conversion ratio between the biphase feeding and precision feeding strategies. This shows the importance of maintaining animal performance to preserve the environmental benefits of precision feeding. In the modelling approach, the potential environmental benefit appears higher, with a 12% reduction in acidification, compared to a biphase feeding strategy with low protein diets. This is linked to the assumption that we will be able (in the future) to estimate the nutrient requirements of individual animals in real time using appropriate genetic and individual data.

For broiler production, using a precision feeding strategy allows to reduce all impacts, although only to a limited extent. Land occupation is reduced by 0.4% between the multiphase control and the precision feeding system. Other impacts are reduced by 4 to 5%, except for phosphorus consumption, which is reduced by 8.5%. These results are linked to the composition of the pre-feeds, the amount of pre-feeds used, and the ability to match diet composition with the requirement of the animals.

Conclusion

The environmental benefits of the innovative feedstuffs depend on the economic context and the incorporation rate of Brazilian soybean meal. In the current context, there is little incentive to use Brazilian soybean meal for pig production. Considering a more "favourable" virtual context for Brazilian soybean meal, a reduction in climate change impacts can be achieved by using alternative sources of protein, especially with European soybean meal, but it will lead to increased land use, resulting in a trade-off question between the benefits and drawbacks. It is necessary to integrate the rebound effects in a larger perimeter of analysis, as shown by Van Zanten et al. (2017). Still, the use of innovative feedstuffs is integrated into the development plans of crop producers and feed manufacturers and there is an ambition to increase production from 150,000 ha of soybean per year in France to 250,000 ha in 2030.

For pig production, precision feeding provides a means to reduce nitrogen excretion, which impacts on acidification and eutrophication. The results of experiments assessed by LCA show that the modest benefits of reduced nitrogen excretion (<5%) can be offset by a reduction in animal performance. With the modelling approach, more interesting environmental benefits have been estimated (e.g., a reduction in acidification of 12%). Individual precision feeding allows to reduce the protein content of feeds and to reduce nitrogen excretion. The environmental benefit measured corresponds to individual multiphase feeding using two different feeds mixed every day: further improvement of performance could be obtained in the future by using three different feeds.

For broiler production, precision feeding can also reduce environmental impacts, but experimental results show only a limited potential with most reductions being between 4 and 5%, with a maximum reduction of 8.5%.

Teams involved:

1) IFIP – deliverable leader
2) INRA
3) ITAVI

Species and production systems considered:

For pig production:

- Conventional pig production in Europe
- Four national economic contexts for the feedstuff prices (France, Germany, Netherlands, and Spain) and four contrasting years.

For poultry production:

- Conventional broiler production in France
- Conventional cage-free egg production in France
- Four economic contexts for feed formulation in France

2. Introduction

The world's population is expected to increase to up to 9.8 billion of people (United Nations, Department of Economic and Social Affairs, Population Division, 2017) by 2050 compared to current level of 7.6 billion. This will result in an important increase in food demand, which will be exacerbated by increasing income levels and changing lifestyles in emerging countries. The Food and Agriculture Organization of the United Nations (FAO, 2011) estimated that the demand for meat will increase by 73% by 2050 compared to 2011, most of which will pig and poultry meat.

Livestock systems face issues concerning productivity but also concerning environmental impacts (Steinfeld et al., 2006). Indeed, livestock is responsible for 14.5 % of global greenhouse gas emissions (Gerber and FAO, 2013) and for a majority of the ammonia emissions (e.g., 64 % in France, CITEPA, 2015). The FAO indicted that there were still no technically or economically viable alternatives to intensive production to provide the nutritional needs of livestock (FAO, 2011). Therefore, it is crucial to find new solutions to improve the efficiency and sustainability of livestock production to minimise environmental impacts and to ensure food security.

Some of the environmental impacts of livestock production are linked to animal feeds

The production of feedstuffs is responsible for a large part of the environmental impact of animal production (expressed per kg of live weight at the farm gate). For example, it contributes to 60 to 67% of climate change impacts, and to 68 to 71% of the non-renewable energy consumption (Dourmad et al., 2014; Espagnol et al., 2012).

Livestock is the most important consumer of cereals and edible protein sources (FAO, 2011). This creates competition between feed and food and contributes to the depletion of global natural resources. There is less workable land because of increasing urban areas and because of climate change. There is also less available water, which has a heterogeneous distribution, and less non-renewable energy.

The use of soybean meal in feed has increased considerably over the past 30 years. This is due to its protein content and its interesting amino acid profile, which suits the requirements of monogastric animals. In the Netherlands, 263 g of soybean is used to produce 1 kg of pig and 575 g to produce 1 kg of broiler (Hoste and Bolhuis, 2010). Around 75% of global soybean production is used to feed animals (WWF, 2014) and the demand continues to increase. Eighty percent of this is cultivated in the Americas where 24 million ha of forest (including primary forests) and pastures were converted to arable land between 2000 and 2010 (WWF, 2014). The reduction of these ecosystems has an impact on climate change. Also, 70% of the global soybean production is cultivated using Genetically Modified Organisms (GMOs); a practice being questioned by consumers.

Another part of the environmental impact depends on the environmental fluxes of animals and their excretions

Despite a permanent improvement in feed efficiency in monogastric animals, a large proportion of the nitrogen and phosphorous intake is excreted in the manure. Inadequate manure management leads to acidification, eutrophication, and climate change.

This deliverable deals with the assessment of the environmental impacts of innovations developed in Feed-a-Gene. It is complementary to other approaches in WP6 concerning acceptability and cost benefit analysis of the innovations.

3. Presentation of the assessed innovations

Two types of innovation developed in Feed-a-Gene have been selected to assess their environmental impact.

The first aims to replace imported soybean meal from Brazil with European protein sources. This is based on locally produced rapeseed meal and soybeans and included technological processes to improve their nutritional quality. These protein sources and technologies are compared to using Brazilian soybean meal.

The second innovation is precision feeding systems. The goal of precision feeding is to improve feed efficiency by better adapting the nutrient supply to the nutritional requirements of (individual) animals. It aims to reduce nitrogen excretion and improve the feed conversion ratio, both of which are of economic and environmental importance.

These two innovations have been developed in WP1 and WP4, respectively. They were considered separately, without considering combinations of innovations (**Erreur ! Source du renvoi introuvable.**).

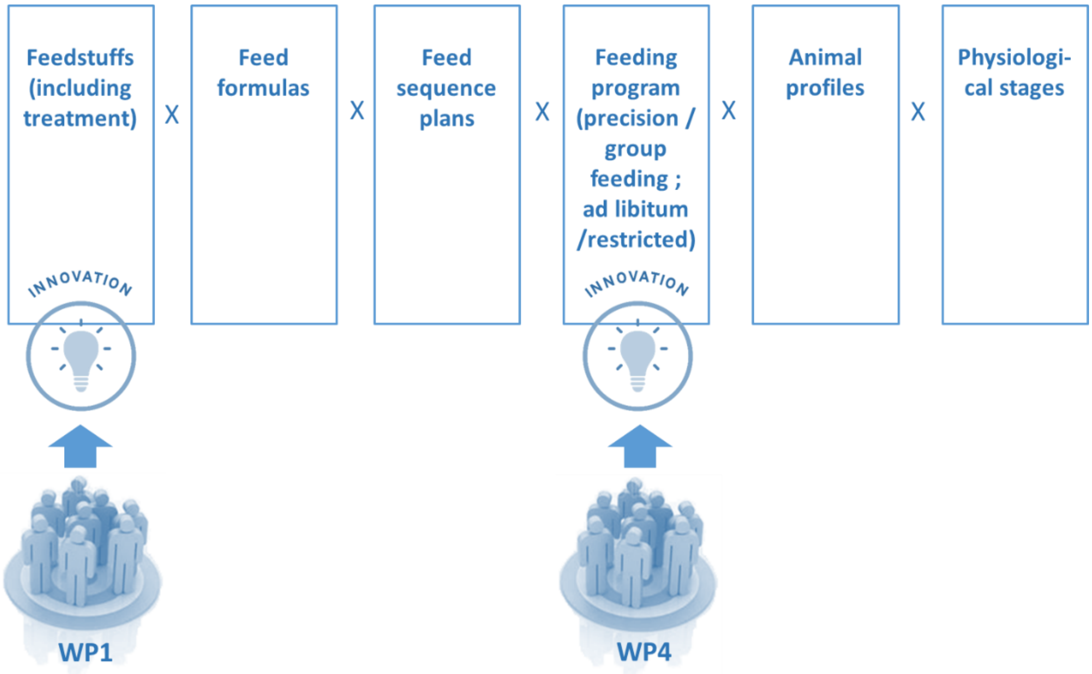


Figure 1: Innovations of Feed-a-Gene considered in the feeding strategies.

3.1 Innovative feedstuffs to replace Brazilian soybean meal

Europe has an important need for soybean meal to provide animal feed. One million tons are produced in Europe while 35 million tons are imported, mainly from South America (WWF, 2014). Fifteen million hectares are required to produce the European consumption of soybean, which represents the equivalent of 90% of the total agricultural area of Germany.

Soybean, and especially soybean meal, is valuable protein source for animal feed. This is due to its high protein content (between 46 and 48%) and amino acids balance, which is close to the ideal protein profile. This makes it difficult to substitute soybean with other ingredients in pig and poultry feeds. The use of Brazilian soybean is controversial in Europe because of its environmental impact (due to deforestation) and the use of GMO soybeans.

As a replacement for Brazilian soybean meal, four innovative feedstuffs developed in Feed-a-Gene were considered (see deliverables D1.1, D1.2, and D1.3 for details):

- A fine fraction of French rapeseed meal obtained through physical treatment (IF1),
- French soybean meal, obtained from dehulled soybeans and with an innovative extrusion process (IF2),
- French soybean meal, obtained from non-dehulled soybeans and with an innovative extrusion process (IF3),
- Danish protein paste extracted from green biomass (IF4).

3.1.1 Fine fraction of rapeseed meal

Locally produced rapeseed meal is a protein source that could be used to replace Brazilian soybean meal (Peyronnet et al., 2014). The production of rapeseed meal increased in France in the 1990s because of biofuel production using rapeseed oil. Rapeseed meal has a lower protein content (33%) than soybean meal and a higher fibre content (13% vs 6% for soybean meal). Experiments showed that rapeseed meal could be used with peas in feeds for fattening pigs: peas are rich in lysine and rapeseed meal is rich in sulphur amino acids and the combination of both allows for a more balanced amino acid profile (Peyronnet et al., 2010). Quiniou et al. (2011) showed that feed based on rapeseed meal and supplemented with valine could substitute soybean meal and resulted in a reduction in the nitrogen content of the feed. Consequently, urinary nitrogen excretion could be reduced by 24%. Currently, rapeseed meal is mainly used for cattle feed (71 % of French consumption vs 24% for pigs, Peyronnet et al., 2014). The presence of anti-nutritional factors is also a potential concern of using rapeseed meal for pigs.

The innovative technological process developed in Feed-a-Gene aims to improve the nutritional value of rapeseed meal. The process is an additional physical treatment applied on “classical” rapeseed meal and consists of sieving the meal to obtain a fine fraction and a coarse fraction (Figure 2). The fine fraction is the innovative feedstuff (IF1), which has a higher protein content and a lower fibre content compared to the original rapeseed meal.

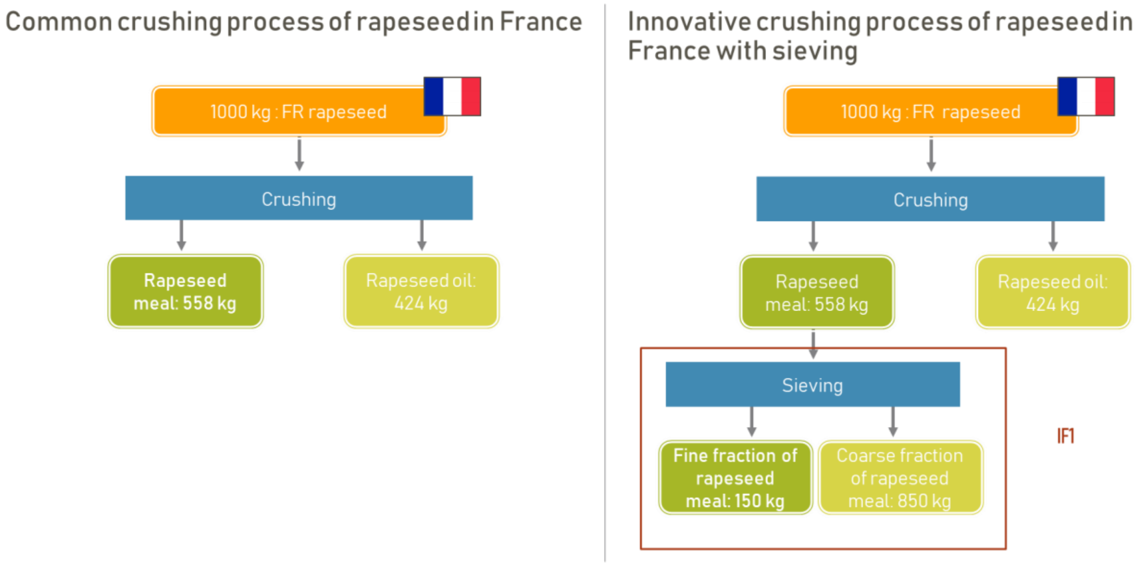


Figure 2: Innovative technological process of rapeseed meal developed in Feed-a-Gene, compared to common the crushing process of rapeseed.

3.1.2 European soybean

In Europe, soybean production occurs mainly in Italy. It is now developing in France and in Eastern Europe (Peyronnet et al., 2014). However, its availability for animal feed remains limited (Quinsac et al., 2012).

Crushing European soybean presents certain practical problems. Brazilian soybean is crushed (e.g., in Brazil or France) using hexane and the resulting meal has a low residual oil content (around 2%). This treatment is only feasible at a large scale. European soybean meal production occurs at low volumes away from existing processing facilities.

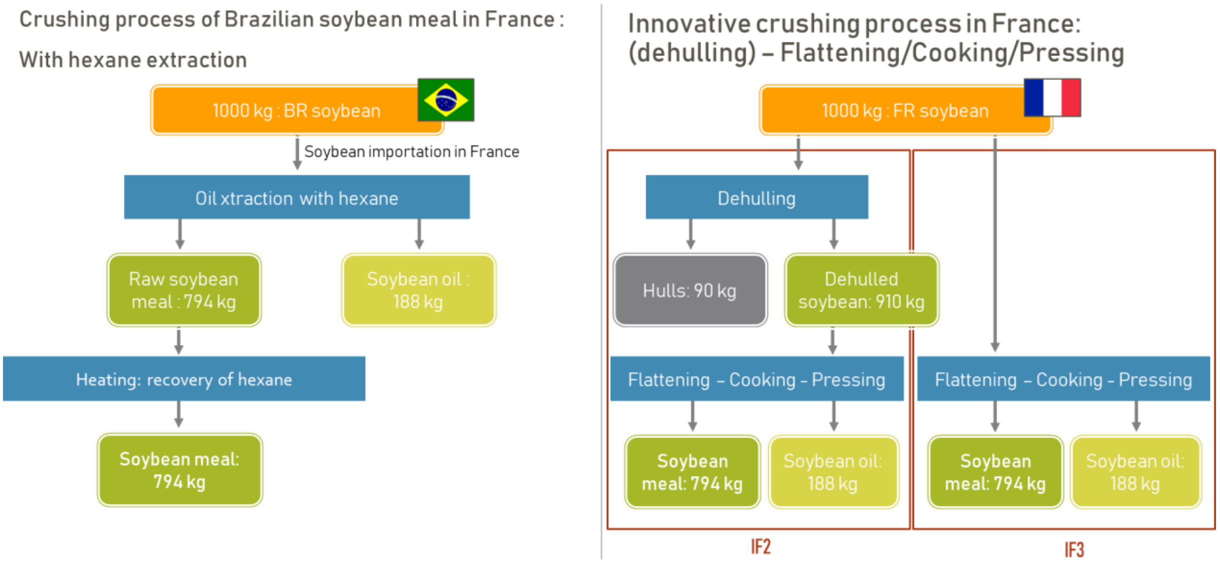


Figure 3: Innovative crushing process for soybean meal in France compared to the crushing process of imported soybean meal.

Innovative processes have been developed in Feed-a-Gene to allow European soybean to be crushed in small plants and thus compete with imported soybean (Figure 3). The process “Flattening-cooking-pressing” produces “Expeller” meal (IF3) and is partially de-oiled (Quinsac et al., 2012). Compared to

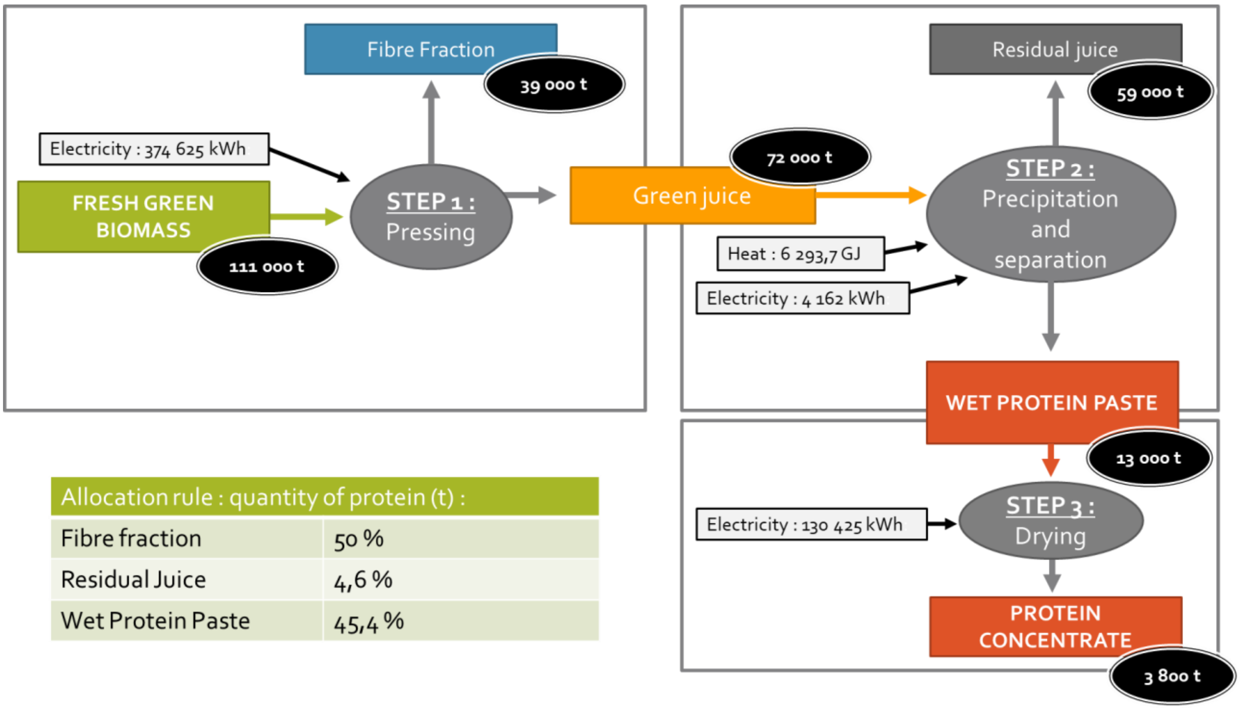
Brazilian soybean meal, European soybean meal contains more energy (i.e., more fat) and less protein. The technological process is also interesting because it could be used for crops such as rapeseed and sunflower (hexane is specifically used for soybean). Dehulling is a pre-treatment of soybean (IF2) before crushing and increases the protein content by 3% (Carré et al., 2017).

3.1.3 Green protein

Denmark has 7% of its agricultural area dedicated to organic production, compared to 5% in France and 3% in the Netherlands (Le Douarin, 2017). The demand for organic products is increasing and organic production in Denmark has grown to meet this demand. Several constraints limit the development of organic farms, especially for pig and poultry farms. For example, soybean meal is a well-balanced protein source but it is difficult to use organic soybean due to its price. Denmark lacks organic protein sources for feed and also lacks organic fertilisers authorized in organic production.

Danish researchers have developed a green bio-refinery process (Figure 4) that uses green biomass and produces several coproducts including a protein paste that can be used to feed monogastric animals (Santamaria-Fernandez et al., 2016). This innovation responds to a very specific demand in Denmark and also deals with European issues concerning the production of locally produced protein sources and the need to reduce competition between food and feed (e.g., grass is not used in human nutrition). The green biomass production contributes to a circular economy because the two other co-products can be valorised in the agricultural sector: the pulp fraction is used as a ruminant feed and the residual juice is transformed into an organic fertiliser.

Several biomass sources can be used in the bio-refinery process such as grass and legumes (e.g., clover and lucerne). The protein paste obtained in the process contains 28% dry matter and the protein content in dry matter varies from 33 to 45%, depending on the biomass used (Hermansen et al., 2017).



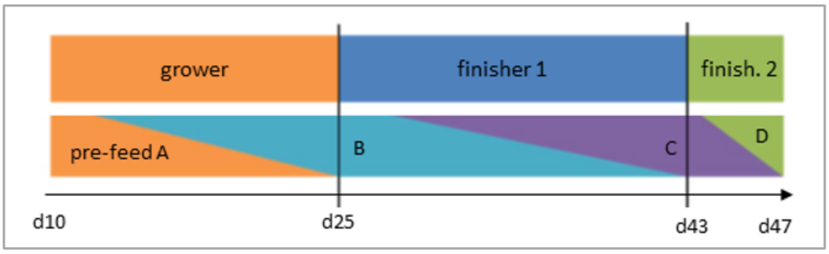
Allocation rule : quantity of protein (t) :	
Fibre fraction	50 %
Residual Juice	4,6 %
Wet Protein Paste	45,4 %

Figure 4: Transformation process of green biomass to produce protein paste.

3.2 Precision feeding strategies

An environmental issue for animal production is to reduce the nitrogen excretion of animals because the main environmental impacts are linked to the nitrogen content of the manure. Nitrogen losses occur during manure management (i.e., storage in buildings and external storage units, and spreading) and contribute to acidification (through ammonia losses), eutrophication (through ammonia losses and nitrate leaching), and climate change (through emission of nitrous oxide). Precision feeding is an innovation which reduces nitrogen excretion because it adapts the nutrient supply to the requirements of (individual) animals. Thanks to precision feeding, less dietary protein is required and nitrogen excretion to the environment is reduced. It also allows to improve feed efficiency, thereby reducing feed cost.

Precision feeding consists of feeding a blend of pre-diets mixed each day in variable proportions to provide a complete ration that best meets the daily requirements of the animal. For the LCA analysis, a solver was used to simultaneously optimise the composition and the daily incorporation rates of the pre-diets while minimising costs (using bilinear optimization).



← Multiphase feeding strategy VS precision feeding strategy (adapted from Dusart et al., 2019) – Strategies from WP4 broiler trial

Figure 5: Precision feeding strategy for broiler production.

For pigs, the precision feeding technology was applied to fattening pigs. For poultry production, it was used only for broilers. At this stage of the project, no data were available about the use of precision feeding for laying hens and egg production.

3.3 Monogastric systems considered to apply innovations

For pig production, the assessments concern conventional farrow-to-finish pig farms, where:

- All animals are housed in buildings dynamically ventilated on fully-slatted floors.
- Slurry is stored below animals during the fattening period.
- At the end of each fattening period, the slurry is removed from the building to an external uncovered pit.
- The spreading of slurry on the land is done using drop pipes.

Broilers were assumed to be raised in a standard broiler production unit, similar to the one studied in the Ecoalim project (Espagnol et al., 2016). Animals are slaughtered at 36 days and the building remains empty for 19 days between batches. The building is 1300 m², with dynamic ventilation and a litter floor. The egg production system considered is the same as in the Agribalyse project (Koch and Salou, 2016). The same SimaPro software was used, except for feeds and emissions, which were modified depending on the scenario. A conventional, indoor cage-free system was chosen to reflect the expected change in the egg production sector in France. For the simulated farms were located in Brittany, France.

4. Environmental assessment methodology

4.1 Life cycle assessment

The environmental impacts were assessed by Life Cycle Assessment (LCA).

4.1.1 Perimeter, functional units, impact categories and allocations

Figure 6 indicates the LCA perimeters and functional units used to assess the environmental impacts of the innovations.

For the innovative feedstuffs two perimeters were considered:

- The first perimeter concerns the production of innovative feedstuffs. It includes the production of inputs to produce the crop, the production on the field with all agricultural operations, the transformation processes and all transport including transport of crop inputs (e.g., fertiliser, water), transport between the field and the transformation plant. The functional unit is a ton of innovative feedstuff at the plant gate.
- The second perimeter is the life cycle of animal production. It includes the first perimeter with the production of feedstuffs and includes the production and supply (transport) of all inputs including the feed, the buildings, and the breeding herd. The perimeter also includes activities associated with the animal and manure management. The spreading of manure was also considered relative to mineral fertilisation: the emissions at the field linked to mineral fertilisation (which would have occurred if there was no manure) are subtracted from the emissions linked to organic fertilisation. Thanks to this methodological choice, only the surplus or the economy of emissions are attributed to animal production. For poultry production, the spreading of manure was not considered. The impacts are expressed per kilogram of animal product at the farm gate (kg of pig, kg of broiler, kg of egg).

For precision feeding, only the animal production perimeter was considered and results are expressed per kilogram of animal product at the farm gate.

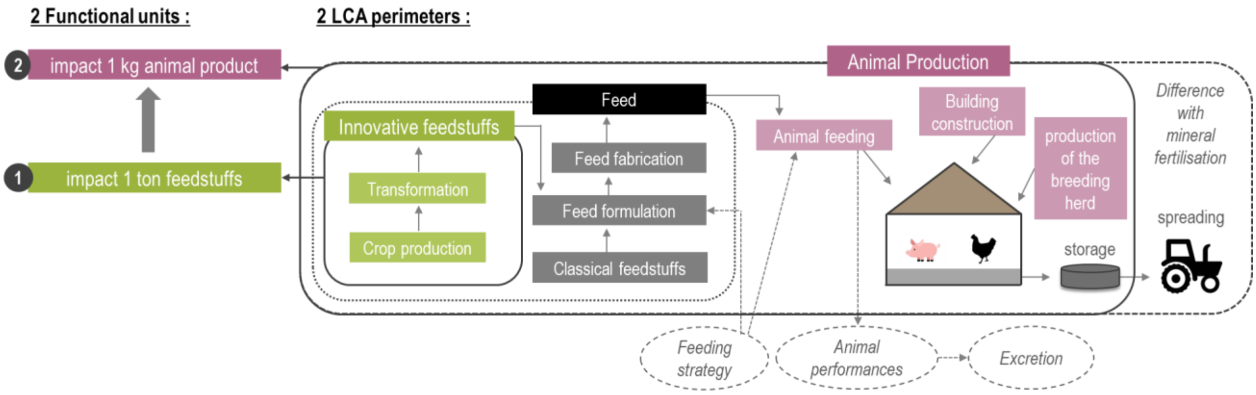


Figure 6: LCA perimeters and functional units.

Six impact categories were assessed by LCA:

- Non-renewable energy consumption (CED 1.8) in MJ,
- Climate change (ILCD) in kg CO_2eq,
- Acidification (ILCD) in mol of H^+ equivalent,
- Eutrophication (CML) in g PO_4^{3-},
- Land occupation (CML) in m^2.year,
- Phosphorous consumption in kg P (only for poultry production)

Concerning the allocations:

- For pig and broiler production, all impacts for the whole production chain considered in the perimeter were allocated to the animal product.
- For egg production, a biophysical allocation was applied similar to the one followed used in Agribalyse (Koch and Salou, 2016). All the impacts regarding the laying period were allocated to egg production, and none of these impacts were allocated to the spent hens. All impacts concerning the production of young hens (before the laying period) are allocated to the spent hens.

4.1.2 Life cycle inventory data and LCA tools

The LCA of innovative the feedstuffs and feeds were assessed using SimaPro (9.0).

Concerning the LCA per kg of animal product:

- For pig production, two methodologies were used:
  - The environmental impacts of the precision feeding strategies with the experimental approach were assessed with SimaPro.
  - The impacts of the simulated strategies (i.e., the strategies with the innovative feedstuffs and the modelled strategies for precision feeding) were simulated using MOGADOR (Cadero et al., 2018). MOGADOR is a model for a pig fattening unit able to (i) simulate the performance of individual pigs, including their variability in interaction with farmer practices and management, and (ii) assess their effects on the associated technical, economic, and environmental performance.

For poultry production, all the LCA per kg of animal product were performed using SimaPro. Data required for the Life Cycle Inventories was derived from different sources (

Table 1).

- From Feed-a-Gene project partners:
    - Transformation processes of the innovative feedstuffs (WP1).
    - Feed formula, animal performance, and energy consumption from experiments on precision feeding (WP4).
- From databases:
    - The Life Cycle Inventories (LCI) and LCA impacts of "classical" feedstuffs used in feeds were taken from the French AGRIBALYSE database. Information on all the ingredients used in the feeds are available (e.g., cereals, meals, oils, minerals, amino acids, imported Brazilian soybean meal). For the assessment, an average Brazilian soybean meal was considered, of which 44% was not associated with deforestation and 56% was associated with deforestation (Wilfart et al., 2016).
- From simulations:
    - Least cost formulation was employed for to determine the feed composition. The results consider the cost of the feedstuffs and their nutritional profiles.
    - The simulations for pig production were done using the MOGADOR model and performance depends on animal characteristics, feed composition, and the feed sequence plan and feeding program.
    - Direct environmental fluxes of livestock were assessed by using emission factors from EMEP (2016) and IPCC (2006), which make the emissions sensitive to excretions (N and volatile solids).
    - Direct water and energy consumption using data per animal, based on previous measurements in livestock.

Data on transport distance, and poultry performance come from internal project expertise.

Table 1: Sources used to complete the Life Cycle Inventories (LCI) of the environmental assessments.

LCI categories	**Pig production**			**Poultry production**	
	Innovative Feedstuffs	**Precision feeding**		**Broilers**	**Laying hens**
		Experimental part	**Modeling part**		
Transformation process of the innovative feedstuffs	Data collected from WP1			Data collected from WP1	
Production process of the other “classical” feedstuffs used in feed	ECOALIM data from AGRIBALYSE database				
Production process of energy used	Average consumption in French pig farms (983 kWh/sow/year; IFIP, 2006) (Ecoinvent for the LCI of 1 kWh)			Average consumption, from ITAVI, 2007	Data from the AGRIBALYSE (egg, conventional, indoor system, non-cage, at farm gate)
Production process of other water used	Average consumption in French pig farms (Massabie et al., 2014)			Average consumption, from Dennery et al. (2012	
Transport	Expertise for the distances (distance from feed plant to livestock: 30 km) (Ecoinvent for the LCI of 1 t.km)				
Feeds formula	Least cost formulation for 4 contrasted economic contexts and 4 European countries	Data collected from WP4	Simulation of least cost formulation for 4 contrasted economic contexts	WP1: Least cost formulation for 4 contrasting economic contexts in France WP4: data collected from WP4	
Feeding strategies	Expertise: biphase feeding	Data collected from WP4	Expertise: biphase feeding (baseline) and precision feeding	WP1: multiphase feeding strategy WP4: data collected from WP4	WP1: one feed during laying period
Animal performances	Simulated by MOGADOR	Data collected from WP4	Simulated by MOGADOR	References, similar to ECOALIM	Data from AGRIBALYSE (Egg, conventional, indoor system, non-cage, at farm gate)
Type of building	Not considered	Average building of AGRIBALYSE	Not considered		
Direct ammonia emissions (NH_3) and nitrogen oxide (NOx)	Simulated by MOGADOR (EMEP/CORINAIR, 2016)	EMEP/CORINAIR 2016	Simulated by MOGADOR (EMEP/CORINAIR 2016)	Simulated thanks to the GEREP Excel calculator – by CITEPA and the French Ministry of Environment NH_3, N_2O and CH_4 emissions Using references from IPCC (2006; CH_4, N_2O) and EMEP EEA (2009), ITAVI (2012), CORPEN (2006) and experts (NH_3)	
Direct nitrous oxide emissions (N_2O)	Simulated by MOGADOR (IPCC 2006)	IPCC 2006	Simulated by MOGADOR (IPCC, 2006)		
Direct methane emissions (CH_4)	Simulated by MOGADOR (IPCC 2006, tier 2)	IPCC 2006 tier 2	Simulated by MOGADOR (IPCC, 2006 tier 2)		
Direct nitrates leaching (NO_3)	Simulated by MOGADOR (IPCC, 2006)	IPCC 2006	Simulated by MOGADOR (IPCC, 2006)	-	-

4.2 Innovative feedstuffs

4.2.1 Nutritional characteristics of the innovative feedstuffs

The nutritional characteristics of the innovative feedstuffs were provided by partners in WP1 (Table 2). The protein paste extracted from green biomass has a high fibre fraction compared to other protein sources. Its protein content lies between that of rapeseed meal and Brazilian soybean meal. The European soybean meal produced without dehulling has a protein content similar to that of the Brazilian soybean meal. With the dehulling process, the protein content is increased by 8% and the fibre content is reduced by 38%. As expected, the European soybean meal have a higher residual oil content compared to the Brazilian soybean meal. Consequently, their energy content is higher. The physical fractionation of the rapeseed meal leads to a fine fraction with a higher protein content (13%) and a lower a fibre content (44%) than the original rapeseed meal.

Table 2: Nutritional characteristics of innovative feedstuffs, compared to Brazilian soybean meal and French rapeseed meal.

For 1 kg of feedstuff	Protein content (g)	Crude fibre (g)	Total fat (g)	Net energy for pigs (MJ)	Digestible lysine g/MJ net energy
Brazilian soybean meal	463	59	16	8.3	3.12
French rapeseed meal	339	128	22	6.7	2.03
Fine fraction rapeseed meal (IF1)	385	72	17	7.1	2.16
European soybean meal dehulling-cooking-pressing (IF2)	505	32	59	9.6	2.96
European soybean meal cooking-pressing (IF3)	466	51	78	9.6	2.72
Protein paste (IF4)	337	205	63	5.1	2.59

Regarding protein content, the innovative protein sources can replace Brazilian soybean meal. However, the ratio of digestible lysine to net energy is systematically lower compared to that of Brazilian soybean meal. To provide the amino acids required by the pigs, it is then necessary to supply more protein in the diet, which may result in more nitrogen excretion.

4.2.2 Feed formulation

Several scenarios have been used for feed formulation to estimate the potential of the innovative feed ingredients to reduce the environmental impact of pig and broiler production.

For pig production, a biphase feeding strategy was considered for the fattening period using a growing and a finishing feed. For broiler production, a starter feed, a grower feed and a finisher feed were formulated. For each scenario, a least-cost feed formulation was performed (Figure 7). For the "classical" ingredients (i.e., not for the innovative feedstuffs), we used:

- Average annual prices of four contrasting economic contexts (for the periods 2010-2011, 2012-2013, 2013-2014, and 2016-2017) resulting in variability in diet formulas. These contexts were chosen by tracking the prices of cereals (wheat) and proteins (Brazilian soybean meal).
  - For pig production, the price contexts were considered for four European countries (i.e., France, the Netherlands, Spain, and Germany). For each country, a list of feedstuffs with prices were defined.
  - For boiler production, the French price contexts were used.
- Nutritional values were obtained from the feed tables of INRA-CIRAD-AFZ (https://feedtables.com).

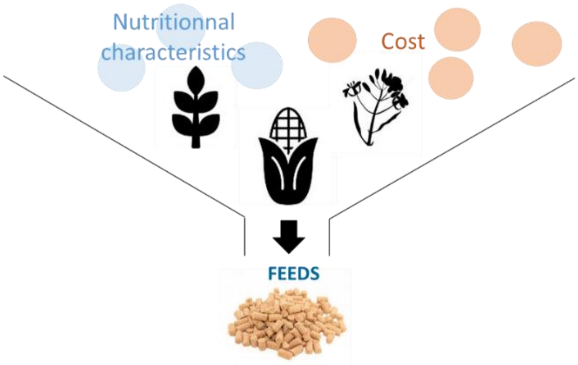


Figure 7: Least cost formulation of feeds.

A *Baseline* feed formulation (Figure 8) was performed to produce baseline feeds in the different economic contexts, without incorporation of innovative feed ingredients. For pig production, a second *Virtual baseline* feed formulation (Figure 8) was performed to produce baseline feeds in which the incorporation of soybean meal was maximised. This new baseline was obtained without the incorporation of the innovative feed ingredients and by setting the price of soybean meal to 0€. For poultry production, the incorporation of soybean meal in the baseline feeds was already high.

For pig production, the effects of incorporation of the innovative feed ingredients was tested in two scenarios, further referred to as *Innovative feed ingredient* and *Max Innovative feed ingredient* (Figure 8) by formulating:

- Feeds incorporating one of the innovative feed ingredients tested at the minimum price of its reference classical feed ingredient (protein concentrate from green biomass at 150€/t, French soybean meal at 290€/t, and the fine fraction of rapeseed meal at 190€/t) (Annex 1).
- Feeds incorporating one of the innovative feed ingredients tested at a price set to 0 €.

Formulation scenarios	*Baseline*	*Virtual baseline*	*Innovative feed ingredient*	*Max Innovative feed ingredient*
List of feed ingredients	All ingredients except innovative Feedstuffs	All ingredients except innovative Feedstuffs	All ingredients with innovative Feedstuffs one by one	All ingredients with innovative Feedstuffs one by one
Prices *Only for pig production*	4 months of prices (from different years) *4 countries (France, Germany, Netherlands, Spain)*	4 months of prices (from different years) *4 countries (France, Germany, Netherlands, Spain)*	4 months of prices (from different years) *4 countries (France, Germany, Netherlands, Spain*	4 months of prices (from different years) *4 countries (France, Germany, Netherlands, Spain)*

Figure 8: Scenarios of feed formulation for the innovative feedstuffs

For poultry production, the effects of incorporation of innovative feed ingredients was tested by formulating feeds with innovative feedstuffs at a price of 0€.

Minimum and maximum nutritional constraints for feed formulation are provided for each scenario in Annex 2. The list of ingredients (Annex 3) and minimum and maximum incorporation rates for all feed ingredients in each scenario (related to the fibre content and presence of anti-nutritional factors) are given in Annex 2.

For broiler production, for the precision feeding system assessment, economic scenarios were assessed for the situation inSeptember 2011, June 2012, August 2013, and February 2014.

4.2.3 Methodology of benefit measurement

Two benefits are measured. The first concerns the **benefit** that can be obtained in the current context. It compares the impacts of one kilogram of animal product for the *Innovative feed ingredient* scenario compared to the *Baseline* (Figure 9). We expect the impacts to be reduced. If impacts are increased, it is considered as a pollution transfer among impacts. The second is the **potential benefit** that would be obtained in a context where: (1) the Brazilian soybean meal would be incorporated at its maximum rate in feed for the baseline, and (2) the innovative feedstuff would also be incorporated at its maximum rate in the innovative scenario. The potential benefit is the difference in impact between the *Max innovative feed ingredient* scenario and the *Virtual baseline*.

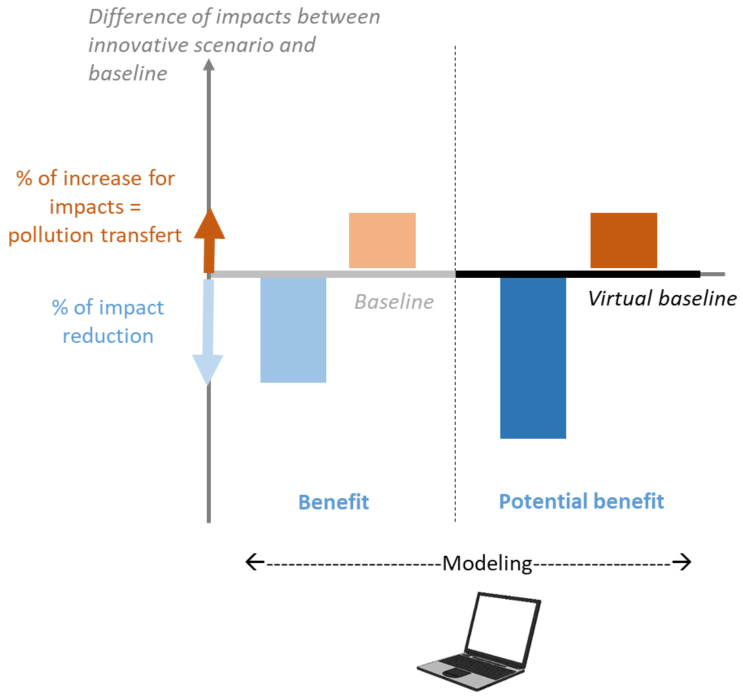


Figure 9: Experimental plan for the innovative feedstuffs.

For poultry production, only the maximum potential benefit is measured. Brazilian soybean meal is used in significant proportions in poultry feeds. Feeds were formulated using innovative feedstuffs at 0 €.

4.3 Precision feeding

4.3.1 Pig production

Two different precision feeding strategies were considered (*ad libitum* and restricted feeding) and two approaches were applied to assess their environmental impacts (Figure 10). The first approach was based on experimental data obtained from experiments in Feed-a-Gene and the second approach was based on the MOGADOR model to assess the potential environmental performance that could be expected from innovative strategies.

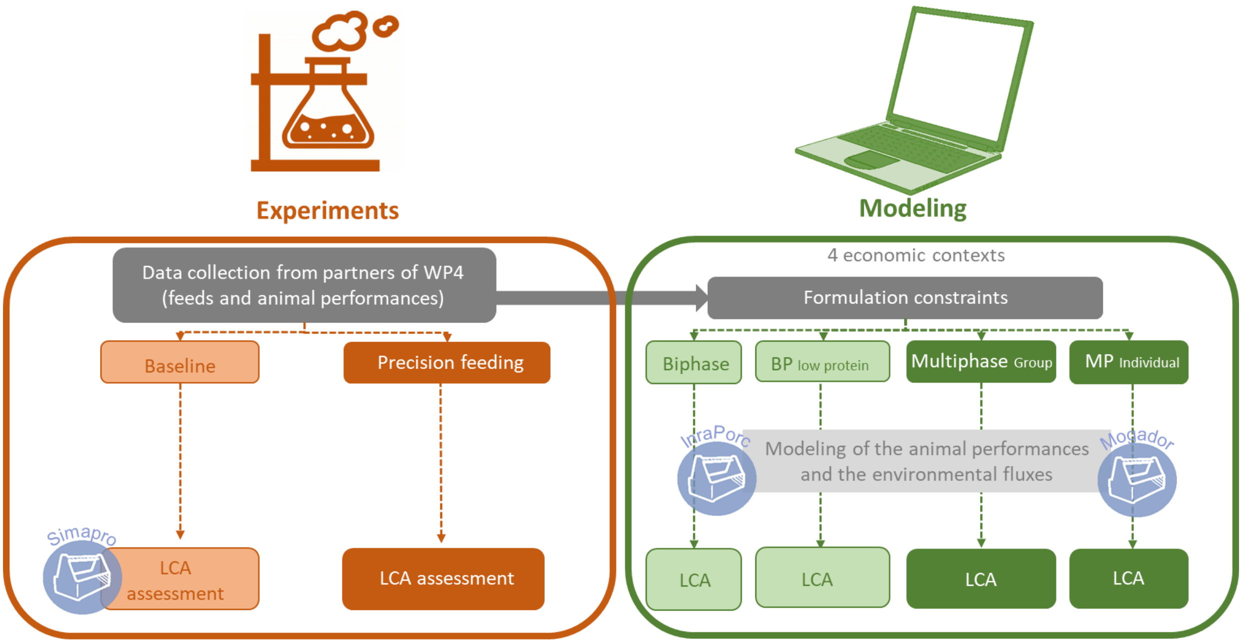


Figure 10: Experimental plan for the innovative feedstuffs.

Experimental approach

Two types of experiment were conducted in Feed-a-Gene concerning precision feeding for fattening pigs:

- INRA tested *ad libitum* precision feeding in the experimental facilities in aint-Gilles (France).
- IFIP tested restricted precision feeding at the experimental facilities in Romillé (France).

For each experiment, pigs were fed individually. Each precision feeding strategy was compared to a biphase feeding strategy applied to a group of pigs. To perform the LCA, data on feeding strategy (i.e., feed formulas, feed sequence plan), animal performance, and direct energy consumption were collected.

Modelling approach

Modelling was performed using the MOGADOR model. For each feeding strategy (*ad libitum* and restricted), different steps were considered to assess benefits incrementally.

- A biphase feeding strategy in which the fattened pigs are fed in groups with two different successive feeds: feed A with 16% protein for the growing period and feed B with 15% protein for the finishing period.
- A biphase feeding strategy using diets with a low protein content (while ensuring the amino acid supply). In this strategy, the pigs are also fed in groups with two different successive feeds: feed A with 15% protein for the growing period and feed B with 13% protein for the finishing period.
- A multiphase feeding strategy for groups. The pigs are fed daily in groups based on the requirements of an average pig. Feeds with different proportions of feed A (17% protein) and feed B (with 10% protein) are formulated daily and blended.
- The innovative feeding strategy assessed in Feed-a-Gene consisting of an individual multiphase feeding strategy. Each pig is fed daily according to its individual nutrient requirements by blending feed A and feed B (i.e., the same feeds as the multiphase feeding strategy in groups). The model

adapts the daily supply of nutrients to each animal because the individual animal requirements are used as inputs. As a result, the model simulates an optimized precision feeding strategy.

The characteristics of each strategy are given in Table 3.

Table 3: Main nutritional constraints used in the feed formulation for each feeding strategy assessed with MOGADOR.

	Feed	Biphase		Biphase low protein		Multiphase	
		Min	Max	Min	Max	Min	Max
Net energy (MJ/kg)	A	9.5	9.5	9.5	9.5	9.5	9.5
	B	9.5	9.5	9.5	9.5	9.5	9.5
Protein (g/kg)	A	160	160	160	160	170	170
	B	150	150	150	150	100	100
Digestible phosphorus (g/kg)	A	2.2	-	2.2	-	2.3	-
	B	2	-	2	-	1.8	-
Minimum of lysine (in % of the requirement)	A	100%	-	100%	-	110%	-
	B	100%	-	100%	-	100%	-

Table 4: Reference live weight and corresponding mean lysine requirement of the pig population for feed formulation in each feeding strategy.

	Feed	Biphase	Biphase low protein	Multiphase
Lysine requirements of the average pig (g/MJ net energy)	A	0.95	0.95	0.95
	B	0.73	0.73	0.43
Reference live weight (kg)	A	30	30	30
	B	65	65	120

Benefit measurement

The benefits of innovations were measured by comparing the innovative scenarios to baselines. In the case of the experimental approach, the benefit is the difference between the impacts of the precision feeding strategy and the baseline (i.e., low protein content biphase strategy, Figure 11). In the modelling approach, the benefit is measured by comparing the different steps to a baseline (i.e., the low protein biphase feeding in groups):

- Difference of impacts between biphase feeding and the low protein biphase feeding strategies.
- Difference of impacts between group multiphase feeding and low protein biphase feeding strategies.
- Difference of impacts between individual multiphase feeding and low protein biphase feeding strategies.

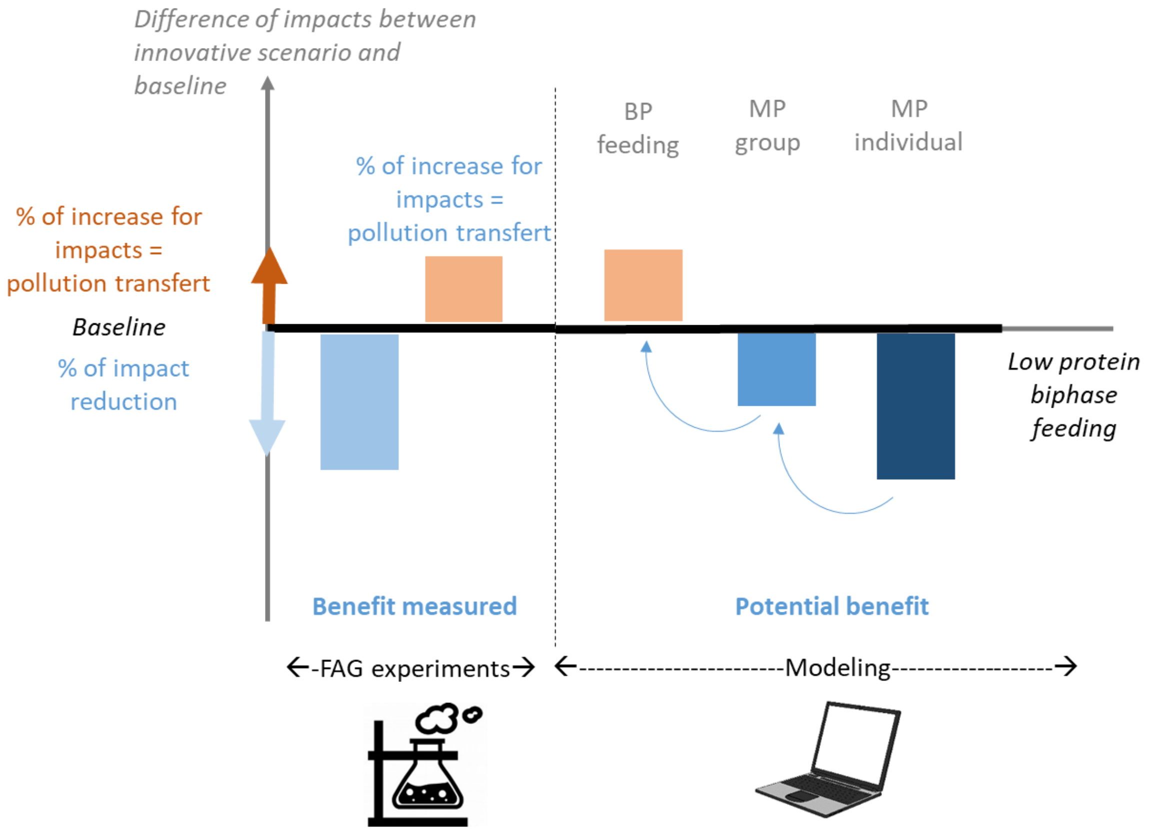


Figure 11: Experimental plan for the innovative feedstuffs.

4.3.2 Poultry production

Experimental approach

For broiler production, data from a broiler trial was provided by ITAVI. In that trial, broilers were raised for 47 days. However, in our simulated commercial system, we stopped the production period at 32 days, as broilers attained a live weight of 1.863 kg at that age whereas standard broilers are typically slaughtered at 36 days. The need to have data for the LCA requires certain compromises to be made and it is acknowledged that performance in commercial conditions can be different from that obtained in experimental conditions.

It was assumed that experimental animals were raised in the same conditions as "baseline" animals (as simulated for the innovative feedstuffs), meaning the building was 1300 m² with dynamic ventilation and a litter floor. Energy, gas, and fuel consumption were adapted (reduced) according to the fact that animals were raised for 32 days instead of 36.

The precision feeding strategy assessed here consists of feeding blends of pre-diets mixed each day in variable proportions to recreate a complete diet that best meets the daily requirements of the birds. A solver was used to simultaneously optimise the composition of the pre-diets and the daily incorporation rates of the pre-diets while minimising costs (bilinear optimisation). Multiphase feeding (i.e., grower, finisher 1, and finisher 2) and precision feeding strategies (using four pre-diets: A, B, C, and D) were compared for broilers fed between 10 to 47 days of age during the trial. In the LCA, hypotheses were made to transpose these results to a theoretical situation of commercial poultry farming with modified performance.

Benefit measurement

The benefits of innovations were measured by comparing the innovative scenario (i.e., precision feeding strategy) with a baseline (i.e., multiphase strategy), for four different economic contexts (i.e., 2011, 2012, 2013, and 2014).

Table 5: Innovative feeding strategies assessed for pig production.

		Feedstuffs	Feed formulas	Feed sequence plans	Feeding program	Animal profiles	Physiological stages	Animal performance
Innovative Feedstuffs	***Baseline***	*Classical feedstuffs*	*Classical least cost formulation*	*Biphase*	*Group / restricted*	*Conventional pigs*	*Growing / finishing*	*Calculated by modeling*
	Virtual baseline (max soybean meal)	*Classical feedstuffs*	*Classical least cost formulation with cost of soybean meal = 0€*	*Biphase*	*Group / restricted*	*Conventional pigs*	*Growing / finishing*	*Calculated by modeling*
	Innovative strategy IF1	Local rapeseed with physical fractionation of meal (without enzyme)	From methodology of formulation	Biphase	Group / restricted	Conventional pigs	Growing / finishing	Calculated by modeling
	Innovative strategy IF2	Local soybean meals with innovative trituration process + seed dehulling (without enzyme)	From methodology of formulation	Biphase	Group / restricted	Conventional pigs	Growing / finishing	Calculated by modeling
	Innovative strategy IF3	Local soybean meals with innovative trituration process (without enzyme)	From methodology of formulation	Biphase	Group / restricted	Conventional pigs	Growing / finishing	Calculated by modeling
	Innovative strategy IF4	Green protein from green biomass	From methodology of formulation	Biphase	Group / restricted	Conventional pigs	Growing / finishing	Calculated by modeling
Precision feeding	***Baseline BP Ad lib***	*Classical feedstuffs*	*Methodology of formulation*	*Biphase*	*Group / Ad libitum*	*Conventional pigs*	*Growing / finishing*	*Calculated by modeling*
	Baseline BP Rest	*Classical feedstuffs*	*Methodology of formulation*	*Biphase*	*Group / restricted*	*Conventional pigs*	*Growing / finishing*	*Calculated by modeling*
	Baseline BP Low prot Ad lib	*Classical feedstuffs*	*From FAG experiment or methodology of formulation*	*Biphase*	*Group / Ad libitum*	*Conventional pigs*	*Growing / finishing*	*Experimentation + modeling*
	Baseline BP Low prot Rest	*Classical feedstuffs*	*From FAG experiment or methodology of formulation*	*Biphase*	*Group / restricted*	*Conventional pigs*	*Growing / finishing*	*Experimentation + modeling*
	Intermediate innovative strategy MP Group Ad lib	Classical feedstuffs	Methodology of formulation	Daily multiphase	Group / Ad libitum	Conventional pigs	Growing / finishing	Calculated by modeling
	Intermediate innovative strategy MP Group Ad lib	Classical feedstuffs	Methodology of formulation	Daily multiphase	Group / restricted	Conventional pigs	Growing / finishing	Calculated by modeling
	Innovative strategy MP indiv Ad lib	Classical feedstuffs	From FAG experiment or methodology of formulation	Daily multiphase	Individual precision feeding ad libitum	Conventional pigs	Growing / finishing	Experimentation + modeling
	Innovative strategy MP indiv Rest	Classical feedstuffs	From FAG experiment or methodology of formulation	Daily multiphase	Individual precision feeding restricted	Conventional pigs	Growing / finishing	Experimentation + modeling

🟦 **Innovations tested in the project FeedAGene**

Baselines

Table 6: Innovative feeding strategies assessed for poultry production.

		Feedstuffs	Feed formulas	Feed sequence plan	Animal profiles	Physiological stages	Animal performance
Innovative feedstuffs	*Baseline*	Classical feedstuffs	Classical least cost formulation	Multiphase (broilers) OR one feed (laying hens)	Conventional broilers + Conventional cage free laying hens	All for broilers, laying period for laying hens	From national statistics (broilers) OR from AGRIBALYSE (laying hens)
		🟦 Local rapeseed with physical fractionation of meal (without enzyme)	See methodology of formulation	Multiphase (broilers) OR one feed (laying hens)	Conventional broilers + Conventional cage free laying hens	All for broilers, laying period for laying hens	From national statistics (broilers) OR from AGRIBALYSE (laying hens)
	Innovative strategies	🟦 Local soybean meals with innovative trituration process + seed dehulling (without enzyme)	See methodology of formulation	Multiphase (broilers) OR one feed (laying hens)	Conventional broilers + Conventional cage free laying hens	All for broilers, laying period for laying hens	From national statistics (broilers) OR from AGRIBALYSE (laying hens)
		🟦 Local soybean meals with innovative trituration process (without enzyme)	See methodology of formulation	Multiphase (broilers) OR one feed (laying hens)	Conventional broilers + Conventional cage free laying hens	All for broilers, laying period for laying hens	From national statistics (broilers) OR from AGRIBALYSE (laying hens)
		🟦 Green protein (protein paste) from green biomass	See methodology of formulation	Multiphase (broilers) OR one feed (laying hens)	Conventional broilers + Conventional cage free laying hens	All for broilers, laying period for laying hens	From national statistics (broilers) OR from AGRIBALYSE (laying hens)
Precision feeding	*Baseline*	Classical feedstuffs	Classical least cost formulation	Multiphase	Conventional broilers with modified performances (from trial)	All physiological stages	From trial + national statistics
	Precision feeding	Classical feedstuffs	See methodology of formulation	🟦 Precision feeding	Conventional broilers with modified performances (from trial)	All physiological stages	From trial + national statistics

🟦 Innovations tested in the FeedAGene project

Baselines

5. Results

5.1 Innovative feedstuffs

5.1.1 Impacts of innovative feedstuffs

The relative LCA impacts of the innovative feedstuffs compared to those of Brazilian soybean meal are presented in Figure 12 and the absolute values are given in Table 7.

Table 7: LCA impacts of innovative feedstuffs.

Impacts / ton	Fine fraction of rapeseed meal (IF1)	Partially de-oiled soybean meal, dehulling cooking-pressing (IF2)	Partially de-oiled soybean meal, cooking-pressing (IF3)	Protein paste from biorefinery process (IF4)	Brazilian soybean meal, crushed in France
Non-renewable energy consumption (MJ)	3371	7793	8371	4304	8884
Climate change (kg CO_2 eq)	447	396	424	459	1151
Acidification (molc H^+ eq)	9.29	3.91	4.25	23.23	6.98
Eutrophication (kg PO_4^{3-} eq)	3.68	6.28	6.88	5.50	4.82
Land competition (m^2.year)	1377	3747	4110	2240	1524

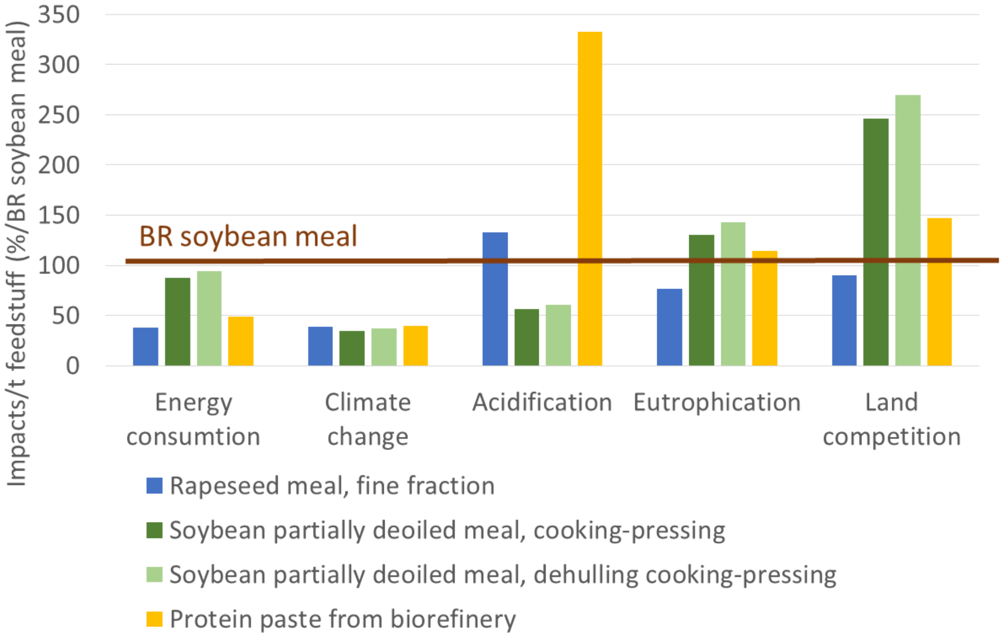


Figure 12: Relative environmental impacts of innovative feedstuffs compared to the impacts of Brazilian soybean meal (base 100%).

The impacts of climate change and energy consumption are systematically reduced. Climate change impacts are reduced by more than 50% for all the innovative feedstuffs compared to Brazilian soybean meal. This is due to the fact that 60% of the impact on climate change of Brazilian soybean meal is linked to deforestation, especially to the Brazilian primary forest (Figure 13).

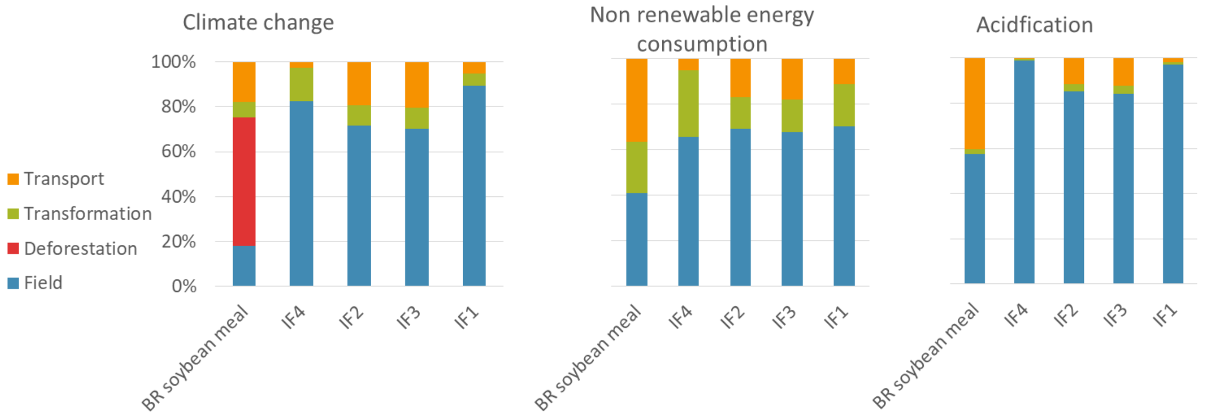


Figure 13: Contribution analysis of the impacts of the innovative feedstuffs and Brazilian soybean meal.

For energy consumption, the impact is due to the transformation process and transport. For the Brazilian soybean meal, the transport from Brazil to the France explains 40% of the energy consumption (
Figure 13), while the transformation process explains 22%. The transformation process for the European soybean explains 12% of the impact of energy consumption.

The energy consumption required to produce protein paste is 85% lower for electricity and 90% lower for heat than that required to produce the Brazilian soybean meal (Figure 14). Processing European soybeans is also efficient since it reduces electricity and heat consumption by 37% and 43%, respectively, compared to crushing using hexane. The dehulling step generates an additional electricity use of approximately 3 kWh/ton. The energy use for rapeseed meal is also lower than that for Brazilian soybean meal, although the physical fractionation leads to an additional energy use of about 15% compared to regular rapeseed meal.

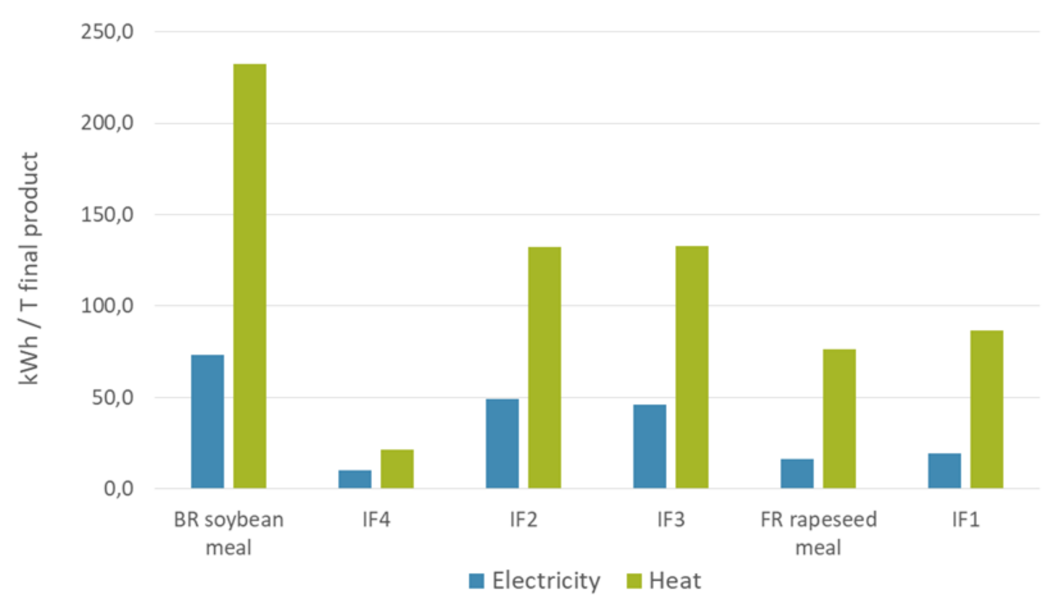


Figure 14: Direct energy consumption of the transformation process for the innovative feedstuffs (kWh/t final product).

Figure 12 *indicates a higher acidification impact for the protein paste and the fine fraction of rapeseed meal compared to Brazilian soybean meal. This impact is explained for more than 95% by the production of the crop and its fertilisation (*

Figure 13). Soybean does not need any fertiliser because it is a legume able to fix nitrogen from the air. Also, Brazil produces two crops of soybean per year which saves land.

The innovative feedstuffs developed in Feed-a-Gene offer advantages compared to Brazilian soybean meal in terms of their ability to reduce energy consumption and the impacts on climate change. However, their use would result increase impacts such as acidification and land use.

5.1.2 Pig production

Incorporation rates of Brazilian soybean meal and innovative feedstuffs

Figure 15 indicates the incorporation rates of Brazilian soybean meal and the innovative feedstuffs in the fattening feed for the pig production scenarios. The average incorporation rate of Brazilian soybean meal in the baseline is quite low (on average 4.5%). Under these circumstances, the potential impact of the innovative feedstuffs is quite low because there is relatively little Brazilian soybean meal to replace. The virtual baseline provides a context more favourable to the use of Brazilian soybean meal where the incorporation rate could reach 13%. In this context, the introduction of the innovative feedstuffs would have a greater impact. The incorporation rates of these feedstuffs in the *Innovative feed ingredient* scenarios and the *Max Innovative feed ingredient* scenarios are quite close to the maximum incorporation rate defined by the formulation constraints.

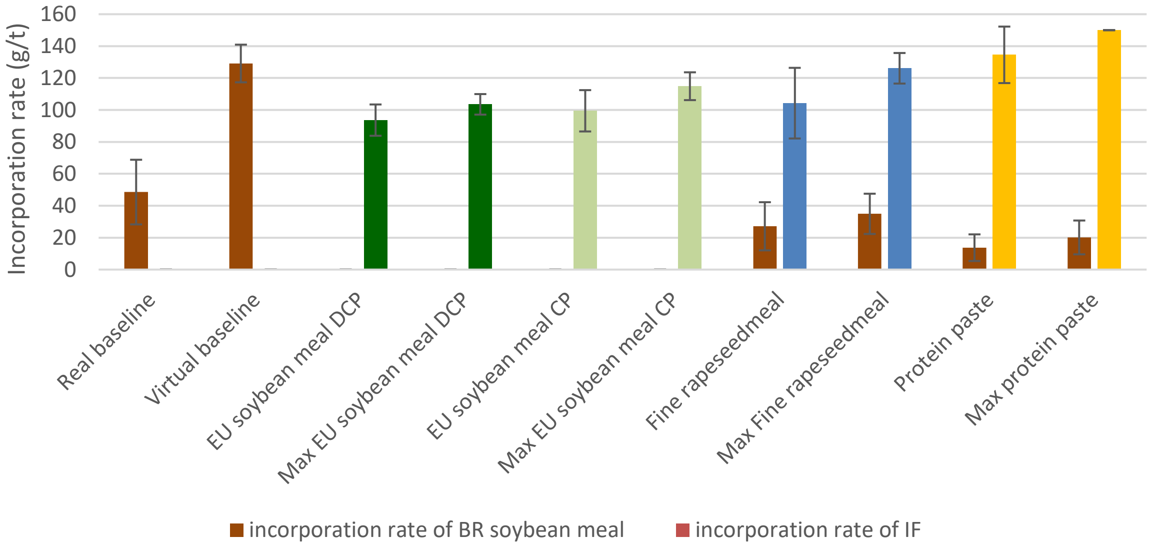


Figure 15: Incorporation rates of Brazilian soybean meal and innovative feedstuffs in finishing feed for pig production scenarios (average and standard deviation among economic contexts and countries).

Animal performance

Animal performance is very stable across scenarios (Table 8). This is due to fact that the same average animal profile is used in the simulation with MOGADOR and that the formulation constraints lead to feeds with a similar nutritional profile.

Table 8: Animal performance among all scenarios.

	Mean	Standard Deviation
FCR* during fattening period	2.74	0.005
N excreted (kg/pig)	3.16	5.535
VS** excreted (kg/pig)	30.41	1.403
Liveweight at the beginning of the fattening period (kg)	29.97	0.026
Liveweight at the end of the fattening period (kg)	116.41	0.109

*FCR : Feed Conversion Ration ; ** VS : Volatile Solids

Environmental benefit of the innovative feedstuffs for pig production

Table 9 gives the absolute values of the environmental impacts expressed per kilogram of pig at the farm gate.

Table 9: LCA impacts of innovative feed ingredients scenarios per kg of pig at the farm gate (average and standard deviation among economic contexts and countries).

Impacts / kg pig		Non-renewable energy consumption (MJ)	Climate change (kg CO_2 eq)	EU Acidification (molc H^+ eq)	Eutrophica-tion (kg PO_4^{3-} eq)	Land competition (m^2.year)
Baseline		18.88 *(0.488)*	2.26 *(0.032)*	0.0702 *(0.000759)*	0.019 *(0.000357)*	3.83 *(0.155)*
Virtual baseline		20.26 *(0.505)*	2.38 *(0.032)*	0.0726 *(0.001764)*	0.019 *(0.000382)*	3.82 *(0.153)*
Innovative feed ingredients scenarios	Fine fraction rapeseed meal	19.32 *(0.449)*	2.29 *(0.014)*	0.0736 *(0.000702)*	0.019 *(0.00034)*	3.91 *(0.138)*
	EU soybean meal dehulling DCP	19.38 *(0.379)*	2.18 *(0.015)*	0.0733 *(0.000598)*	0.019 *(0.0004)*	4.23 *(0.174)*
	EU soybean meal CP	19.18 *(0.431)*	2.16 *(0.014)*	0.0727 *(0.000557)*	0.019 *(0.000396)*	4.19 *(0.181)*
	Protein paste	19.82 *(0.529)*	2.3 *(0.025)*	0.0692 *(0.000522)*	0.019 *(0.000355)*	4.04 *(0.15)*
Max innovative feed ingredients scenarios	Fine fraction rapeseed meal	19.77 *(0.271)*	2.3 *(0.01)*	0.0744 *(0.000544)*	0.019 *(0.000196)*	3.86 *(0.091)*
	EU soybean meal dehulling DCP	19.72 *(0.499)*	2.19 *(0.015)*	0.0741 *(0.000473)*	0.019 *(0.000334)*	4.3 *(0.138)*
	EU soybean meal CP	19.68 *(0.626)*	2.17 *(0.014)*	0.0735 *(0.000445)*	0.019 *(0.000301)*	4.29 *(0.12)*
	Protein paste	20.07 *(0.271)*	2.31 *(0.016)*	0.0692 *(0.000437)*	0.019 *(0.000339)*	4.07 *(0.143)*

Figure 16 and Figure 17 provide details of the environmental benefits of the innovative feedstuffs expressed per kilogram of live weight pig at the farm gate for the various economic contexts over the last ten years and for a virtual context favourable to the uptake of Brazilian soybean meal.

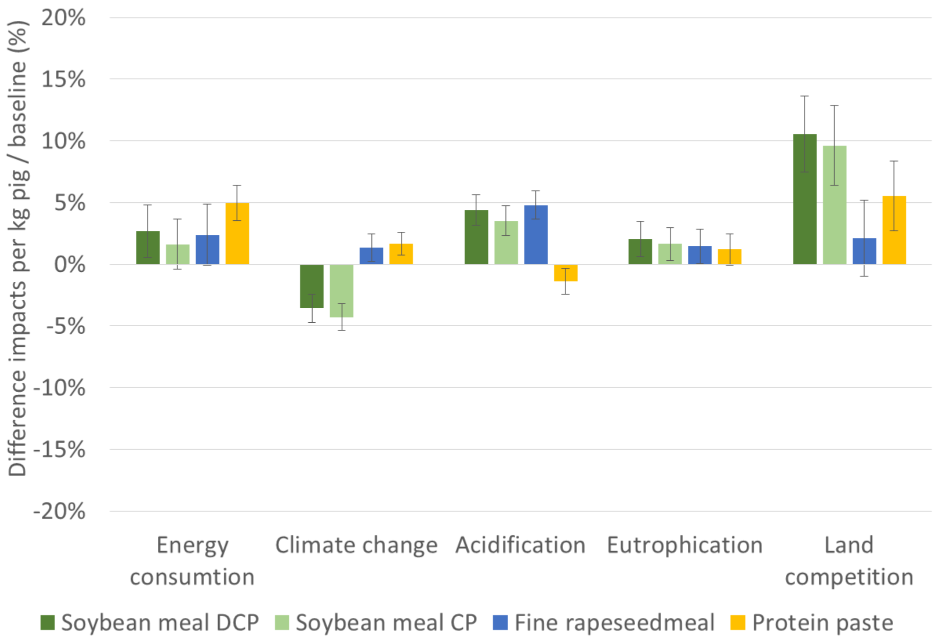


Figure 16: Difference of impacts between Innovative feed ingredients scenarios and the Baseline (average and standard deviation among economic contexts and countries).

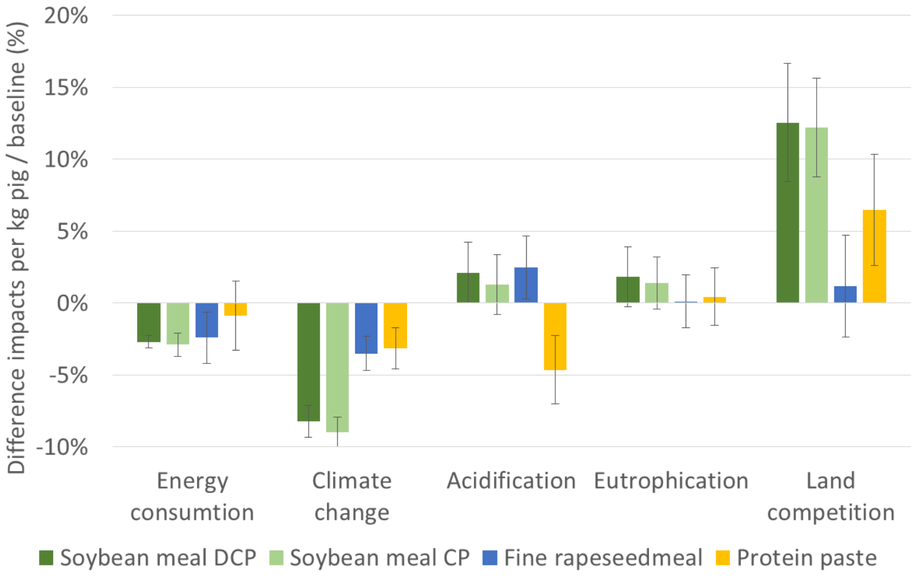


Figure 17: Difference of impacts between Max Innovative feed ingredient scenarios and the Virtual baseline (average and standard deviation among economic contexts and countries).

In the current context, the innovative feedstuffs would have little impact. Climate change impacts are reduced by less than 5% with the European soybean meal. The other impacts increase compared to the baseline, which is due to the fact that Brazilian soybean meal is currently only a small fraction of diet formulas because of its cost relative to other protein sources such as rapeseed meal and sunflower meal.

In a virtual context favourable to Brazilian soybean meal, use of the innovative feedstuffs reduces the impacts on climate change (e.g., a reduction of 8-9% for climate change compared to the baseline) and energy consumption. However, the impact on land occupation increases compared to the baseline (by 12% for the European soybean meal).

The relative reduction of acidification from using green biomass is explained by the fact that its nitrogen digestibility is quite low compared to that of other protein sources. Consequently, the fraction of nitrogen excreted via the faeces is relatively higher and lower in urine (i.e., less ammonia nitrogen). The emission factor of ammonia is applied to the ammoniacal nitrogen excreted (TAN) content which is lower in the biomass scenario (Figure 18), so the ammonia emissions are lower and so is the acidification impact.

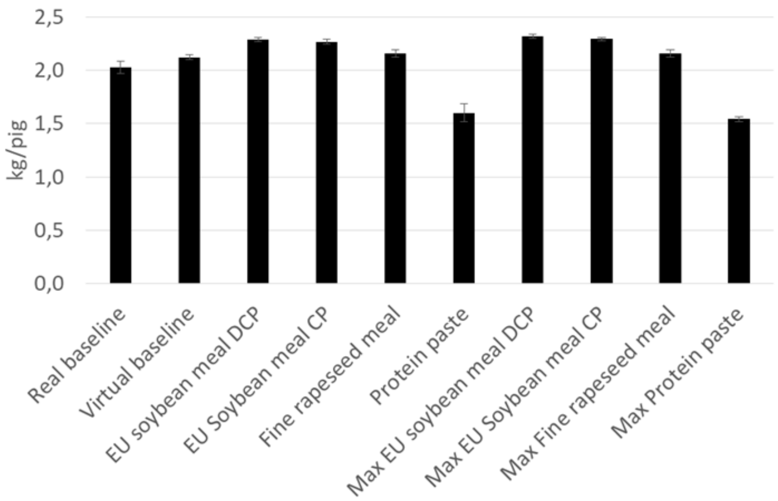


Figure 18: Ammoniacal nitrogen excreted per fattening pig for the different scenarios (average and standard deviation among different economic contexts and countries).

5.1.3 Poultry production

a. Broiler production

Context – Average composition of control feeds used in WP1 – Broiler production

Figure 19 represents the composition of the control feeds for broiler production, averaged over the four economic contexts.

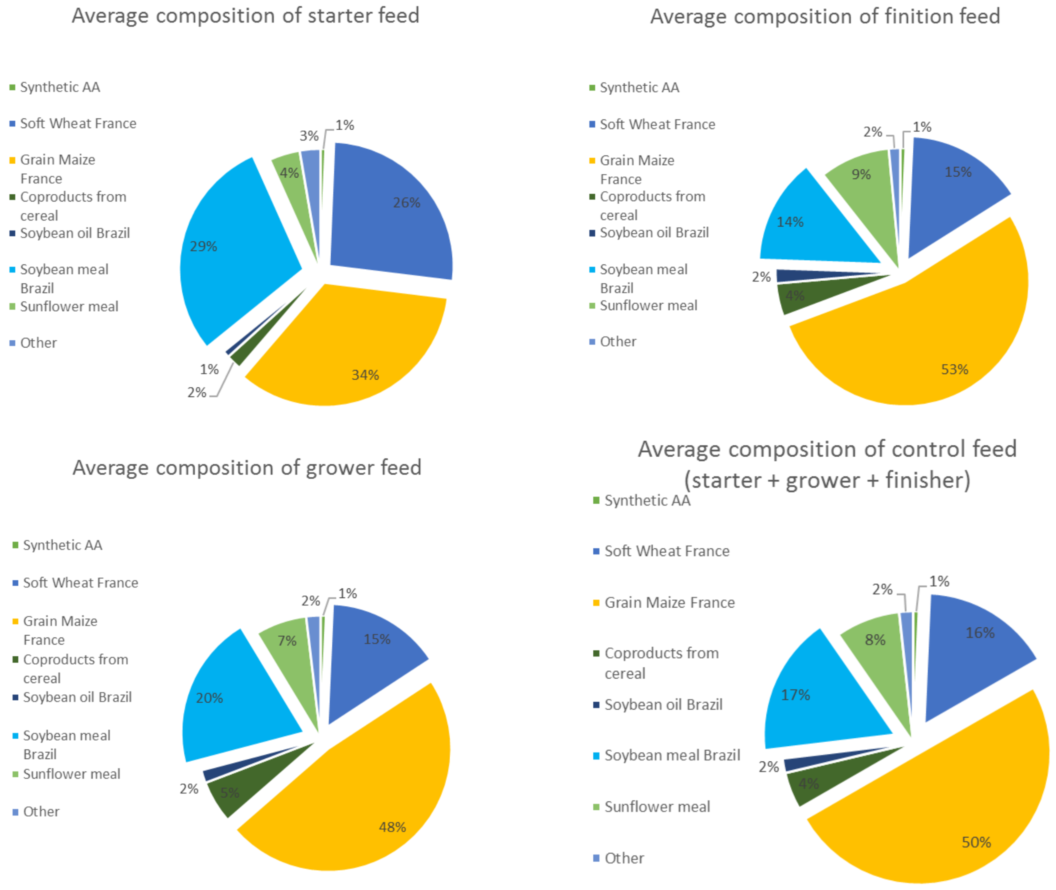


Figure 19: Composition of control feeds, average of four economic contexts.

The predominant feedstuffs are always grain maize, soft wheat, and Brazilian soybean meal, with an increase in the proportion of maize when animals get older, and a decrease in the proportion of soybean (as well as wheat) between the starter and grower feeds. The Brazilian soybean meal is a very important source of proteins in current broiler feeds. An average feed (averaged for the starter, grower, and finisher feeds) calculated using a weighted average of the amounts eaten by the animals, contains 50% grain maize, 17% Brazilian soybean meal and 16% soft wheat.

Table 10 : Impacts for 1 ton of feed, control feeds, average control feeds.

		Control feed (average) - Impact for 1 ton of feed					
		Starter	*standard deviation*	Grower	*standard deviation*	Finisher	*standard deviation*
Phosphorus consumption	kg P	9.96	*0.17*	8.22	*0.35*	6.63	*0.44*
Non-renewable energy consumption	MJ	7113.27	*162.49*	7314.37	*84.27*	6896.74	*179.78*
Climate change	kg CO_2 eq	795.35	*7.51*	758.75	*10.45*	698.34	*15.20*
Acidification	molc H^+ eq	10,63	*0.23*	11.13	*0.10*	11.33	*0.11*
Eutrophication	kg PO_4^{3-} eq	4.46	*0.08*	4.60	*0.17*	4.55	*0.19*
Land occupation	m^2.year	1403.74	*80.50*	1431.21	*122.96*	1470.39	*144.75*

The average environmental impacts of these feeds are given in **Erreur ! Source du renvoi introuvable.**.

For the starter feed and for the 2012-13 economic context, a sizeable proportion of the impact is caused by the Brazilian soybean meal and the grain maize. For phosphorus consumption, an important part of the impact is due to the inclusion of dicalcium phosphate in the starter feed (see Figure 20).

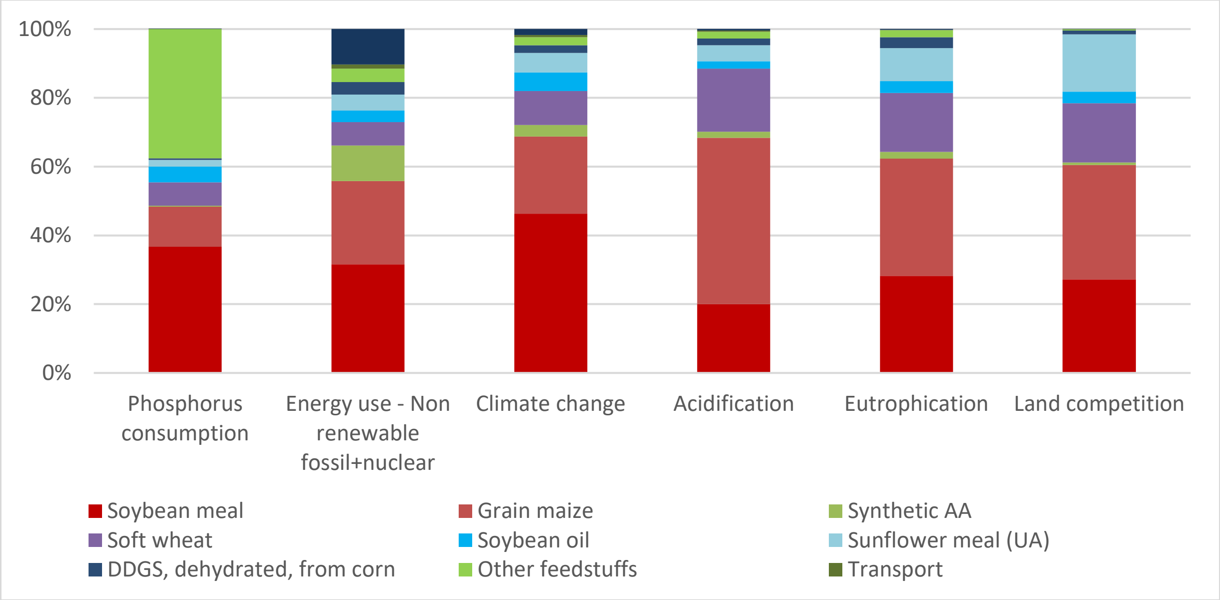


Figure 20: Contributions to impacts of a starter feed (2012-2013 context).

<u>*LCAs for one ton of feed*</u>

Feeds were formulated using feedstuffs at 0€ to estimate the maximum potential of innovative feedstuffs to contribute to a reduction in environmental impacts. The changes in percentages of impact when changing from a control feed to a feed using innovative feedstuffs are summarised in Table 11.

Table 11: Changes in impacts for feeds using innovative feedstuffs - [S] = starter feed, [G] = grower feed, [F] = finisher feed – standard deviation in brackets. In red, impacts that were increased.

		FCP dehulled Soybean Meal			FCP whole beans Soybean Meal			Green Biomass			Rapeseed Meal		
Difference in %, compared to control feed (average of all economic contexts)		[S]	[G]	[F]	[S]	[G]	[F]	[S]	[G]	[F]	[S]	[G]	[F]
Phosphorus consumption	kg P	-29.7 *(1.9)*	-25.6 *(3.3)*	-23.8 *(5.0)*	-30.1 *(1.3)*	-25.1 *(3.2)*	-16.3 *(11.2)*	-2.8 *(0.4)*	1.9 *(2.9)*	13.3 *(18.4)*	-5.09 *(0.2)*	-2.32 *(0.6)*	-4.34 *(5.0)*
Energy use – Non-renewable fossil and nuclear	MJ	-8.2 *(0.3)*	-11.8 *(0.6)*	-11.1 *(2.4)*	-7.7 *(1.7)*	-11.5 *(1.0)*	-9.2 *(5.0)*	3.1 *(1.6)*	-3.6 *(1.1)*	-0.2 *(6.4)*	-1.71 *(0.5)*	-7.41 *(0.2)*	-9.24 *(2.4)*
Climate change	kg CO_2 eq	-41.1 *(0.9)*	-38.0 *(0.9)*	-32.7 *(1.4)*	-42.2 *(0.6)*	-37.6 *(0.9)*	-32.7 *(1.7)*	-0.2 *(0.3)*	0.6 *(0.5)*	4.5 *(6.9)*	-3.53 *(0.1)*	-3.87 *(0.5)*	-5.13 *(1.2)*
Acidification	molc H^+ eq	-10.5 *(0.4)*	-7.8 *(1.1)*	-6.5 *(0.9)*	-12.7 *(1.5)*	-10.2 *(0.8)*	-10.8 *(5.5)*	18.9 *(2.2)*	20.2 *(0.7)*	16.8 *(4.1)*	1.63 *(0.6)*	0.78 *(0.2)*	1.44 *(0.5)*
Eutrophication	kg PO_4^{3-} eq	9.2 *(2.0)*	2.4 *(3.8)*	0.5 *(4.3)*	6.6 *(1.9)*	1.1 *(3.7)*	0.9 *(6.2)*	7.2 *(0.9)*	7.1 *(2.7)*	5.6 *(1.4)*	0.09 *(0.3)*	-1.65 *(0.2)*	-3.01 *(3.4)*
Land occupation	m^2.year	50.1 *(8.7)*	37.9 *(12.0)*	25.4 *(12.9)*	48.0 *(8.5)*	37.1 *(11.9)*	29.2 *(16.6)*	10.7 *(1.1)*	19.2 *(5.8)*	11.2 *(5.5)*	1.27 *(0.4)*	4.05 *(0.8)*	1.93 *(5.7)*

Feeds incorporating European dehulled soybean meal

Using European soybean meal tends to decrease the impacts of feeds in terms of phosphorus consumption, energy use, climate change, and acidification. It slightly increases the eutrophication impact, and strongly increases land occupation. For dehulled European soybean meal at 0€, Brazilian soybean meal is completely removed from all feeds (i.e., starter, grower, finisher), as is the dried distillers' grains made from maize. European soybean meal has a lower impact than the replaced feedstuffs on phosphorus consumption, because Brazilian agricultural land requires fertilization with phosphate. The reduction of (non-renewable) energy use is due to the more efficient transformation processes and transport for European soybean meal. Transport represents almost 40% of this impact for Brazilian soybean meal. The climate change impact is reduced when removing Brazilian soybean meal from the feed, because of its strong impact on deforestation. The acidification impact is partially due to nitrogen fertilisation, which is low for soybean meal. It decreases for feeds using European soybean meal because of the removal of dried distillers' grains from the formula. The eutrophication and land occupation impacts increase strongly for feeds using European soybean meal compared to the control, as European soya can only be harvested once a year, while Brazilian soya can be harvested twice a year.

"Whole bean" European soybean meal

This European soybean meal is not dehulled, but has the same characteristics as the dehulled European soybean meal. All tendencies observed for the dehulled European soybean meal are also observed for the "whole bean" soybean meal.

Protein paste/Green biomass

Introducing protein paste in broiler feeds increases the impacts on acidification, eutrophication and land occupation but does not change the other impacts significantly. Protein paste is incorporated at its upper limit for starter and grower feeds and slightly under the upper limit for finisher feeds. These limited proportions (i.e., 8, 10, and 10% respectively) do not avoid the need to use Brazilian soybean meal, the proportion of which is only slightly reduced. Moreover, the feeds with green biomass contain more soybean oil than the control feed. Protein paste has a lower impact per kilogram than Brazilian soybean meal regarding phosphorus consumption, energy use, and climate change. However, the difference between the control feeds and the feeds using protein paste is not very pronounced as both feeds incorporate Brazilian soybean meal. The soybean oil, used in the "protein paste feeds", increases the impacts for some feeds. Protein paste has a strong impact on acidification compared to Brazilian soybean meal, because of the nitrogen fertiliser needed to grow clover (used to make protein paste). This has a direct consequence on the acidification impact per ton of feed (see Table 11). The impacts on eutrophication and land occupation are also more pronounced for feeds using protein paste, mostly due to the production of protein paste where a large amount of grass or clover has to be grown on a large area of fertilised land, to produce a relatively small final amount of protein paste.

The fine fraction of European rapeseed meal

Incorporating the fine fraction of rapeseed meal in feeds results in a small reduction in phosphorus consumption, cumulative energy demand (non-renewable), and climate change impacts for starter, grower, and finisher feeds averaged over the four economic contexts. However, it slightly increases, and not consistently depending on the economic context and the feed category, the impacts on acidification and land occupation. The eutrophication impact is decreased by a small percentage.

For an average broiler feed (weighted average of starter-grower-finisher feeds), there is an overall tendency towards a decrease in phosphorus consumption, non-renewable energy demand, eutrophication and climate change impact, and a small increase in acidification and land occupation. Phosphorus consumption is decreased because of the smaller proportion of Brazilian soybean meal in the feeds and because Brazilian soybeans need phosphate fertiliser as indicated earlier.

Energy demand is decreased thanks to a more energy efficient transformation and transport process for European rapeseed meal compared to Brazilian soybean meal. The production of European rapeseed meal is also not linked with deforestation, which allows for a lower climate change impact. However, it requires nitrogen fertilisation, which leads to a higher eutrophication impact.

Despite the marked differences in terms of impacts when considering the LCAs at the feedstuff level, the changes induced by the introduction of European rapeseed meal in the feed are limited per kg of feed. This is due to the fact that rapeseed meal was used in a small proportion in the formulated feeds and did not enable a significant in the amount of Brazilian soybean meal used. This can be explained by the fixed incorporation limits. These upper limits were always met, with respectively 8, 10, and 15% of rapeseed meal used in the starter, grower and finisher feeds.

The use of innovative feedstuffs in broiler feeds could enable a decrease in climate change and in phosphorus consumption, but increases land occupation. The influence on other impacts depends on the feedstuffs considered. It should be noted that no innovative feedstuff seems to be able to reduce all the impacts considered; there is always a pollution transfer to consider.

Impacts for 1 kg of chicken (live weight)

When using the innovative feedstuffs to formulate feeds, gas emissions during fattening and from the storage of manure can be modified due to the different protein content of the feeds consumed. Besides the direct impact of feeds and the indirect impacts due to a change in emissions, all other parameters of the simulated broiler system remained unchanged. Differences in impacts (for 1 kg of live weight and in percentage) between the "control"/baseline broiler production system and systems using feeds incorporating innovative feedstuffs are summarised in Table 12. Values were averaged over the four economic contexts.

Table 12: Changes in impacts for 1 kg of chicken using innovative feedstuffs in feed formulation. In red, impacts that were increased.

		Average for four economic contexts			
Δ in % compared to control ↘		FCP dehulled Soybean Meal	FCP whole beans Soybean Meal	Green Biomass	Rapeseed Meal
Phosphorus consumption	kg P	-22.3 *(3.7)*	-21.7 *(3.6)*	1.5 *(2.4)*	-3.3 *(2.1)*
Non-renewable energy consumption	MJ	-8.2 *(1.1)*	-7.8 *(1.4)*	-2.1 *(0.7)*	-5.9 *(1.0)*
Climate change	kg CO_2 eq	-26.3 *(1.0)*	-26.0 *(1.0)*	0.9 *(0.5)*	-3.3 *(0.4)*
Acidification	molc H^+ eq	-1.3 *(1.1)*	-2.2 *(1.1)*	8.8 *(0.3)*	1.4 *(0.4)*
Eutrophication	kg PO_4^{3-} eq	1.9 *(2.4)*	1.1 *(2.4)*	5.0 *(2.3)*	-1.2 *(1.4)*
Land occupation	m^2.year	27.0 *(10.5)*	26.3 *(10.4)*	14.1 *(3.5)*	2.1 *(3.1)*

European soybean meal (both dehulled and "whole bean")

When considering impacts per kg of live weight, a decrease is seen in phosphorus consumption, non-renewable energy consumption, climate change, and (to a lesser extent) acidification. The same pattern could be found for impacts per kg of feed. Feed represents an important part of these impacts (see Figure 21), so this result could be expected.

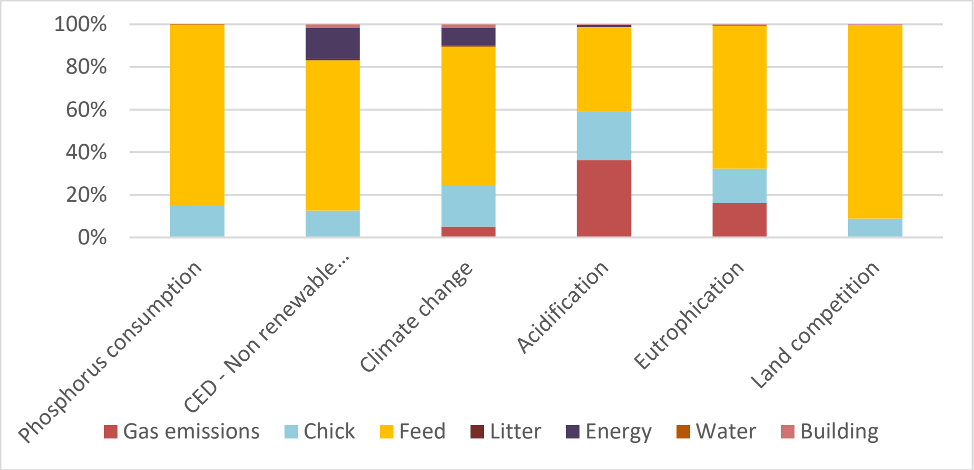


Figure 21: Impacts for 1 kg of chicken, 2012-2013 context, dehulled European soybean meal.

The acidification impact partly depends on the gas emissions during the batch and on the global "chick" impact. The "chick" impact encompasses all of the upstream steps leading to the production of one-day-old chicks, including the rearing, feeding, and housing of their progenitors. The fact that feed only represents 40% of the acidification impact explains why the final difference between baseline production and production using European soybean meal is so low (< 2.2% reduction). In comparison, using European soybean meal results in a reduction of 6.5 to 12.7% of the acidification impact.
Changing feeds leads to an increase in eutrophication and land occupation. Feed is indeed an important contributor to these impacts and the changes of impacts per kg of feed reverberates in the impacts per kg of chicken.

Green biomass/protein paste

Introducing green biomass as a new feedstuff results in a decrease in non-renewable energy use by 2.1% per kg of chicken (live weight). However, all of the other impacts are increased. The same tendencies can be observed per kg of feed, with differences depending on the feed (i.e., starter, grower, or finisher). Finisher feed is consumed in the largest quantities, followed by grower feed and then starter feed. This explains why tendencies per kg of chicken resemble those per kg of grower and finisher feeds. Acidification and eutrophication impacts depend on the nitrogen content of the feeds. The nitrogen content is slightly higher in feeds containing protein paste, meaning that emissions are slightly higher when using these feeds. When compared to differences per kg of feed, the increase in acidification is more limited, feed being only one of the components of the acidification impact.

Rapeseed meal

The conclusions are the same as those per kg of feed. All impacts are reduced, in a limited proportion, except for acidification and land occupation. For 1 kg of chicken, the use of innovative feedstuffs in feed formulation could enable a decrease in non-renewable energy consumption, in the climate change impact, but would lead to an increase in land occupation. The most promising feedstuffs to reduce impacts seem to be European soybean meal and their use could decrease all impacts per kg of chicken, except for land occupation (and a slight increase in eutrophication). Green biomass seems to generally increase impacts, except energy consumption. Rapeseed meal decreases most impacts but only in a very limited proportion. Once again, there is always a pollution transfer when introducing new feedstuffs, and the question always becomes a trade-off.

b. Egg production

Context - Average composition of control feeds – Egg production

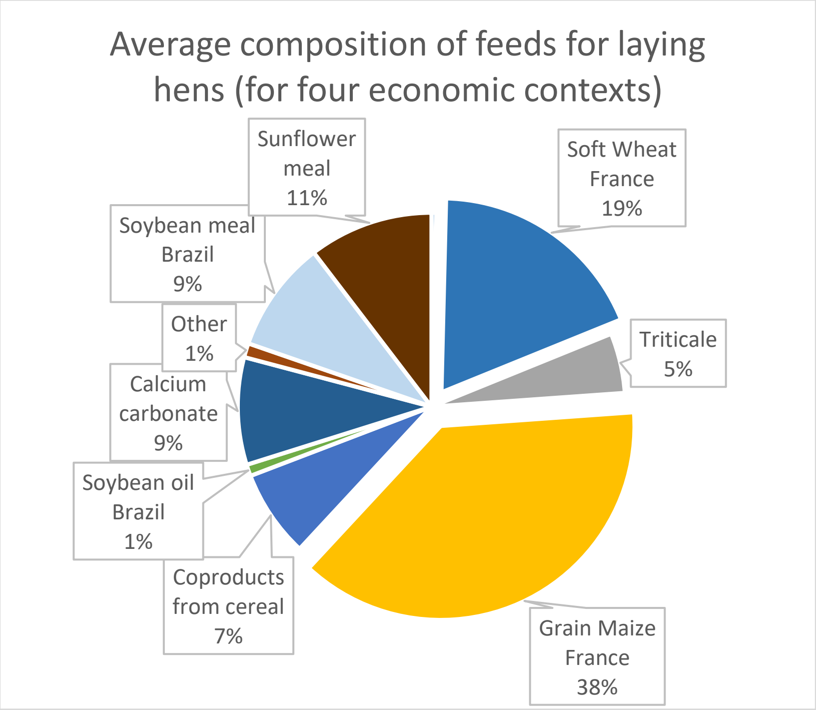


Figure 22: Average composition of laying hen feed (across four economic contexts).

The average composition of feeds for laying hens (averaged across the four economic contexts) is shown in Figure 22. Compared to broiler feeds, the proportion of Brazilian soybean meal is smaller. The most common ingredients are grain maize, soft wheat and sunflower meal, then Brazilian soybean meal and calcium carbonate.

The 2016-17 economic context is different from the others, with a smaller proportion of maize and the introduction of triticale (absent from feeds in other economic contexts). **Erreur ! Source du renvoi introuvable.** shows these differences in composition. The proportion of sunflower meal is variable depending on the economic context.

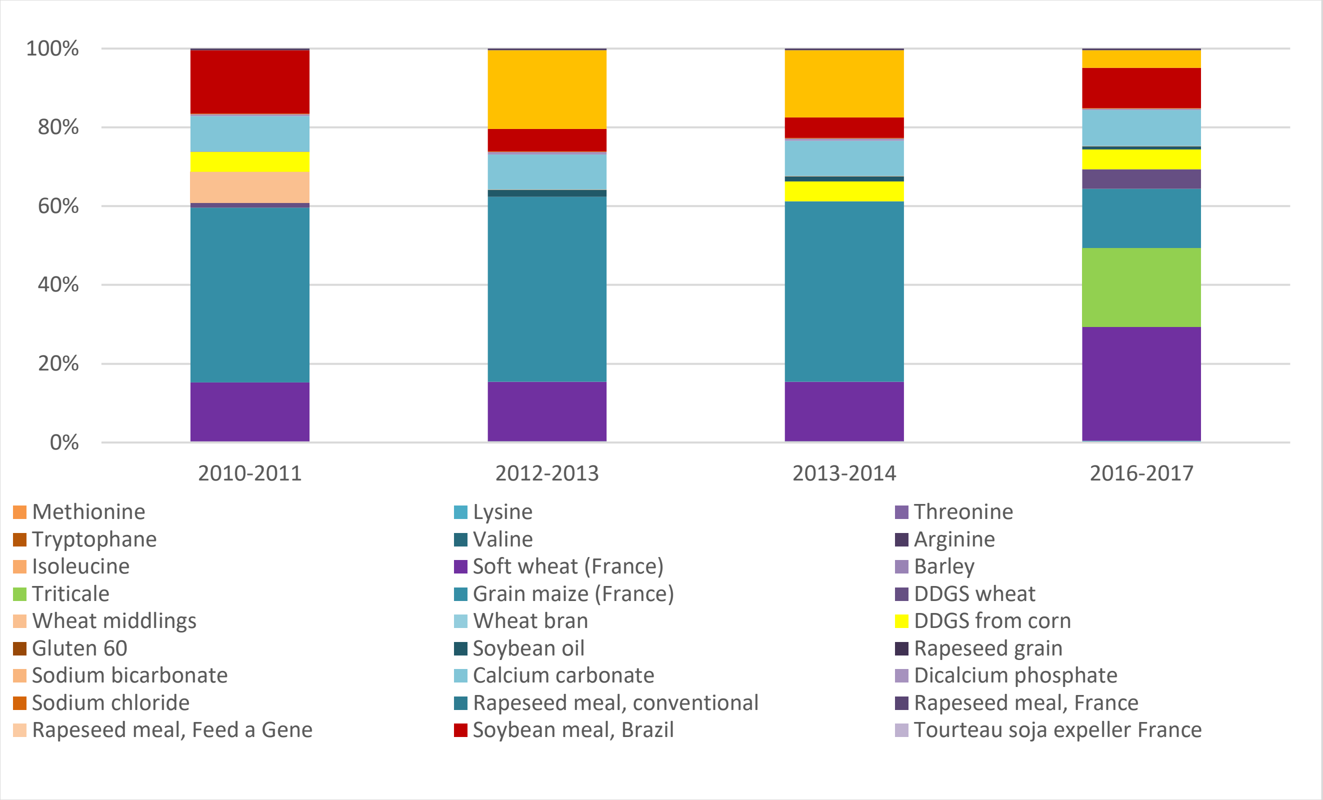


Figure 23: Composition of feed for laying hens, control feed.

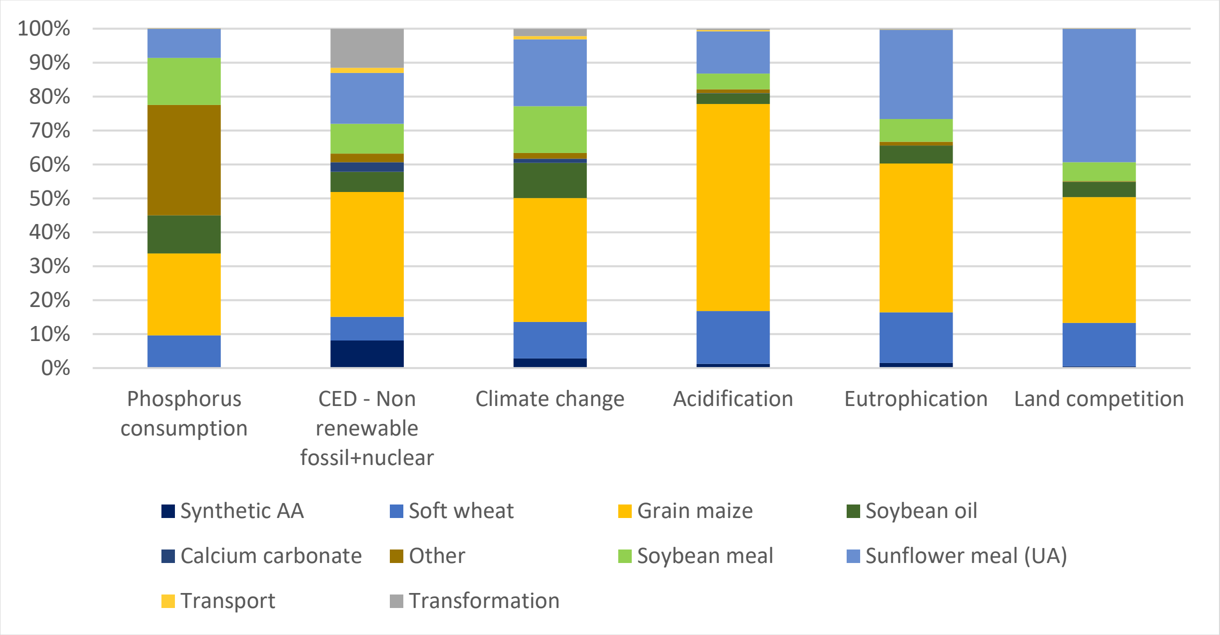


Figure 24: Impacts for feed for laying hens, control feed, 2012-2013.

As an example, if we consider the feed for laying hens for the 2012-13 context, the contributions of different feedstuffs to the environmental impacts of the feed are represented in Figure 24. Maize represents a significant part of most impacts, along with sunflower meal from the Ukraine which has a large impact on land occupation and eutrophication, and dicalcium phosphate which influences phosphorus consumption.

Impacts per kg of feed – Laying hen

Feeds for laying hens were formulated to estimate the maximum impact of the introduction of innovative feedstuffs and a decision was made to fix the price of innovative feedstuffs at 0€. Table 13 summarises the differences (in percentage) between feeds using innovative feedstuffs and control feeds for laying hens.

Table 13: Differences between feeds using innovative feedstuffs and control feeds. In red, impacts that were increased.

		Average, for four economic contexts			
		Dehulled soybean meal	"Whole bean" soybean meal	Green biomass	Rapeseed meal fine fraction
Phosphorus consumption	kg P	-12.0 *(3.2)*	-14.3 *(3.6)*	-2.9 *(2.7)*	-6.4 *(5.8)*
Non-renewable energy consumption	MJ	-6.9 *(5.6)*	-8.0 *(6.3)*	1.9 *(2.9)*	-3.8 *(3.3)*
Climate change	kg CO_2 eq	-28.5 *(0.6)*	-29.8 *(1.0)*	-0.5 *(0.6)*	-5.4 *(5.5)*
Acidification	molc H^+ eq	-10.0 *(2.4)*	-11.7 *(2.1)*	32.0 *(2.9)*	1.5 *(2.7)*
Eutrophication	kg PO_4^{3-} eq	1.1 *(6.0)*	-0.4 *(6.0)*	7.8 *(5.8)*	-2.8 *(3.9)*
Land occupation	m^2.year	27.4 *(22.2)*	25.9 *(21.9)*	6.9 *(13.2)*	-5.2 *(6.3)*

Dehulled European soybean meal

Compared to the average control feed, impacts are decreased for phosphorus consumption, non-renewable energy consumption, climate change and acidification. The eutrophication impact and land occupation both increase slightly for eutrophication, or in a large proportion for land occupation (≈27% for land occupation).

The average feed using dehulled European soybean meal has the following characteristics:
- only one synthetic amino acid is used (methionine), instead of four;
- barley is incorporated and the proportion of soft wheat is decreased;
- there is a marked reduction in the use of Brazilian soybean oil;
- no incorporation of cereal coproducts;
- removal of the use of sunflower meal (from Ukraine);
- replacement of Brazilian soybean meal by European soybean meal in a larger amount (22% instead of 9%).

Having a zero price for the European soybean meal leads to a large incorporation of this feedstuff and to the overall simplification of the feed formula (less synthetic amino acids and coproducts). Despite this relatively high proportion of soybean in the formula, its European origin leads to a decrease in the four impacts mentioned above, by completely removing the presence, and thus the impacts, of Brazilian soybean oil and sunflower meal.

The eutrophication impact is not strongly modified and is mainly due to grain maize, sunflower meal, and Brazilian soybean meal in the control feed, or to grain maize and European soybean meal in the innovative feed. The land occupation impact is strongly increased for the innovative feed (+27%), with an important variation depending on the economic context (sd = 22.2). This is due to the fact that this impact is more important for European soybean meal (approx. 4,110 m^2.year per ton at the feed factory) than for Ukrainian sunflower meal (3,037 m².year per ton) and Brazilian soybean meal (1,518 m².year per ton), the last two feedstuffs being replace by European soybean meal in the innovative feed.

"Whole bean" European soybean meal

Compared to the average control feed, the average innovative feed using "whole bean" European soybean meal reduced phosphorus consumption, energy consumption, climate change impacts and eutrophication impacts. The land occupation impact is increased (≈26%).

The innovative feed has the following characteristics:

- reduced incorporation of synthetic amino acids (except methionine);
- incorporation of barley;
- removal of the use of cereal coproducts and Brazilian soybean meal;
- replacement of Brazilian soybean meal by European soybean meal in a larger proportion (23% instead of 9%);
- no Ukranian sunflower meal.

The conclusions are very close to those for dehulled European soybean meal.

Protein paste/green biomass

The use of protein paste enables a slight decrease in phosphorus consumption and climate change impacts, but increases in all the other impacts, particularly acidification.

The average feed when incorporating protein paste has the following characteristics:

- incorporating protein paste at its maximum incorporation rate of 12%;
- removing wheat coproducts;
- decreasing the amount of Brazilian soybean oil;
- strong decrease in the incorporation of Ukrainian sunflower meal;
- halving the amount of Brazilian soybean meal for one economic context (2010-2011), but not for the others (may even lead to a slight increase).

The impact on phosphorus consumption of the innovative feed is decreased thanks to the decrease in the incorporation rate of Brazilian soybean oil (for the 2012-2011 context) and sunflower meal. The impact on climate change is decreased as a result of a decrease in the incorporation rate of Brazilian soybean meal and from the partial replacement of sunflower meal by protein paste. Protein paste has a much higher acidification impact that Ukrainian sunflower meal (30.9 vs 6.4 molc H^+ eq) which it replaces, thus increasing the acidification impact of the whole feed. It also has a slightly higher eutrophication impact.

Fine fraction of rapeseed meal

All the impacts are slightly decreased for the innovative feed using rapeseed meal, except for the acidification impact. The rapeseed meal is incorporated at its maximum rate (6%). The amount of Brazilian soybean meal is slightly decreased (less than 2%), as is the amount of sunflower meal (4%). Rapeseed meal has a higher acidification impact that sunflower meal and Brazilian soybean meal, which explains why the innovative feed has a higher impact than the control feed. Rapeseed meal has lower impacts than soybean or sunflower meal in terms of eutrophication, land occupation, climate change impacts, and non-renewable energy consumption, hence resulting in the tendencies observed per kg of feed. The phosphorus consumption is reduced as a result of the reduced amount of Brazilian soybean meal in the formula.

As was the case for broilers, European soybean meal seem to be the most promising feedstuffs to decrease environmental impacts. However, their use could still lead to an increase in eutrophication and especially land occupation. Protein paste seems to increase most impacts. Rapeseed meal decreases most impacts and could be an interesting feedstuff to limit environmental impacts, but the differences in percentage appear to be very limited.

Impacts for 1 kg of eggs

The 2012-13 context was used to study the potential impact of the introduction of innovative feedstuffs in feeds for laying hens. Table 14 summarises the differences in impacts (in percentage), per kg of egg (at the farm gate), compared to the control/baseline (laying hens eating control feed).

Table 14: Differences in impacts per kg of egg, compared to baseline. In red, impacts that were increased.

Impact category	Unit	Control (%)	FCP dehulled Soybean Meal	FCP whole beans Soybean Meal	Green biomass	Fine fraction of rapeseed meal
Phosphorus consumption	kg P	100	-14.0	-15.4	-2.4	-3.1
Non-renewable energy consumption	MJ	100	-0.5	-1.1	2.4	-1.9
Climate change	kg CO_2 eq	100	-24.4	-25.2	-0.5	-2.4
Acidification	molc H^+ eq	100	1.4	0.7	11.7	0.7
Eutrophication	kg PO_4^{3-} eq	100	1.5	0.6	3.5	-1.8
Land occupation	m^2.year	100	9.2	8.1	-1.5	-5.7
Nitrogen content for the 2012-2013 context	g/kg	25,60	27.20	27.20	25.60	25.60

To compare the difference induced by the introduction of innovative feedstuffs per kg of feed and per kg of egg, the differences between control feed and innovative feeds are summarised in Table 15 for the 2012-13 economic context.

Table 15: Differences per kg of feed between innovative feeds and control feeds, 2012-13. In red, impacts that were increased.

Impact category	Dehulled soybean meal	"Whole bean" soybean meal	Green biomass	Fine fraction of rapeseed meal
Phosphorus consumption	-14.0	-15.4	-2.4	-3.1
Non-renewable energy consumption	-0.7	-1.4	3.1	-2.5
Climate change	-28.6	-29.5	-0.6	-2.8
Acidification	-10.0	-11.9	30.2	1.7
Eutrophication	-1.7	-3.0	5.1	-2.6
Land occupation	9.3	8.1	-1.5	-5.8

We assume that animal performance is not modified by a change in feed, meaning that egg production, body weight of the hen, feed intake, etc. did not change. The only changes per kg of egg are due to changes in the impacts of the feed and changes in emissions due to the different nitrogen contents of the feeds used.

Results are similar to those per kg of feed, for phosphorus consumption, non-renewable energy consumption, land occupation/occupation and climate change impacts. These impacts are largely due to the feed (see Figure 25) and the extent of the difference is simply slightly attenuated when considering per kg of egg.

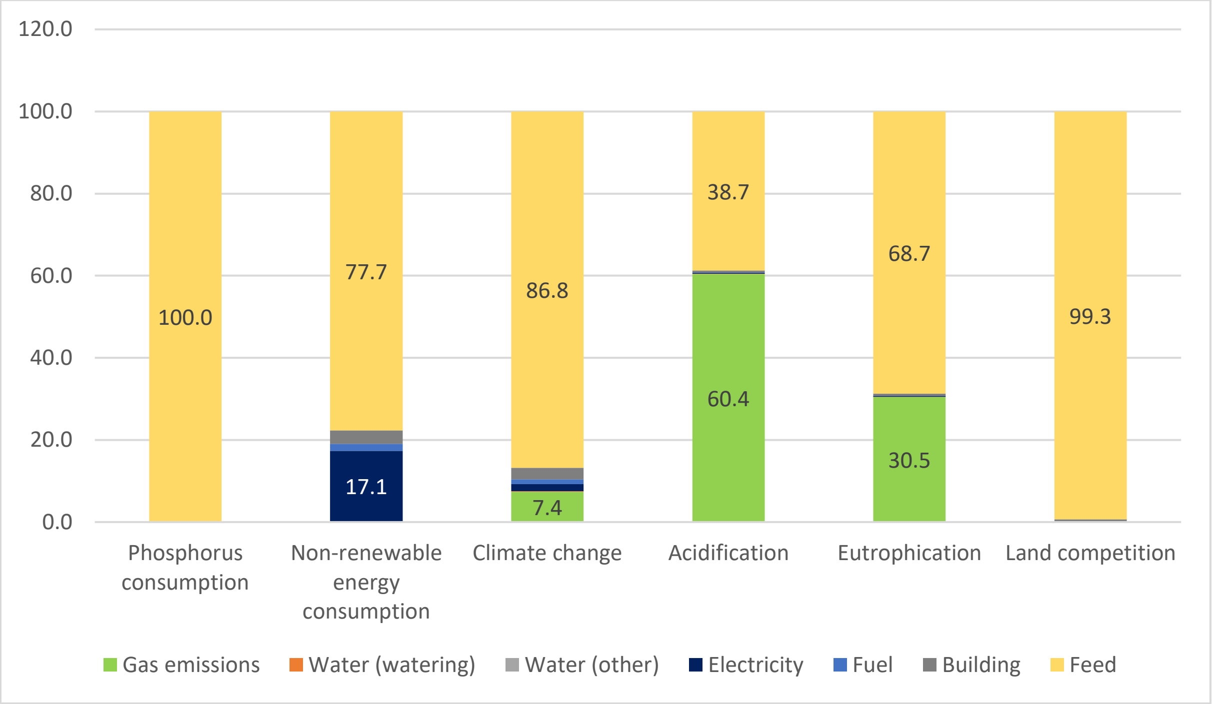


Figure 25: composition (in %) of impacts per kg of egg, control feed, 2012-13 context.

Regarding acidification, the higher nitrogen content of feeds incorporating European soybean meal (i.e., both "dehulled" and "whole bean") leads to an increase in gas emissions, resulting in an increase in acidification per kg of egg. Feeds incorporating protein paste and rapeseed meal have the same nitrogen content as the control feed, so there is no indirect impact of a change of feed through a change in emissions. The direct impact of the change of feed can still be seen per kg of egg, with an increase for both protein paste and rapeseed meal (as explained previously).

The eutrophication impact is also largely due to the feed, as well as to emissions (for approximately a third). The changes in impacts per kg of feed when introducing innovative feedstuffs can thus be found per kg of egg, attenuated for the protein paste and rapeseed feeds, since they do not change emissions (having the same nitrogen content as the control), and are "reversed" for European soybean meal, given that they increase emissions compared to the baseline.

Conclusions for the impacts per kilo of egg are close to those per kg of feed. For all feedstuffs, introducing them in the feed could lead to an increase in some impacts and a decrease in others. Pollution transfer should always be taken into account when considering a change in feedstuffs in the goal of improving environmental impacts.

5.2 Precision feeding

5.2.1 Pig production

Experimental approach

Table 16 reports animal performance measured from experiments in WP4. When pigs have *ad libitum* access to feed, the individual daily adjustment of the nutritional characteristics of the feed allowed the feed efficiency of pigs to be optimised. Indeed, the feed conversion ratio (FCR) was reduced by 5.6% and the intake by 4%, compared to the biphase feeding strategy. The association between nutrient supply intake and nutrient requirements reduces the nitrogen intake by 4.2%. In the restricted feeding strategy, the nitrogen intake is also reduced by 6.5%, and the FCR is increased by 3.1%.

Table 16: Animal performance measured in Feed-a-Gene experiments on precision feeding strategies.

	Ad libitum Biphase	Ad libitum Individual multiphase	Restricted Biphase	Restricted Individual multiphase
Final weight (kg/pig)	*117*	117	*115*	113
Feed conversion ratio	*2.85*	2.69	*2.87*	2.96
Cumulated ingestion (kg/pig)	*234*	222	*214*	218
N ingested (kg N/pig)	*5.21*	4.99	*4.65*	4.35

The composition of the average feed intake is given in Figure 26. It is similar for precision feeding and biphase feeding with *ad libitum* strategies. For restricted strategies, there is a reduction in the use of Brazilian soybean meal in precision feeding compared with biphase feeding. This leads to a decrease in the impacts of feed, especially for climate change because of the high contribution of the Brazilian soybean meal due to deforestation.

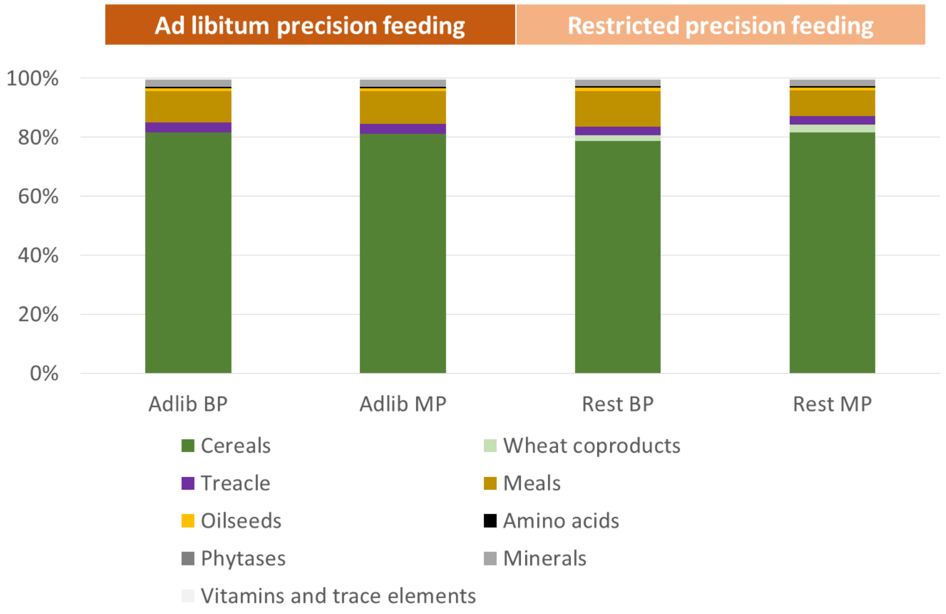


Figure 26: Composition of the average feed intake during the fattening period.

The precision feeding strategies applied to the fattening period have a positive effect on excretions, reducing nitrogen excretions by 8% and 10% respectively for the *ad libitum* and restricted feeding strategies (Figure 27). Consequently, nitrogen emissions in the fattening period are also reduced compared to the baselines.

The results obtained with the restricted feeding strategy are less striking when compared with some results reported in the literature, where reductions in nitrogen excretion are between 22 and 30% with precision feeding compared to biphase strategies (Andretta et al., 2014; Pomar et al., 2010). Energy consumption is increased by almost 20% due to the additional equipment required to feed the animals individually.

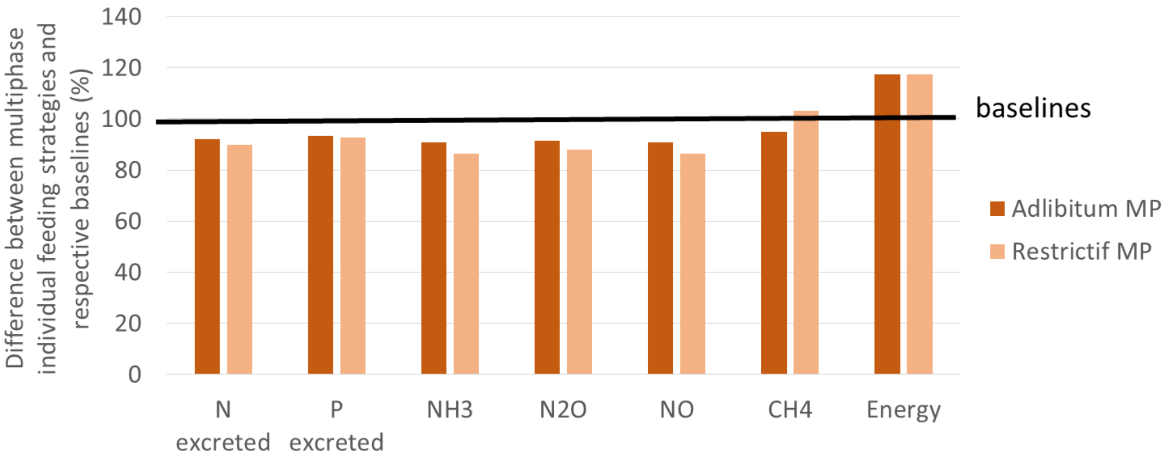


Figure 27: Difference of direct environmental fluxes for the fattening period between precision feeding strategies and baselines.

The LCA considers the fattening period but also the global life cycle of pig production. This adds the contribution of the sow, production of feeds, activities of the breeders, etc. (Figure 6). The impacts (per kg of pig at the farm gate) of the precision feeding strategies are presented with their absolute values (Table 17), relative to their individual baselines (biphase strategies), in Figure 28.

Table 17: Impacts per kg of pig at the farm gate concerning precision feeding with the experimental approach.

Impacts / kg pig	Non-renewable energy consumption (MJ)	Climate change (kg CO_2 eq)	Acidification (molc H^+ eq)	Eutrophication (kg PO_4^{3-} eq)	Land competition (m^2.year)
Biphase restricted	21.19	2.47	0.0779	0.0173	3.79
Multiphase individual restricted	21.32	2.47	0.0746	0.0170	3.85
Biphase *ad libitum*	21.38	2.48	0.0822	0.0179	3.85
Multiphase individual *ad libitum*	21.02	2.40	0.0777	0.0171	3.72

For the *ad libitum* precision feeding strategy, all the impacts are reduced compared to the biphase feeding strategy (Figure 28). Land occupation decreases by 3%, which is due to the reduction in feed intake because more than 95% of this impact is explained by feed. Climate change, acidification, and eutrophication are also reduced by 4, 6, and 5% respectively, as a result of reduced excretions. The reduction in energy consumption is only 2% because the decrease due to the reduced feed intake is offset by an increase in direct energy consumption, due to the energy requirement for the automatic feed dispensers (Figure 28).

With the restricted precision feeding strategy, environmental improvement for impacts is still present for acidification (a reduction of 4% compared to the baseline) but are almost absent for the other impacts (Figure 28). The decline in the FCR reduces environmental gains because more resources are needed to produce the same quantity of pig. However, beyond precision feeding, these results confirm the positive effect of feed rationing on the environmental impacts since the restricted biphase scenario leads to a reduction in acidification and eutrophication by 4 and 3% respectively, compared to the *ad libitum* biphase scenario.

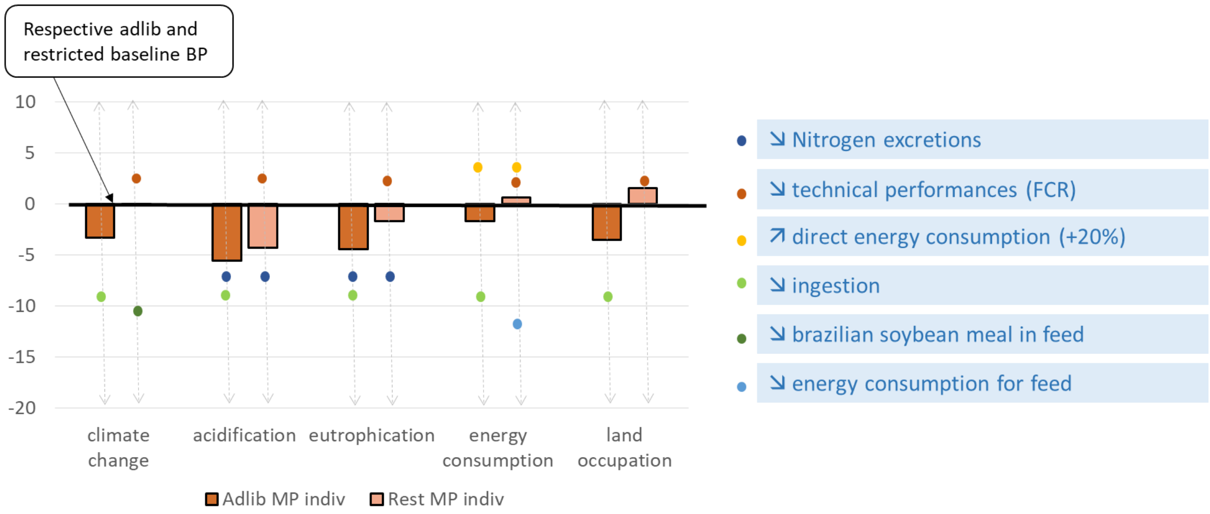


Figure 28: Difference of impacts (per kg of pig at the farm gate) between precision feeding strategies (ad libitum and restricted) and their respective baselines (ad libitum biphase and restricted biphase).

Modelling approach

The animal performance modelled by MOGADOR for the different feeding strategies is given in Table 18. The final average weight is similar among strategies. The FCR is slightly declined (2%) between the biphase feeding strategies and multiphase feeding strategies.

By improving the feeding strategy (i.e., going from group biphase feeding to individual multiphase feeding), nitrogen excretion is reduced for both the *ad libitum* and restricted strategies, going from 3.8 to 2.7 kg N/pig (-29%) for *ad libitum* feeding, and from 3.7 kg to 2.6 kg N/pig (-30%) for restricted feeding.

Table 18: Animal performance modelled by MOGADOR concerning the different feeding strategies.

	Adlib BP	*Adlib BP low prot.*	*Adlib MP group*	**Adlib MP indiv**	*Rest BP*	*Rest BP low prot.*	*Rest MP group*	**Rest MP indiv**
Final weight (kg)	*118*	*118*	*117*	117	*117*	*117*	*117*	116
FCR	*2.78*	*2.78*	*2.83*	2.83	*2.75*	*2.74*	*2.80*	2.80
Cumulated ingestion (kg/pig)	*248*	*247*	*249*	249	*240*	*239*	*241*	240
N excreted (kg N/pig)	*3.8*	*3.3*	*3.2*	2.7	*3.7*	*3.2*	*3.1*	2.6

Two areas of significant improvement are achieved concerning the reduction of nitrogen excretions (Figure 29):

- the first is from biphase feeding to biphase feeding with a low protein diet, leading to a reduction of 16%;
- the second is from group multiphase feeding to individual multiphase feeding, with a reduction of 17%.

The improvement between biphase feeding using diets with a low protein content and multiphase feeding in groups is much smaller (2%). Indeed, the improvement obtained by the reduction of N intake on a daily basis is mostly lost due to the increase in the FCR.

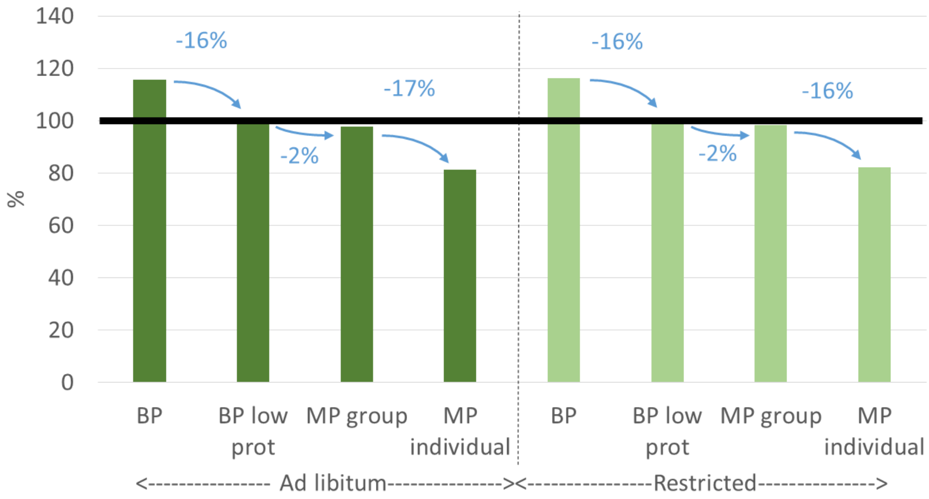


Figure 29: Nitrogen excretion expressed relative to the biphase feeding with low protein content for ad libitum and restricted strategies.

The LCA impacts are given in Table 19 for the absolute values and in Figure 30 and Figure 31 for the relative values compared to those of the biphase strategy with diets with a low protein content.

Table 19: LCA impacts per kg of pig at the farm gate (average and *standard deviation* among economic contexts).

	Impacts / kg pig	Non-renewable energy consumption (MJ)	Climate change (kg CO_2 eq)	Acidification (molc H^+ eq)	Eutrophication (kg PO_4^{3-} eq)	Land competition (m^2.year)
Ad libitum strategy	Biphase, group feeding	18.26 *(0.469)*	2.26 *(0.0270)*	0.0784 *(0.00040)*	0.0203 *(0.00021)*	4.08 *(0.0756)*
	Biphase, low protein, group feeding	19.08 *(0.420)*	2.29 *(0.0484)*	0.0718 *(0.00082)*	0.0192 *(0.00045)*	3.92 *(0.1834)*
	Multiphase, group feeding	19.39 *(0.410)*	2.32 *(0.0411)*	0.0716 *(0.00064)*	0.0191 *(0.00038)*	3.94 *(0.1023)*
	Multiphase, individual feeding	19.23 *(0.270)*	2.27 *(0.0240)*	0.0630 *(0.00047)*	0.0178 *(0.00041)*	3.87 *(0.1309)*
Restricted strategy	Biphase, group feeding	18.20 *(0.469)*	2.25 *(0.0283)*	0.0771 *(0.00048)*	0.0201 *(0.00023)*	4.06 *(0.0780)*
	Biphase, low protein, group feeding	18.99 *(0.402)*	2.27 *(0.0478)*	0.0703 *(0.00084)*	0.0190 *(0.00046)*	3.89 *(0.1804)*
	Multiphase, group feeding	19.31 *(0.406)*	2.30 *(0.0415)*	0.0704 *(0.00061)*	0.0189 *(0.00038)*	3.91 *(0.1014)*
	Multiphase, individual feeding	19.21 *(0.266)*	2.26 *(0.0266)*	0.0624 *(0.00048)*	0.0177 *(0.00043)*	3.85 *(0.1312)*

The individual precision feeding strategies appear to be an improvement compared to biphase precision feeding with diets with a low protein content in terms of their impact on acidification and eutrophication, with a reduction of 12% and 7% respectively. This is due to the reduction in nitrogen excretion and the emissions linked to it. The energy consumption is slightly increased because of the equipment required. For climate change and land occupation, the variation of impacts is quite low and depends on the feedstuffs used in the different strategies with the same tendency among ad libitum and restricted strategies.

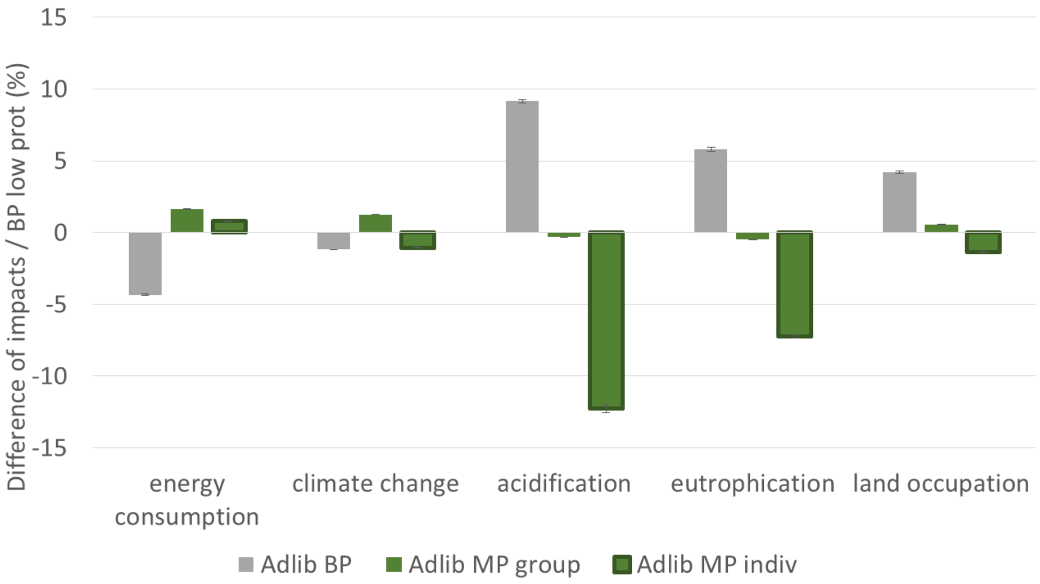


Figure 30: Relative LCA impacts of the different ad libitum strategies compared to biphase strategy with diets with a low protein content.

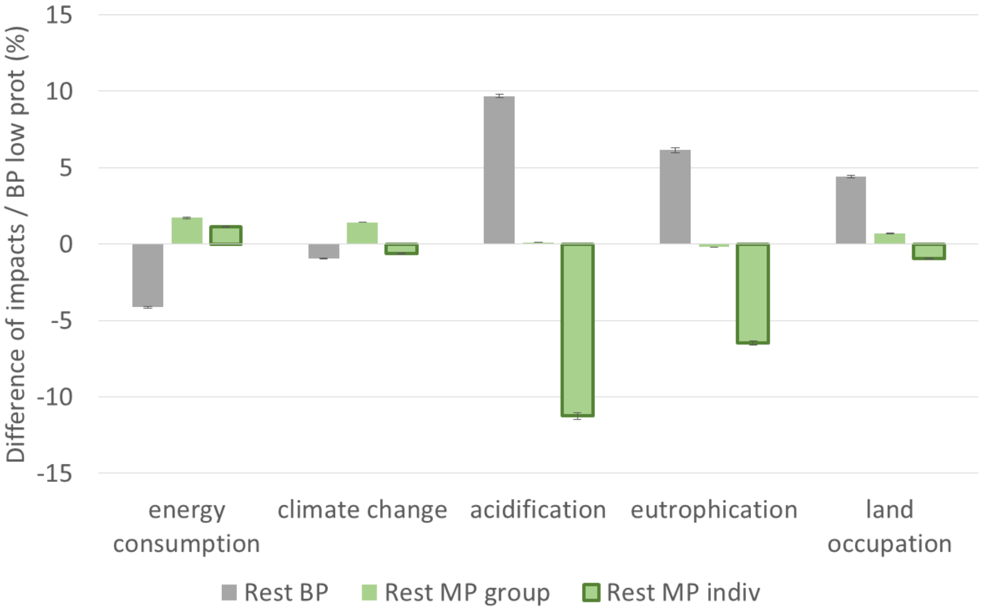


Figure 31: Relative LCA impacts of the different restricted strategies compared to biphase strategy with diets with a low protein content.

5.2.2 Poultry production

Impacts per kg of feed

The following graphs (**Erreur ! Source du renvoi introuvable.** and **Erreur ! Source du renvoi introuvable.**) represent the impacts for one kilogram of feed, for each of the four feeds of the control diet and each of the five pre-feeds of the precision feeding diet.

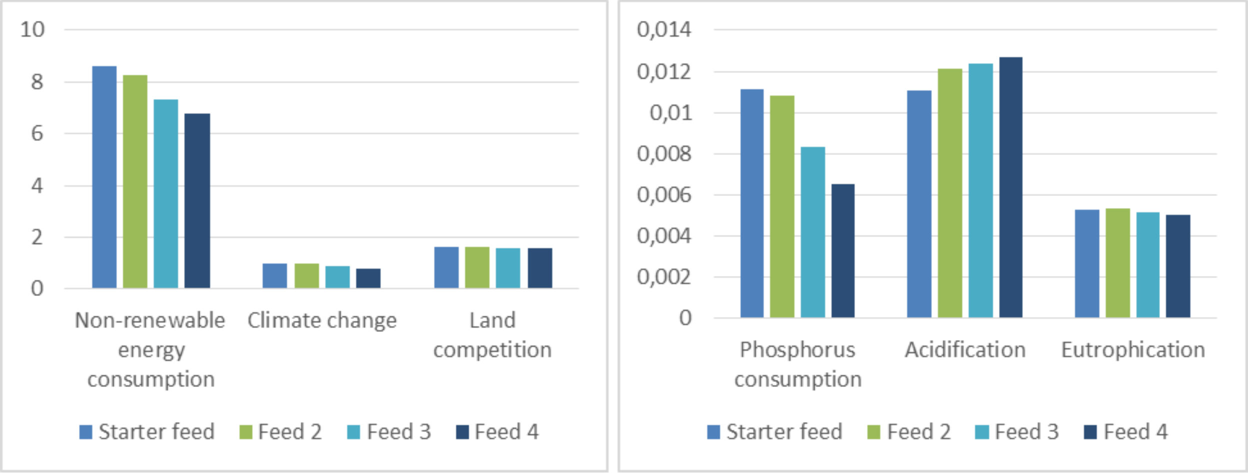


Figure 32: Impacts for average control feeds.

The starter feed, that animals eat until day 10, is shared by both the control and the precision feeding systems.

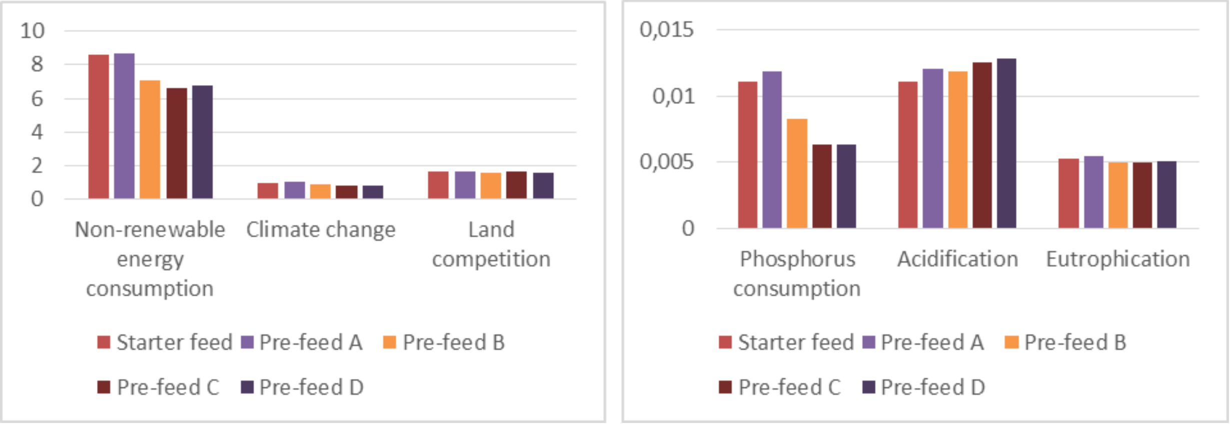


Figure 33: Impacts for average "precision feeding" feeds/pre-feeds.

For the control feeds, impacts tend to decrease with each feed, from starter feed to finisher feed (feed 4), for non-renewable energy consumption, climate change impacts, phosphorus consumption, land occupation, and eutrophication. The acidification impact tends to increase, which is linked to an increasing proportion of maize in the feeds and a decreasing proportion of Brazilian soybean meal and dicalcium phosphate (see impacts of feedstuffs). A similar trend can be observed for pre-feeds in the precision feeding diet. Going from pre-feed A to pre-feed D, the proportion of cereals tends to increase and the proportion of Brazilian soybean meal decreases.

When considering the composition of the average control versus precision feeding feeds (average over four economical contexts, and weighted average over starter-grower-etc or pre-feed A, B, C etc), there is no obvious difference in composition. However, the protein content of the average feed is decreased by 4.7% in the precision feeding system (19.76 vs 20.73%). This enables a decrease in the acidification impact per kg of broiler.

Per kg of feed, the following trends can be observed:

- a decrease of the phosphorus consumption impact by 9.24%. Due to a decrease incorporation of soybean meal, extruded soybeans and dicalcium phosphate in the average precision feeding feed and despite an increase in the incorporation of soft wheat.

- a decrease of the non-renewable energy consumption by 6.39%, for the same reasons.
- a decrease of the climate change impact, by 5.08%. Mainly due to a more limited use of soybean meal and extruded soybeans (despite an increase in the impact of grain maize and soft wheat).
- a decrease of the acidification impact by 2.12%, due to a combined effect of a decrease in the impacts of feedstuffs derived from soya (i.e., soybean meal, extruded soybean, soybean oil).
- a decrease of the eutrophication impact by 3.99%, for the same reasons.
- a slight decrease (by 0.59%) of the land competition impact. Despite the higher impact due to a larger incorporation of sunflower meal, soft wheat and grain maize, it is compensated by the smaller proportion in the average feed of soybean meal, maize gluten, extruded soybean and rapeseed grains.

Overall, the change in diets enables a decrease in all impacts, but not drastically. The only impacts that are decreased by more than 5% are the phosphorus consumption, non-renewable energy consumption, and climate change.

Impacts per kg of chicken (live weight)

Differences when comparing the impacts of a precision feeding system with a control system are summarised in **Erreur ! Source du renvoi introuvable.**

Table 20: Differences (in %) between impacts for a precision feeding system and control system.

	Phosphorus consumption (kg P)	Non-renewable energy consumption (MJ)	Climate change (kg CO_2 eq)	Acidification (molc H+ eq)	Eutrophication (kg PO_4^{3-} eq)	Land occupation (m^2.year)
Difference between precision feeding and control (%)	-8.56 *(2.23)*	-4.77 *(1.67)*	-4.25 *(0.56)*	-4.21 *(1.38)*	-4.22 *(1.50)*	-0.40 *(3.72)*

Precision feeding enables a reduction in all of the impacts considered, due to a reduction in the nitrogen content of the diet (better matching of the requirements of the broilers and the nutritional composition of their diet). The total feed intake was the same for the control system and the precision feeding system.

The biggest impact is the reduction, on average across the four economic contexts, of phosphorus consumption. Other reductions are less important, around 4 to 5%, except for land occupation with only a 0.4% difference.

For the average diet eaten by the animals (weighted average) for the "September 2011" context, the reduction in phosphorus consumption is due to:
- a decrease of the impact due to Brazilian soybean meal;
- a decrease of 20% of the impact due dicalcium phosphate;
- an increase of 11% of the impact due to grain maize.

This leads to a global decrease in the phosphorus consumption impact of the average feed (-6%). In this example, the impact for one kilo of chicken is reduced by 5.6% for phosphorus consumption.

6. Discussion

6.1 Importance of the LCA methodology in the results

This part summarizes several relevant methodological choices made for LCA which condition the results. Presenting them make the reader more aware of them and will help to better interpret and use the results:

- Attributional LCA vs consequential LCA

LCA can be performed in an attributional or consequential way. In attributional LCA (ALCA): the perimeter relates directly to the production process. In consequential LCA (CLCA), the perimeter relates to a wider scope of study since it allows to take into account any changes caused by the production process. Indeed, if we compare two products, one can have less environmental impacts compared to the other by ALCA; but higher ones by CLCA.

Although CLCA seems to be a more complete method, it is rarely applied because of its complexity and uncertainty since it is based on a numerous assumptions and scenarios about the different possible consequences (Schmidt, 2008, Chen et al., 2012). This is why we decided to apply an attributional LCA. This is also the methodology chosen for the environmental labelling in the European PEF (Product Environmental Footprint).

Still, the transfer of pollution identified in our results should be analysed at a larger perimeter in a complementary study to conclude especially for innovative feedstuffs (cf. 6.2.3).

- Functional unit: kilogram of animal product at the farm gate

The LCA impacts are expressed per kilogram of animal product at the farm gate. This unit is considered as the most suitable for animal production processes. It is a product-based approach, which associates environmental problems with products and aims to reduce emissions per unit of product (van der Werf, 2018). The solution lies in modifying production systems to reduce emissions per unit of product. Focussing on a product-based functional unit may result in decisions in favour of efficient systems (van der Werf, 2018). The consequence could lead to system with more pollutants per unit of land occupied. A more in-depth analysis of results should then be made, for example by considering the ratio between the pollutant emissions (e.g., acidification with ammonia emissions) and the impact of land occupation.

- Environmental impacts

The environmental impacts chosen are climate change, land occupation, non-renewable energy consumption, phosphorous consumption, acidification, and eutrophication. Among these, several are global impacts (e.g., climate change, phosphorous and energy consumption, and land occupation), while others have a regional impact (e.g., acidification and local as eutrophication). Local impacts are more difficult to interpret because they do not locate the fluxes in the perimeter and do not consider the sensitivity of the environment. For this reason, it is recommended advised to consider mainly the global and regional impacts. Also, impacts such as biodiversity or water consumption are not considered here. This is because the methodology to assess them is complex and not ready to be implemented. Consequently, it is important to acknowledge that the assessment is partial.

- Impacts linked to deforestation

The incidence of deforestation is considered in the impact on climate change for the Brazilian soybean meal. We consider that only a part of the Brazilian soybean meal used in Europe is linked to deforestation. This depends on the supply of Brazilian soybean meal to Europe. The difference of impacts between Brazilian soybean meal and American soybean meal is only due to deforestation. If we had considered that all the Brazilian soybean meal was linked to deforestation, the reduction of climate change impacts between scenarios with innovative feedstuffs and baselines would have been higher. On the other hand, if Brazilian soybean is not associated to deforestation, there would be no difference in impacts between Brazilian and American soybean meal.

6.2 Question of scale assessment

6.2.1 Importance of multi-scale assessment

The results show the importance of considering the life cycle of animal production to assess feeding strategies.

- Feedstuffs differ from one to another because of nutritional characteristics. The different protein sources differ in protein content, amino acid profile, and energy content. It is not possible to reduce the environmental impacts of a feed simply replacing one feedstuff with high impacts by a feedstuff with lower impacts. The feed is formulated to meet the nutritional recommendations and all the feedstuffs contribute to this. If an innovative feedstuff appears promising to improve the environmental performance of feed, it also has to have appropriate the nutritional characteristics required for the feed formulation.
- The difference of impacts between two protein sources per ton of feedstuff can change at the scale of feed (environmental impacts per ton of feed). This is due to the substitutions of feedstuffs which occurs when a feed with a specific protein source is substituted by another feed with another protein source. These substitutions can mask the positive or negative impacts that may be observed per kg of feed.
- Feed markets are highly dynamic. Feed formulation is based on least cost optimization and a wide range of ingredients are available in Europe. Therefore, feedstuffs used in the diet can change easily resulting in different environmental impacts. The environmental assessment of feeding strategies should include a sensitivity analysis (e.g., different feed prices or different marginal products) to provide a range of possible outcomes to make the results more robust, as was done in this analysis.
- Expressing impacts per kg of feed is not enough because feeds are part of feeding strategies and several feeds are used in monogastric productions. Just as a set of feedstuffs defines the nutritional profile of a feed, a set of feeds and their use in a feeding plan define the nutritional input of animals. A feeding strategy that uses feeds with lower impacts may lead to a reduction in animal performance, resulting in a trade-off issue between environmental and economic aspects of sustainability.

Consequently, aspects at different scales (e.g., feedstuff, feed, feeding strategies, animal product) are necessary to assess the environmental interest of innovative feeding strategies.

6.2.2 Need for a larger perimeter to consider the rebound effects

The results concerning innovative feedstuffs indicate a transfer among environmental impacts. If innovative protein sources show an effective reduction in climate change compared to Brazilian soybean meal, it is associated to an increase in land use. The raises the question what would be best for the planet. Indeed, no new fertile land is available to further expand crop areas. On the contrary, the general trend is a reduction of exploitable arable land because of global warming and an increase in artificialized (urban) surfaces. An extensification of production is therefore detrimental to another production that must be reduced or stopped. These indirect consequences are called rebound effects and have to be considered at a larger assessment scale to see the global benefit or damage to the environment. This can be achieved through a consequential LCA (CLCA), instead of the attributional LCA (ALCA) used in this analysis.

Van Zanten et al. (2017) used ALCA and CLCA to compare the environmental impacts of using soybean meal and two other protein sources (rapeseed meal and meal of larvae fed with food waste) for finishing pigs. For CLCA, only the consequences related to the change of feedstuff were considered. By ALCA, the use of rapeseed meal allowed a decrease of land use by 14% compared to the use of soybean meal. On the other hand, by consequential LCA, replacing soybean meal with rapeseed meal resulted in a 10% increase in land use, 15% increase in climate change, and 12% increase in non-renewable energy consumption. To gain insight in the environmental impact of feed, Van Zanten et al. (2017) recommended to perform a CLCA to assess the net environmental impact of a potential feeding strategy.

Espagnol et al. (2018) assessed rebound effects associated to the production of eco-feed (i.e., feed with lower environmental impacts) in a different way. The question was to identify the environmental consequences for a virtual territory that produced feed ingredients for a pig farm, when replacing feed ingredients to produce eco-feeds and changing crop rotations. Attributional LCA was performed using multiple functional units and system perimeters: kg of pig live weight at the farm gate, ha of land used, economic value produced and number of people fed. The situation in which eco-feeds are produced can appear better or worse than the situation in which standard feeds are produced. It highlighted the possibility to complete ALCA by a more global study at a larger perimeter.

7. Conclusions

The environmental benefits of the innovative feedstuffs depend on the economic context and the incorporation rate of Brazilian soybean meal. In the current context, there is little incentive to use Brazilian soybean meal for pig production. For poultry, Brazilian soybean meal is used at a much larger scale. Considering a favourable virtual context, including favourable prices for innovative feedstuffs, a reduction in climate change impacts can be achieved by using alternative sources of proteins, especially with European soybean meal, but it will lead to increased land use. This raises the question of trade-offs among impact. It is necessary to integrate the rebound effects in a larger perimeter of analysis. The use of innovative feedstuffs is part of the development plans of crop producers and feed manufacturers and there is an ambition to increase production from 150,000 ha of soybean per year in France to 250,000 ha in 2030.

For pig production, precision feeding provides a means of reducing nitrogen excretion, which impacts on acidification and eutrophication. The results of experiments assessed by LCA show that the modest benefits of reduced nitrogen excretion (<5%) can be offset by a reduction in animal performance. With the modelling approach, more interesting environmental benefits were indicated (e.g., a reduction of acidification by 12%). Individual precision feeding allows a reduction in the protein content of feeds and a reduction in nitrogen excretion. The environmental benefit measured corresponds to individual multiphase feeding using two different feeds mixed every day. Further improvements in performance may be obtained in the future by using of three different feeds (providing more possibilities to mixe diets each day).

For broiler production, precision feeding can also reduce environmental impacts, but experimental results show only a limited potential with reductions varying between 4 and 5%, with a maximum reduction of 8.5%.

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9. Annexes

9.1 Average annual cost of reference feedstuff for cereals and protein sources

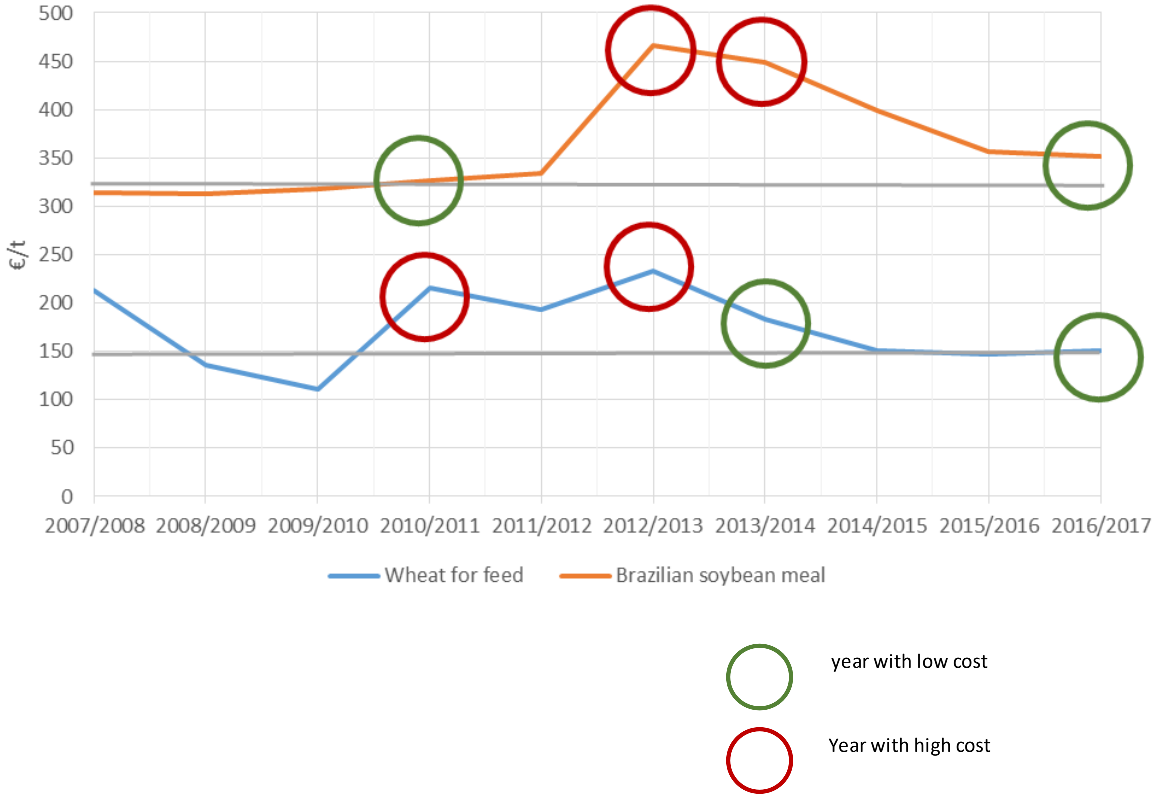

Figure 34: Annual cost of reference feedstuffs for wheat and Brazilian soybean meal.

9.2 Formulation constraints for pig and poultry

Table 21: Nutritional constraints for feed formulation for conventional pig production.

	Baseline				Max Soybean meal				Max Innovative feed ingredient			
	Growing		Finishing		Growing		Finishing		Growing		Finishing	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Dry matter (%, DM)	0.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0
NE[b] (MJ/kg)	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Crude protein %	15.0	15.0	13.5	13.5	15.0	15.0	13.5	13.5	15.0	15.0	13.5	13.5
Fat %	0.0	100	0.0	100.0	0.0	100	0.0	100.0	0.0	100	0.0	100.0
Crude fibre	0.0	55.0	0.0	60.0	0.0	55.0	0.0	60.0	0.0	55.0	0.0	60.0
Total P %	0.0	0.48	0.0	0.44	0.0	0.48	0.0	0.44	0.0	0.48	0.0	0.44
Available P %	2.2	100.0	2.0	100.0	2.2	100.0	2.0	100.0	2.2	100.0	2.0	100.0
Ca %	0.65	0.75	0.6	0.7	0.65	0.75	0.6	0.7	0.65	0.75	0.6	0.7
Cl %	0.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0
Na %	0.15	0.25	0.15	0.25	0.15	0.25	0.15	0.25	0.15	0.25	0.15	0.25
dLys[e] %	0.82	100	0.72	100	0.82	100	0.72	100	0.82	100	0.72	100
dMet[e] %	0.25	100	0.22	100	0.25	100	0.22	100	0.25	100	0.22	100
dTSAA[e] %	0.49	100	0.43	100	0.49	100	0.43	100	0.49	100	0.43	100
dThr[e]	0.55	100	0.49	100	0.55	100	0.49	100	0.55	100	0.49	100
dTrp[e]	0.16	100	0.14	100	0.16	100	0.14	100	0.16	100	0.14	100
dVal[e]	0.53	100	0.47	100	0.53	100	0.47	100	0.53	100	0.47	100

Table 22: Nutritional constraints for feed formulation for poultry production.

	Broilers						Laying hens	
	Starter		Grower		Finisher			
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
ME kcal/kg	2750	2800	2850	2900	2900	2950	2600	2700
Crude protein %	21,5	22	19,5	20	17,5	18	16	17
Fat %	0	10	0	10	0	10	3	4
Ca	0,88	0,88	0,74	0,74	0,6	0,6	3,8	100
Total P	0	100	0	100	0	100	0	100
Available P	0,44	0,44	0,37	0,37	0,3	0,3	0,3	100
Cl	0,18	0,24	0,18	0,27	0,18	0,28	0,2	0,3
Na	0,15	0,18	0,15	0,18	0,15	0,18	0,13	0,18
Lys	1,15	100	1,05	100	0,935	100	0,7	100
Met	0,43	100	0,4	100	0,365	100	0,36	100
Met+Cys	0,85	100	0,8	100	0,73	100	0,58	100
Thr	0,75	100	0,69	100	0,625	100	0,52	100
Trp	0,18	100	0,17	100	0,15	100	0,15	100
Val	0,86	100	0,8	100	0,72	100	0	100
Arg	1,18	100	1,09	100	0,9825	100	0	100

Table 23: Constraints on incorporation rates of feedstuffs for feed formulation in the French context, in percentage.

	Baseline				Max Soybean meal				Max Innovative feed ingredient			
	Growing		Finishing		Growing		Finishing		Growing		Finishing	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Premix	5	5	5	5	5	5	5	5	5	5	5	5
Wheat distillers grains, starch > 7%, dried	0	100	0	100	0	100	0	100	0	100	0	100
Maize distillers grains with solubles, ethanol production, dried	0	100	0	100	0	100	0	100	0	100	0	100
Faba bean, white flowers	0	30	0	30	0	30	0	30	0	30	0	30
Rapeseed, whole	0	50	0	50	0	50	0	50	0	50	0	50
Wheat gluten feed	0	100	0	100	0	100	0	100	0	100	0	100
Processed animal proteins, pig	0	15	0	15	0	15	0	15	0	15	0	15
Sunflower seed, whole	0	15	0	15	0	15	0	15	0	15	0	15
Rapeseed oil	0	15	0	15	0	15	0	15	0	15	0	15
Palm oil	0	15	0	15	0	15	0	15	0	15	0	15
Soybean oil	0	15	0	15	0	15	0	15	0	15	0	15
L-Lysine HCl	0	1000	0	1000	0	1000	0	1000	0	1000	0	1000
Maize	0	650	0	650	0	650	0	650	0	650	0	650
DL-Methionine	0	1000	0	1000	0	1000	0	1000	0	1000	0	1000
Barley	0	500	0	500	0	500	0	500	0	500	0	500
Dicalcium phosphate dihydrate	0	1000	0	1000	0	1000	0	1000	0	1000	0	1000
Monocalcium phosphate	0	1000	0	1000	0	1000	0	1000	0	1000	0	1000
Phytase	0	0.05	0	0.05	0	0.05	0	0.05	0	0.05	0	0.05
Phytase	0	0.06	0	0.06	0	0.06	0	0.06	0	0.06	0	0.06
Phytase	0	0.04	0	0.04	0	0.04	0	0.04	0	0.04	0	0.04
Phytase	0	0.05	0	0.05	0	0.05	0	0.05	0	0.05	0	0.05
Spring peas	0	100	0	100	0	100	0	100	0	100	0	100
Wheat middlings	0	100	0	100	0	100	0	100	0	100	0	100
Salt (Sodium chloride)	0	1000	0	1000	0	1000	0	1000	0	1000	0	1000
Wheat bran	0	100	0	100	0	100	0	100	0	100	0	100
Sorghum	0	50	0	50	0	50	0	50	0	50	0	50
Rapeseed meal	0	150	0	150	0	150	0	150	0	150	0	150

L-Threonine	0	1000	0	1000	0	1000	0	1000	0	1000	0	1000
Triticale	0	100	0	100	0	100	0	100	0	100	0	100
L-Tryptophan	0	1000	0	1000	0	1000	0	1000	0	1000	0	1000
Soybean meal	0	1000	0	1000	0	1000	0	1000	0	1000	0	1000
Sunflower meal, non dehulled	0	100	0	100	0	100	0	100	0	100	0	100
Sunflower meal, partially dehulled	0	100	0	100	0	100	0	100	0	100	0	100
L-valine	0	1000	0	1000	0	1000	0	1000	0	1000	0	1000
Oats	0	50	0	50	0	50	0	50	0	50	0	50
Sodium bicarbonate	0	0	0	0	0	0	0	0	0	0	0	0
Wheat, soft	0	650	0	650	0	650	0	650	0	650	0	650
Calcium carbonate	0	1000	0	1000	0	1000	0	1000	0	1000	0	1000
Maize gluten feed	0	100	0	100	0	100	0	100	0	100	0	100
Beet pulp, dried	0	0	0	0	0	0	0	0	0	0	0	0
Protein concentrate from green biomass [1]	0	0	0	0	0	0	0	0	0	150	0	150
French soybean meal, from dehulled and extruded soybeans [1]	0	0	0	0	0	0	0	0	0	1000	0	1000
French soybean meal, from extruded soybeans [1]	0	0	0	0	0	0	0	0	0	1000	0	1000
Rapeseed meal, fine fraction[1]	0	0	0	0	0	0	0	0	0	150	0	150

[1] maximal incorporation rates of innovative feed ingredients are set different from 0 separately for each scenario investigating the potential of each innovative feed ingredient.

9.3 List of feedstuffs used in different countries

Table 24 : List of prices of feed ingredients used for feed formulation of the different French scenarios

Prices (€/t)	2010		2011		2012		2013		2013		2014		2016		2017	
	Aug.	Nov.	Aug.	Nov.	Feb.	May.	Feb.	May.	Aug.	Nov.	Feb.	May.	Aug.	Nov.	Feb.	May.
Premix	522	522	522	522	522	522	522	522	522	522	522	522	522	522	522	522
Wheat distillers grains, starch > 7%, dried	-	228	-	247	-	-	-	342	-	-	-	293	225	227	-	237
Maize distillers grains with solubles, ethanol production, dried	-	-	-	216	365	334	330	325	249	279	278	288	-	234	234	217
Faba bean, white flowers	-	242	288	298	329	369	388	375	270	302	295	300	207	202	220	216
Rapeseed, whole	-	452	504	487	523	495	491	477	387	398	406	394	372	426	426	420
Wheat gluten feed	-	-	-	-	247	253	226	228	181	200	203	205	156	154	163	157
Processed animal proteins, pig	-	870	-	-	908	734	669	690	680	674	658	625	632	718	793	715
Sunflower seed, whole	-	487	513	473	534	506	496	470	325	362	339	344	363	373	388	363
Rapeseed oil	869	978	1138	919	1047.442	902.583	915.752	855.985	979	751.646	740.503	724.295	712	827.621	800.27	778.997
Palm oil	869	978	1138	919	896.478	772.497	783.768	732.615	838	643.314	633.777	619.905	610	708.339	684.93	666.723
Soybean oil	869	978	1138	919	1034	891	904	845	727	742	731	715	703	817	790	769
L-Lysine HCl	1750	1750	1950	1900	1850	2000	1900	1450	1400	1300	1200	1200	1400	1320	1400	1400
Maize	210	214	246	244	270	257	229	224	205	176	179	177	179	179	183	187
DL-Methionine	3700	3800	3900	3850	3300	3300	3200	3050	3000	2800	2800	2800	3150	2750	2500	2500
Barley	188	195	225	207	238	251	225	217	171	184	178	169	141	146	153	146
Dicalcium phosphate dihydrate	380	380	380	380	560	560	650	650	650	650	650	650	650	650	650	650
Monocalcium phosphate	672	672	672	672	672	672	672	672	672	672	672	672	672	672	672	672
Phytase	9500	9500	9500	9500	9500	9500	9500	9500	9500	9000	9000	9000	9000	9000	9000	9000
Phytase	9500	9500	9500	9500	9500	9500	9500	9500	9500	9000	9000	9000	9000	9000	9000	9000
Phytase	9500	9500	9500	9500	9500	9500	9500	9500	9500	9000	9000	9000	9000	9000	9000	9000

Phytase	9500	9500	9500	9500	9500	9500	9500	9500	9500	9000	9000	9000	9000	9000	9000	9000
Spring peas	228	242	282	258	322	326	310	284	253	259	287	284	240	243	244	247
Wheat middlings	178	195	196	173	219	230	220	211	174	182	184	189	140	123	145	139
Salt (Sodium chloride)	112	112	112	112	112	112	112	112	112	112	112	112	112	112	112	112
Wheat bran	158	163	179	134	198	196	187	183	140	131	145	144	101	96	127	107
Sorghum	999999	213	244	999999	255	258	244	999999	999999	195	199	197	179	204	186	209
Rapeseed meal	224	236	246	212	324	319	306	327	247	260	300	266	223	223	244	221
L-Threonine	1900	1900	2300	2050	1900	2350	2000	1750	1750	1650	1600	1650	1650	1550	1580	1580
Triticale	202	213	230	250	258	267	252	249	197	206	201	195	146	143	152	145
L-Tryptophan	18000	16000	16000	14000	11000	27000	20000	11000	12000	10000	12000	13000	7000	7000	7500	9000
Soybean meal	338	350	363	315	551	472	439	452	454	449	486	456	379	353	378	340
Sunflower meal, non dehulled	197	191	204	159	278	249	243	250	203	199	190	191	201	165	165	161
Sunflower meal, partially dehulled	999999	258	245	219	336	321	301	306	266	261	258	280	243	229	223	213
L-valine	12022	12022	12022	12022	12022	12022	12022	12022	12022	12022	12022	12022	6000	6000	6200	6200
Oats	999999	186	999999	999999	281	265	250	214	182	169	159	164	183	195	178	184
Sodium bicarbonate	552	552	552	552	552	552	552	552	552	552	552	552	552	552	552	552
Wheat, soft	209	215	259	247	252	264	239	236	174	195	192	188	161	166	172	168
Calcium carbonate	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Maize gluten feed	191	200	216	202	254	261	241	238	213	220	215	225	175	165	180	172
Beet pulp, dried	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-