Economic and environmental evaluations of selection for feed efficiency in pigs

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Summary

The aim of this thesis was to develop an approach to evaluate breeding strategies for feed efficiency in pigs to identify mitigating solutions for environment and economy. A life cycle environmental assessment model (LCA) and a bio-economic model were developed at the individual level. It enabled to assess varieties of feed efficiency scenarios on an individual basis. The models were applied to assess the impacts of selection for feed efficiency alone or combined with diet optimisation as a strategy to achieve overall farm feed efficiency. Data from two pig lines selected for feed efficiency based on residual feed intake (RFI), showing genetically contrasted feed efficiency, were used. A multiple objective diet optimisation was developed using genetic line nutritional requirements as constraints, and minimising a score combining environmental impacts and/or cost. The consistency of the models was obtained from considering net energy as the core linkage between line requirements, ingredients dietary composition, price, and environmental impacts. The individual performance traits in response to new optimised diets for each line were simulated with the InraPorc® pig growth simulation software. For a least cost, a least environmental impacts, and a joint economic-environment diets, these performances were used as inputs to the LCA and bio-economic models. The individual economic and environment assessments showed that selection for improved feed efficiency in pigs increases the profitability by 23.4% and reduces the environmental footprint by 7%. Selection for feed efficiency combined with diet optimisation even enhanced these economic and environmental improvements through restoring part of the advantages of selection that did not emerge due to feeding the lines the same diet. Thus, for increased pig sustainability, a selection for feed efficiency should be combined to diet optimisation including environmental constraints. However, feeding less efficient pigs an optimised diet strongly reduced the genetic differences and alleviated most of the economic and environmental burdens. Finally, the assessment at the individual level gave access to the covariances between the performance traits and the environmental impacts and profit. High correlations of feed conversion ratio with environmental impacts and profit in both lines confirmed the importance of feed efficiency as a lever for the sustainability of pig production, and the moderate correlations with RFI pointed this trait as a potential lever to improve environmental impacts with limited correlated effects on other production traits. These results and tools will contribute to move from breeding goals essentially based on economic objectives to more holistic breeding goals, to contribute to increased sustainability in pig production.

Résumé

L'objectif de cette thèse était de proposer une approche pour évaluer les stratégies d'élevage et de sélection pour l'amélioration de l'efficacité alimentaire chez le porc en croissance, afin d'identifier des leviers pour conjointement atténuer les impacts environnementaux, et améliorer les résultats économiques de la filière porcine. Un modèle d'évaluation environnementale par analyse de cycle de vie (ACV) et un modèle bio-économique applicables à l'échelle de l'individu ont été développés. Ils ont permis d'évaluer des scénarios variés d'amélioration de l'efficacité alimentaire. Les impacts de la sélection pour l'efficacité alimentaire seule ou combinée à l'optimisation du régime alimentaire comme stratégie pour atteindre une efficacité alimentaire globale de la ferme ont ainsi pu être quantifiés. Les données individuelles de deux lignées de porcs sélectionnées pour une efficacité alimentaire (consommation moyenne journalière résiduelle ou RFI) génétiquement contrastée ont été utilisées. Un module d'optimisation multi objectifs de la composition de l'aliment a été développé en combinant la contrainte des besoins nutritionnels de chaque lignée génétique, et la minimisation d'un score intégrant divers impacts environnementaux et / ou le coût de l'aliment. La cohérence des modèles a été obtenue en considérant l'énergie nette comme le lien central entre les besoins des lignées, la composition nutritionnelle des ingrédients, leurs prix et impacts environnementaux. Les performances individuelles en réponse à de nouveaux régimes optimisés pour chaque lignée ont été simulées avec le logiciel de simulation de croissance des porcs InraPorc®. Après des optimisations de l'aliment à moindre coût, à moindre impact environnemental, ou conjointement pour les objectifs économiques et environnementaux, ces performances simulées ont été utilisées comme données d'entrée pour les ACV et les modèles bio-économiques. Les évaluations économiques et environnementales individuelles ont montré que la sélection pour une meilleure efficacité alimentaire chez les porcs augmente de 23,4% le résultat économique, et réduit l'empreinte environnementale de 7% par rapport à des porcs peu efficaces avec un aliment standard. La sélection pour l'efficacité alimentaire combinée à l'optimisation du régime alimentaire a encore diminué les impacts environnementaux et augmenté le résultat économique, rétablissant une partie des avantages de la sélection qui ne ressortaient pas lorsque les lignées sont nourries avec le même régime alimentaire. Ainsi, pour une durabilité accrue de la production porcine, la sélection génétique de l'efficacité alimentaire doit être combinée à l'optimisation du régime alimentaire, si possible incluant une contrainte environnementale. Cependant, nourrir des porcs moins efficaces avec une alimentation optimisée a fortement réduit les différences génétiques et allégé la plupart des différences

économiques et environnementales, ce qui souligne l’importance de la combinaison des approches pour atténuer les défauts des animaux moins efficaces. Enfin, les évaluations au niveau individuel ont donné accès aux covariances entre performance de production, impacts environnementaux et résultat économique. Les corrélations élevées de l’indice de consommation avec les impacts environnementaux et les résultats économiques dans les deux lignées ont confirmé l'importance de l'efficacité alimentaire comme levier pour la durabilité de la production porcine, et les corrélations modérées avec RFI montrent que ce caractère est un levier pour améliorer les impacts environnementaux si l’on souhaite avoir des effets limités sur les autres caractères de production. Les modèles et outils développés dans cette thèse contribueront à l’évolution des objectifs de sélection des porcs en croissance, pour passer d’objectifs essentiellement économiques à des objectifs de sélection plus globaux qui concourent à une durabilité accrue de la production porcine.

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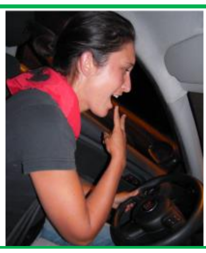
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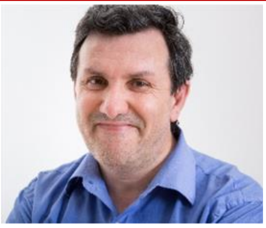
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List of abbreviations

AA: Amino acid

ADG: Average daily gain

ADFI: Average daily feed intake

AP: Acidification potential

BFT: Back fat thickness

BL: Body lipid

BP: Body protein

BW: Body weight

CC: Climate change

CP: Crude protein

DFI: Daily feed intake

EFV: Equivalent fertilizer value

EP: Freshwater eutrophication potential

ECR: Energy conversion ratio

FAO: Food and agricultural organisation

FCR: Feed conversion ratio

GWP: Global warming potential

HRFI: High residual feed intake

Kg: Kilogram

K: Potassium

LCA: Life cycle assessment

LRFI: Low residual feed intake

LO: Land occupation

LW: Live weight

MJ: Megajoule

NE: Net energy

N: Nitrogen

PB/PL: Ratio of protein to lipid in the body

P: Phosphorous

RFI: Residual feed intake

SD: standard deviation

WD: Water depletion

Chapter 1 **Literature review**

1.1 **Pig production**

It is expected that world human population will exceed 9.8 billion people by 2050 (FAO, 2017). The ever-growing trend of human population by 2100 (Figure 1, source HYDE database (2016) and UN's World Population Prospects (2019)) involves augmentation in food production.

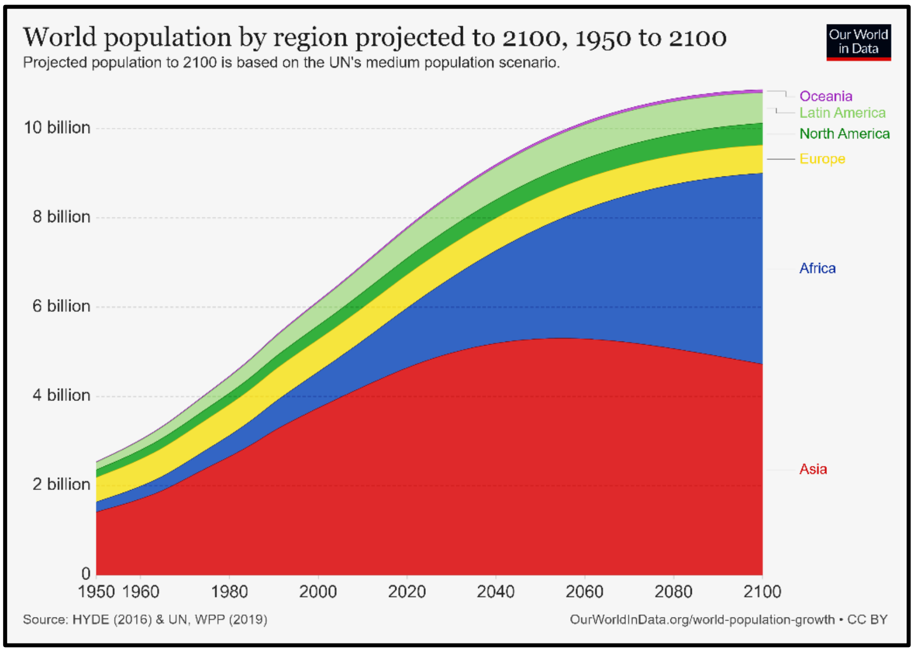

Figure 1. Trend of human population by 2100 (https://ourworldindata.org/future-population-growth)

In the livestock industry, the monogastric animals (essentially pigs and poultry) have had faster growing production than the ruminants (Steinfeld et al., 2006). The most widely consumed source of animal protein, pork, represents more than 40% (Figure 2) of the globally produced meat (~120 million tons) in 2018 (FAO 2020), with an increasing trend (Figure 3). Among European countries, France is the 3rd producer and 4th consumer of pig meat (FAOSTAT, 2020).

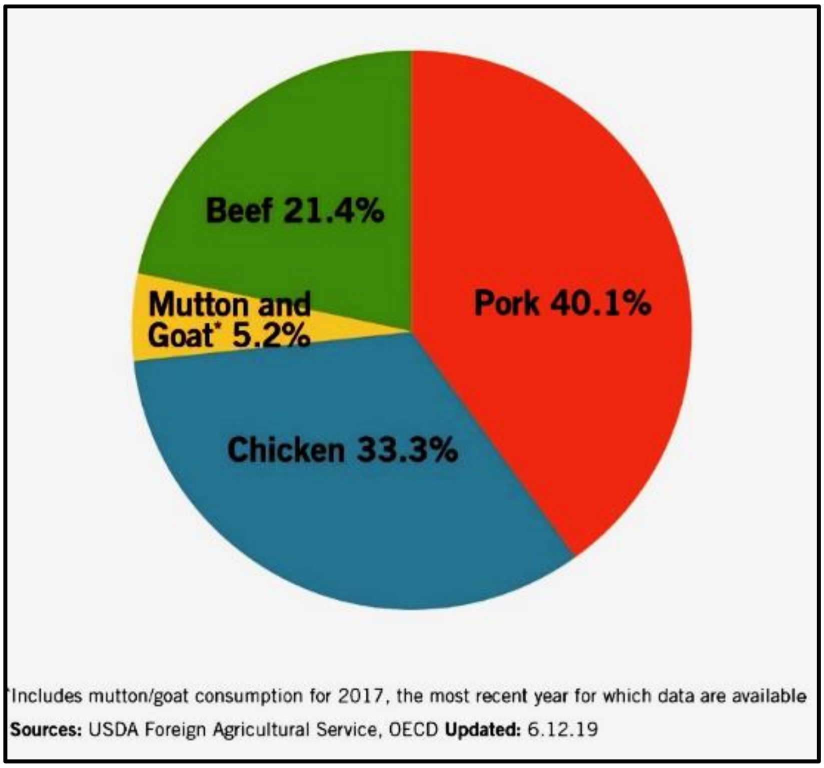

Figure 2. Consumed sources of animal protein

(https://www.pork.org/facts/stats/u-s-pork-exports/world-per-capita-pork consumption/)

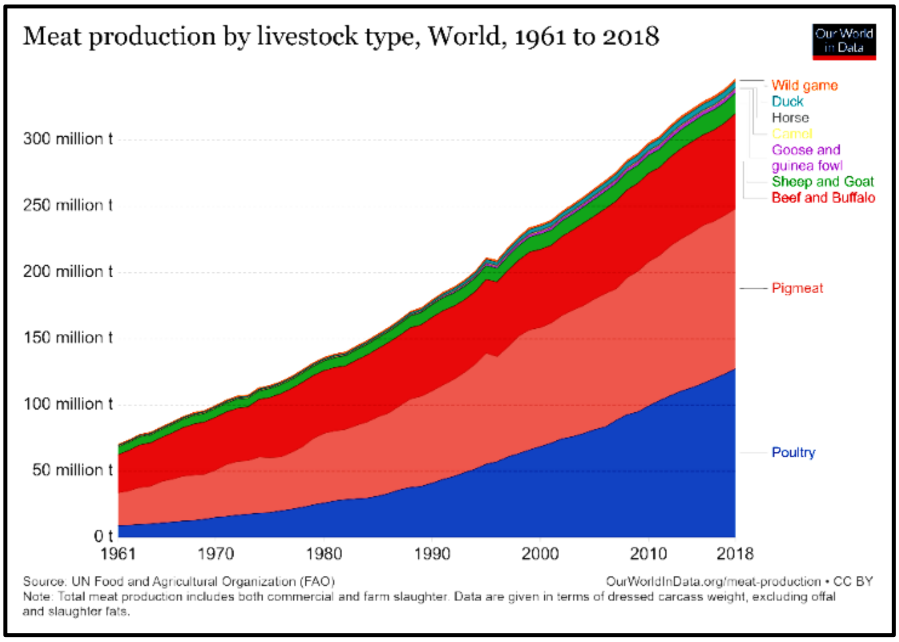

Figure 3. Globally produced meat

Competition with land use between pig feed ingredients and human food (Godfray et al., 2010; Hume et al., 2011), along with global challenges such as climate change, human population growth, and economic crises may influence over human food security. Demand increase for pig production intensifies competition for feed ingredients, mostly the same cereal grains that could directly be consumed by humans (Ali et al., 2018). This competition, along with resources scarcity, maintains continuous pressure on feed costs, which could be up to 60% to 75% of the total cost of pig production (Cadéro et al., 2018). The increase in competition for access to the resources which are also used for human edible crops and for the production of biofuels involves a cascade of pollutions activities including deforestation and land use changes. Pig production areas are subjected to high environmental impacts mainly due to its concentrated distribution in very limited areas. Figure 4 illustrates the number of sows across Europe. This uneven concentration of pig farms is associated with some challenges. The high density of pig production in limited areas causes local overproduction of emissions and excretions along with lack of sufficient agricultural surface for manure spreading. For example, around 57 % of pigs in France are produced in Brittany (Figure 5), while this region represents only 6% of the total agricultural area (IFIP, *Institut de la Filière porcine*, Le Porc par les Chiffres, Edition 2020-2021).

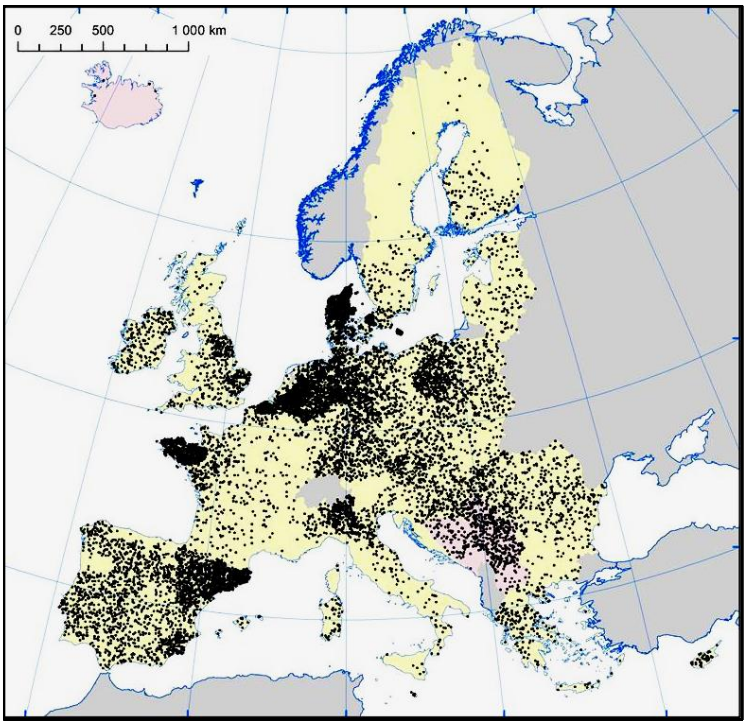

Figure 4. Number of sows by region (2013)
(ec.europa.eu/eurostat/statistics)

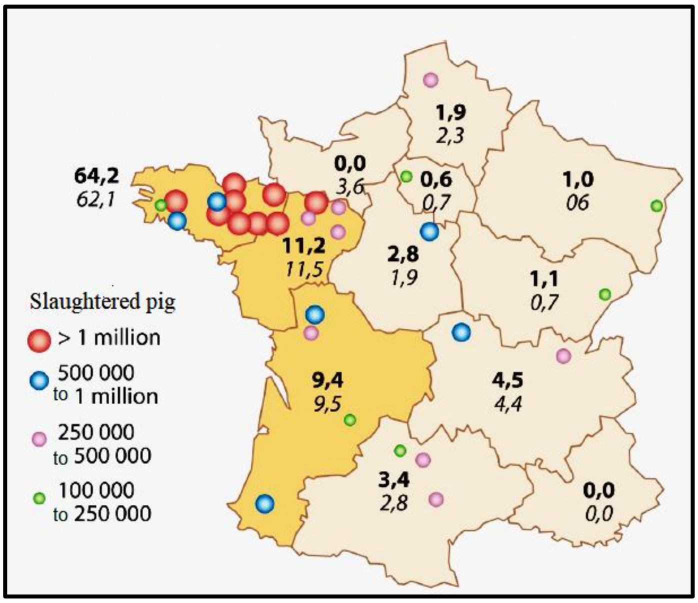

Figure 5. Geographical distribution of slaughtered pigs
It corresponds to the distribution of the French production (IFIP, le Porc par les Chiffres, edition 2020-2021)

Having severe impacts on air, water and soil quality, and competing for scarce resources such as energy, water and land (de Vries and de Boer, 2010), the livestock sector production has a major environmental footprint either at a global (greenhouse gases) or at a local (eutrophication potential (EP), acidification potential (AP)…) levels (Rigolot et al., 2010). Globally, livestock contribute up to 80% of methane (CH_4) and nitrous oxide (N_2O) emissions, both greenhouse gases, from world agricultural activities (Steinfeld et al., 2006). Globally, pig production produces 668 million ton equivalent of CO2 per year (Macleod et al., 2013), with the highest levels of EP and AP of the livestock industry (de Vries and de Boer, 2010). In intensive pig production regions of Europe, pigs are responsible for nitrogen and phosphorus excretion as the major sources of local environmental burdens in agriculture (Williams, 1995). Livestock farming accounts for 70% of the EU's agricultural land (Weishaupt et al., 2020). The European livestock sector contribution is 81% for global warming, 80% for soil acidification and air pollution (ammonia and nitrogen oxides emissions), 73% for water pollution (both N and P), and 78% for terrestrial biodiversity loss (Leip et al., 2015). For instance, Figure 6 shows the total greenhouse gas emissions from the various emission sources associated with livestock production in the Europe (Lesschen et al., 2011).

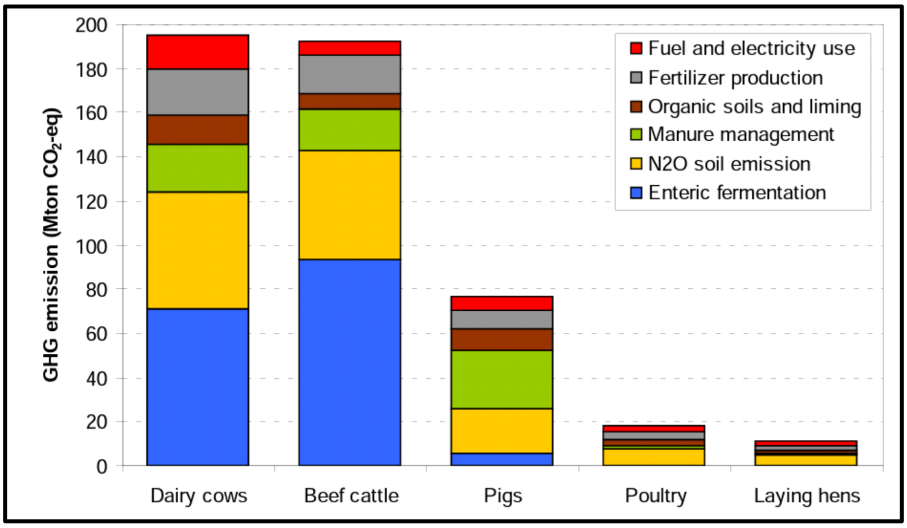

Figure 6. Total greenhouse gas emissions associated with livestock production in the EU-27

1.2 **Feed efficiency in pigs**

1.2.1 ***Feed use in pigs***

Feed costs represent up to 75% of the total pig production costs (Cadero et al., 2018) which is a main constraint in profitability of pig production enterprises. Beyond being the economic bottleneck, feed greatly contributes to the environmental impacts of pig farming (van der Werf et al., 2005; Nguyen et al., 2011; McAuliffe et al., 2016). Consequently, improvement in feed efficiency is the major goal of sustainability through the reduction in economic and environmental burdens of pig production. As the most massive land used activity, the livestock industry exploits 75% of the total land (Foley et al., 2011; Cassidy et al., 2013). Moreover, for monogastric livestock, feed production impacts are responsible for up to 85% climate change, 97% EP, 96% energy use, next to 100% LO (Garcia-Launay et al., 2018), and up to 90% of non-renewable resource use (Mackenzie et al., 2015) of whole environmental impacts associated to the production of 1 kg of meat. Fattening feed, ie feed delivered to pigs from about 10 weeks of age up to slaughter around 115 kg body weight (BW) (~5.5 to 6 months of age), is the main contributor to total feed costs in pigs (Mullan et al., 2011), and fattening pigs are responsible to up to 70% of the nitrogen (N) and phosphorous (P) on farm excretion of an entire farrow to finish farm (Dourmad et al., 1999), which is the typical French farm.

Consequently, feed efficiency improvement of fattening pigs is a key driver towards profitability and sustainability in pig production through lowering farming cost, manure production (O'Shea et al., 2012; Bartoš et al., 2016) and feed production associated environmental burdens. The difficulty of direct selection for feed efficiency stands in the lack of direct measurement (Hoque and Suzuki, 2008), and feed efficiency is generally expressed as ratio or residual traits (Berry and Crowley, 2013). Feed efficiency, most commonly expressed inversely as feed conversion ratio (FCR) in pigs, stands for body weight gain per unit of feed consumed during a given period.

Improving animal feed efficiency is possible at two stages of the pig utilisation of the diet. The first stage arises from the interaction between feed and animal in the digestive tract: it improves conversion of feed gross energy (GE) and nutrients into metabolisable energy (ME) and nutrients. The second stage improves the partitioning of uptaken net energy (NE) and nutrients between maintenance and tissue accretion through protein and lipid deposition (Nguyen et al., 2005). The total energy of feed ingredients, GE subtracted for energy in feces, stands for digestible energy (DE) (Figure 7), which, minus the excreted energy in urine and emitted as fermentation gases turns into ME, which represents the potential usable energy availed for animal requirements (de Lange and Birkett, 2005; Moehn et al., 2005). Ultimately, the energy available for maintenance and tissue accretion, net energy NE represents ME minus the heat increment due to energy losses during nutrient metabolic processes (Kil et al., 2013). To estimate the available energy value of a diet from its chemical composition, three main systems (Kil et al., 2013) of digestible and metabolisable energy (Noblet and Perez, 1993), net energy (French system by Noblet et al. 1994 and Dutch system by Blok 2006), and Danish potential physiological energy system (PPE) (Boisen, 2007) have been developed.

In the energy partitioning concept, the uptaken energy would be allocated to tissue accretion (protein and lipid deposition) as the retained energy and to heat release (basal metabolism, excretion, physical activity, thermoregulation and immune response) as the energy losses. This energy allocation establishes a baseline to develop separate models to quantify energetic requirements for production (tissue accretion) and maintenance. The required energy for maintenance is usually quantified as a linear function of metabolic body weight (mBW), BW with the exponent of 0.60 for growing pigs (Noblet et al., 1999).

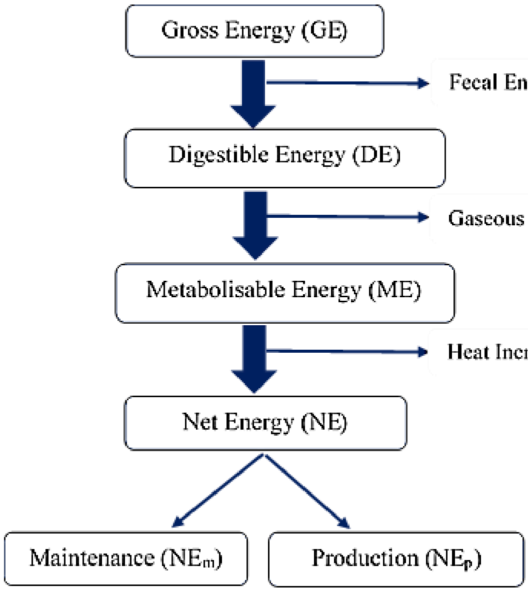

Figure 7. Partitioning of feed energy in pigs

Several studied have reported the superiority of NE system over DE and ME systems, with the main advantage of the NE system to better predict growth performance and body composition of pigs (Verstegen, 2001; Noblet, 2007; Oresanya et al., 2008). The NE system is also better to estimate the dietary energy of multi-ingredient diets (Patience and Beaulieu, 2005; Lange, 2008), and using the NE system, more accurate diet compositions could be obtained to decrease the waste excretion (Le Bellego et al., 2002; Noblet, 2007). In addition, it was shown that fattening pigs are able to regulate their spontaneous feed intake over a wide range of net energy density (Cole et al., 1967; Nyachoti et al., 2004; Quiniou and Noblet, 2012; Kil et al., 2013). However, severe reduction in dietary energy, like low energy high fibre diets, may restrict the energy intake mainly because of gut fill limitation (Kyriazakis and Emmans, 1995). Accordingly, within usual ranges of dietary energy contents, the NE system is more precise than DE or ME systems in prediction of ad libitum feed intake of growing pigs.

International efforts have been undertaken to improve feed efficiency through improvements in diet composition, feeding plan and genetic selection for feed efficiency since decades. For instance, it is reported that limited feed restriction, which does not cause considerable reduction in growth rate, can improve feed efficiency as well as lean meat percentage (Prince et al., 1983; Lovatto et al., 2006; Niemi et al., 2010; Patience et al., 2015). In addition, given the quasi linear relationships between particles size of the diet ingredients and feed efficiency, improvement in feed processing can lead to higher feed efficiency (Healy et al., 1994; Wondra et al., 1995; Mavromichalis et al., 2000). Moreover, switching from static conventional group phase feeding plan to a dynamic individually matched nutritional requirement recognition and real time nutrient satisfaction, precision feeding has been under development since the 1990s when single space electronic feeders enabled individual data collection and investigation of group housed pig individual feeding (Ferket et al., 2002; Pomar et al., 2009; Hauschild et al., 2012; Pomar et al., 2014). Furthermore, reduction in lysine intake and nitrogen excretion with no compromise in growth performance via performing precision feeding technics are reported (Andretta et al., 2012; Andretta et al., 2016), and reduction in the crude protein of feed is one of the key targets for improvement in environmental performance related to pig production (McAuliffe et al., 2016). Genetic selection for feed efficiency as the animal improvement approach will be discussed in the next section.

1.2.2 *Genetic selection for feed efficiency*

Animal selection is the genetic improvement of a population of animals based on a selection criterion. A selection criterion for multi-trait selection can be constructed from traits correlated to the selection objective, combined linearly with weightings to maximise their correlation with the selection objective. The proper weightings can be obtained from using standard deviation of the traits, genetic and phenotypic correlations between each pair of traits and heritable fraction of variance in each trait and their relative economic values (Hazel, 1943). For a viable selection, the trait or the measure must be heritable enough to be transferred from ancestors to descendants. Feed efficiency in fattening pigs, as a complex multifaceted trait, involves contribution of varieties of biological and physiological processes without any direct measurable phenotype. Accordingly, given the resulting polygenic nature of feed efficiency, with many underlying biological mechanisms (Mauch, 2018), a proper strategy to improve feed efficiency is selection at the genomic (whole genome) level rather than gene or single nucleotide polymorphism level.

The genetic selection for feed efficiency based on FCR, with a heritability within the range of 0.20 to 0.42 (Fredeen, 1972; Mrode and Kennedy, 1993; Kadarmideen et al., 2004; Cai et al., 2008; Hoque and Suzuki, 2008; Do et al., 2013), has been efficiently implemented and investigated (Rothschild and Ruvinsky, 2011). Selection of animals to improve FCR had some measurement challenges until 1990, when electronic single-space feeders became available. These feeders enabled the daily record of feed intake, and sometimes body weight gain, of any individual or grouped pigs, and facilitated the calculation of FCR. In France, direct selection for lower FCR became available from the earlies of the 1990s, when performance monitoring stations were equipped with ACEMA 48 followed by ACEMA 64 from 2005 (Saintilan et al., 2013), and resulted in major improvements of the traits in the main pig populations (Figure 8). Similarly, a systematic selection for reduced FCR in Norwegian landrace has resulted in highly feed efficient pigs due to high lean meat growth (Martinsen et al., 2015).

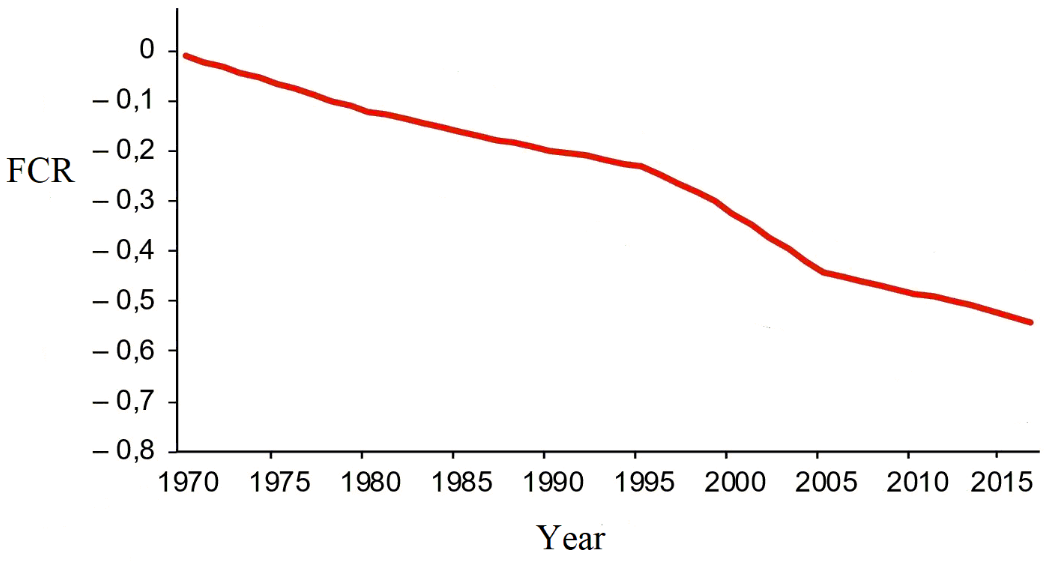

Figure 8. Trend of improvement of FCR (kg feed intake /kg weight gain) in French Large White pig populations since the 70’s (Bidanel et al., 2020)

A general problem with selection for ratio traits is the uneven selective pressure applied on the numerator and denominator traits, involving uncontrolled statistical variation in the traits among the selected animals (Gunsett, 1984). Thus, a reduction in FCR cannot be necessarily assigned to an improvement (decrease) in feed intake (Crews, 2005). Accordingly, as an alternative trait to FCR, in 1963, Koch et al. introduced a more targeted measure for feed efficiency called residual feed intake (RFI). The RFI, which can be obtained from a linear combination of other production traits, is defined as the difference between observed feed intake and the feed intake expected from individual maintenance and production requirements (Koch et al., 1963; Kennedy et al., 1993). Contrary to FCR, RFI has the advantage to be independent from production and maintenance requirements, which offers an opportunity to select for reduced feed intake with no compromise on production performance (Kennedy et al., 1993; Van der Westhuizen et al., 2004). In other words, removing average daily feed intake (ADFI) required for growth and maintenance requirements, the remaining (residual) variation in ADFI represents RFI. The portion of feed intake for production requirements can be predicted from different traits between species and studies (Gilbert et al., 2017). For growing pigs, since the main portion of variation in ADFI (up to 66%) comes from variation in ADG and BFT (Cai et al., 2008), these traits were mostly applied for predicting the requirements for growth and the composition of body weight gain. However, varied prediction approaches for production and maintenance requirements can make it difficult to compare the calculated RFIs among different studies (Hoque and Suzuki, 2008; Do et al., 2013; Do et al., 2014). As a biologically and genetically complex of combined traits, RFI has no major representative genes, but numerous genes with small contributions (Mauch, 2018). Variations in RFI can originate from variation in functions using energy and nutrients including maintenance, physical activity, body composition, immune response, digestibility, thermoregulation and energy efficiency (Herd et al., 2004). A negative (low) of RFI stands for high feed efficiency and positive (high) quantity of RFI assigns low feed efficiency (Figure 9).

The RFI was reported to be moderately heritable in growing pigs, 0.13-0.45 (Nguyen et al., 2005; Saintilan et al., 2013) with a genetic correlation of 0.39±0.12 with FCR (Gilbert et al., 2017). During the last two decades, the potential of RFI to improve feed efficiency in growing pigs has been studied through development of experimental divergent selected lines in France at INRAE (Gilbert et al., 2007) and in USA at Iowa State University (Cai et al., 2008), resulting in LRFI pigs (low RFI, more efficient) and HRFI pigs (high RFI, less efficient). Details about these populations and the main outcomes of the selection experiments are provided in Frame 1.

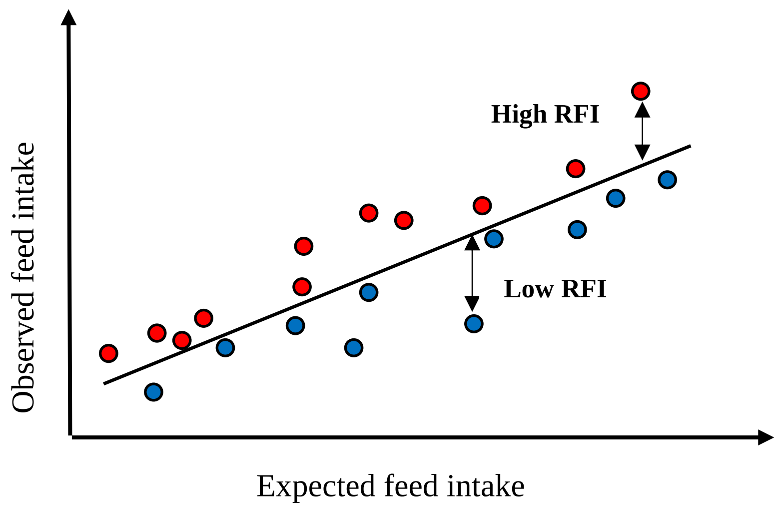

Figure 9. Schematic representation of residual feed intake (RFI)
It is computed as the difference between expected feed intakes based on maintenance and tissue accretion requirements on the x-axis and observed feed intake on the y-axis

In these populations, as well as in commercial populations, it was shown that RFI has positive genetic correlations with ADFI, FCR, lean meat percentage (LMP), low negative correlation with ADG, and next to zero correlation with carcass backfat (Hoque and Suzuki 2008; Cai et al., 2008; Saintilan et al., 2013; Gilbert et al., 2017). Lower maintenance requirements, physical activity and water intake are also reported for pigs with low RFI (Barea et al., 2010; Renaudeau et al., 2013; Meunier-Salaün et al., 2014). These studies showed that energy partitioning between maintenance, physical activity and production is the main drivers of the line efficiency differences (Gilbert et al., 2017).

Finally, despite the massive amount of investigations on the correlated impacts of selection for feed efficient on different aspects of the pig production, to date, these impacts have not been thoroughly assessed from an environmental point of view. Few studies used nutritional individual models to predict nitrogen (N) and phosphorus (P) retention and excretion of individual pigs, and moderate to high correlations between P (Saintilan et al., 2013) and N excretion and feed efficiency traits (Shirali et al., 2012, 2014) were reported. The estimated correlations were close to 1 with FCR in these studies. However, by focusing on individual pigs these approaches neglect the overall environmental impacts of the pig production, and specifically the impact of feed production, that we previously reported as major.

Frame 1 – Pig line selection for RFI at INRAE

The impacts on production and reproduction performances were reported (Cai et al., 2008; Young and Dekkers 2012; Gilbert et al., 2012, 2017). Pigs in the LRFI line compared with HRFI pigs were more feed efficient, with greater carcass lean, lesser BFT and average daily gain. The impacts of selection on animal physiology were investigated in terms of digestive efficiency, basal metabolism, feeding behaviour, responses to stress, energy and protein metabolism, as reviewed in Gilbert et al., (2017). The experimental selection resulted in no line difference in digestibility of energy and nutrients (Montagne et al., 2014; Labussière et al., 2015), and the higher energy efficiency of LRFI pigs than HRFI pigs was related to lower physical activity and basal metabolic rate (Barea et al., 2010). It was thus concluded that improving feed efficiency through selection based on RFI, when pigs are fed conventional diets, essentially corresponds to the improvement in partitioning of the delivered energy (Gilbert et al., 2017). The French selection experiment for RFI was initiated in the French commercial Large White pigs in 1999 by Dr. Pierre Sellier and Jean Noblet. Initially, 30 litters were obtained from mating 30 sires and 30 dams. A phenotypic selection index of RFI was obtained from earlier correlations between proxies for fat tissue growth (BFT) and body weight gain (AGD) and DFI from 35 to 95 kg BW (RFI(g/d) = DFI (g/d) – [1.06 * ADG (g/d)] – [37 * BF (mm)]; Gilbert et al., 2017). Pigs had ad libitum access to feed delivered as pelleted diet, and individual DFI were collected using single space automatic feeders (ACEMA 64, Pontivy, France), and BFT was measured using an ALOKA SSD-500 echograph (Aloka, Cergy Pontoise, France) and BW was collected on a weekly basis from 10 weeks of age up to planed market weight (Gilbert et al., 2007). A parallel selection experiment on RFI was performed at Iowa State University (ISU, Ames, Iowa) from 2000 in Yorkshire pigs (American branch of Large White pigs) by Prof. Jack CM Dekkers up to ten generations, with consistent results between the two selection experiments. Similar differences between the lines were reported for both INRAE and ISU experiments, except for meat quality indicators. The ISU experiment reported minor impact of selection for RFI on sensory quality of meat and consumer eating indicators, and the INRAE experiment showed impacts on the technological quality of meat (Gilbert et al., 2007; Mauch, 2018).

1.3 **Environmental assessment**

Lord Kelvin, physicist who gave his name to the Kelvin degrees, said “if you cannot measure something, you cannot improve it”. Environmental assessment models have been used to quantify the environmental impacts associated with the procedures and production systems. Several methods of environmental assessment such as Ecological Footprint, Nutrient Balance, Multi Agent System, Multi Linear Programming, and Life Cycle Assessment (LCA) with different approaches, elaboration levels, and limitations have been proposed in the literature. In 1997, Wackernagel and Rees developed the method of Ecological Footprint to assess the individual impacts on the Earth’s natural resources through the quantification of the individual demand for the resources in five categories of consumed land, garden, crop land, pasture land and productive forest. This method does not distinguish local or global natural resources and among the greenhouse gases only considers CO_2, which may underestimate the environmental impacts of a production system (van den Bergh and Verbruggen, 1999). In 2003, de Boer introduced the method of Nutrient Balance for environmental assessment. The method identifies inefficiencies due to loses and leaching from a production system. Nutrient Balance in the crop production can be applied to assess the loss of N, P and K from the consumed fertiliser. However, because it did not consider all the upstream impacts, such as fertiliser manufacturing burdens, it is not appropriate for a global assessment of all the environmental impacts of a process. The method of Multi Agent System was developed since the 1990s (Aulinas et al., 2009) to consider the interactions of the production system in terms of economy, social and environment in the environmental assessment. The incorporated parameters in the model enable to find the best scenario for the production system. Due to integrating social, economy and environmental interactions the method may not be suitable for pure environmental assessment. In the method of Multi Linear Programming, linear optimisation algorithms are used to determine the management scenario with the lowest environmental impacts. The method involved economic, social and technical aspects of a production system to identify the best management approaches with maximum profitability with minimum environmental emissions (Payraudeau and van der Werf, 2005). Finally, in a synthesis to keep the advantages of these environmental assessments methodologies and limit their drawbacks, LCA, as a holistic assessment framework, was proposed to quantify the environmental impacts during the entire life cycle of a product or process (United Nation Environment Programing, 2006). This approach is now generally recognized and retained of environmental assessment, so we retained it for our developments. In the next section its principles of the LCA method and applications are described.

1.3.1 ***Principles of life cycle assessment***

Life cycle assessment (LCA) is the most popular and recognised analysis technique to assess holistically the environmental impacts associated with all the stages of entire life cycle of a product or system (Guinée et al., 2002). The ISO 14040 standard series have provided comprehensive standards to include all four steps of LCA, addressing quantitative assessment methods for the assessment of the environmental aspects of a product or service in its entire life cycle stages. This methodology helps to identify hotspots which have high contribution to the environmental impacts (Thomassen et al., 2008). To conduct an LCA the International Organization for Standardization (ISO) introduced a protocol including four principles for the framework of LCA: define the goal and scope, run the life cycle inventory analysis, run the life cycle impact assessment, and run the interpretation (ISO 14040, 2006, last reviewed in 2016 https://www.iso.org/standard/37456.html). With this framework, the functional unit, the system boundary, and the impact categories to assess with the LCA are first defined at the stage "goal and scope definition". To quantify the performance of a product system, the functional unit is required to be defined in unit of mass or volume (Basset-Mens and van der Werf, 2005; Koch and Salou, 2015). The life cycle inventory step involves quantifying and cumulating all relevant inputs, including raw material and natural resources, and outputs, including products, co-products, emissions and excretion, for all the involved processes within the system boundary. Variety of methods are developed to quantify and classify the emissions of all processes within the system boundary and report them in a set of environmental impact categories, such as global warming potential (GWP), acidification potential (AP), land occupation (LO), freshwater eutrophication potential (EP),based on P emissions, and marine eutrophication potential based on N emissions, etc. In the final stage, the results from the inventory analysis and impact assessment should be interpreted under ISO 14044 guidelines through sensitivity and uncertainty analyses, to identify the hotspots for further process of improvement recommendations (Williams et al., 2009). However, these general guidelines offer wide interpretation from diverse assumptions and developed methodologies, which may potentially mislead the decision makers on the claims of product declarations in terms of environmental impacts (Dong et al., 2018). This could be avoided through harmonization of methodologies and approaches to quantify environmental impacts (Colomb et al., 2016). Thus, an LCA study requires dependable references and guidelines to select appropriate databases, methods and approach. To fulfil this requirement, the inter-governmental panel of climate change (IPCC, 2006) has offered standardization recommendations. More specifically, to conduct an LCA in livestock production systems, the livestock environmental assessment and performance partnership (LEAP) has provided guidelines for GWP, AP, water use and non-renewable energy use (NRE). To respond to these needs for standardisations, a national program was launched in 2000 at INRAE in France to create an integrated platform to provide possibility for researchers to conduct economic, environmental and social assessments in agriculture (Auberger et al., 2013). The resulting MEANS platform (MulticritEria AssessmeNt of Sustainability) is an innovative user-friendly platform with shared databases to perform multi-criteria assessments.

Cross-study comparisons of results can be a challenge due to differences in assumptions and methodological choices such as functional unit, system boundary, and choice of an allocation, attributional or consequential approach (Thomassen et al., 2008; González-García et al., 2015; McAuliffe et al., 2016). Two main approaches for performing LCA are available. On one hand, the attributional LCA refers to model a system "as-is" (status quo situation). It is the most popular approach in different LCA studies, as stated in the review by McAuliffe et al. (2016). This approach accounts for physical flows involved in life cycle of a product (Ekvall and Weidema, 2004). On the other hand, the consequential approach considers the changes in market demand for a product or service (i.e. environmental impacts arising from producing one additional kg of pig meat) and only includes processes affected by such changes (Thomassen et al., 2008; McAuliffe et al., 2016). In other words, this approach does not represent the impacts of an existing supply chain of products, but represents the environmental impacts expected from changes in the life cycle of the product. In addition, an allocation method should be chosen among the main allocation methods for partitioning the inputs or outputs of a production system between the products in case of multiple products and co-products. The International Organization for Standardization (ISO) has developed a procedure for dealing with co-product allocation in the 14044 standard for LCA (ISO, 2006). The applied methodologies for allocation can be broadly classified as I) economic allocation: as the most common method of allocation (de Vries and de Boer, 2010), the environmental impacts of a multi-product system are allocated to the products proportionally to their market economic value, II) physical allocation (e.g. mass or gross energy allocation), III) system expansion, and IV) biophysical allocation (Mackenzie et al., 2017).

Varieties of studies have performed LCA to assess the environmental impacts of livestock products such as chicken (Leinonen et al., 2012; Tallentire et al., 2017), beef (Casey and Holden, 2006; de Vries et al., 2015), eggs (Mollenhorst et al., 2006; Leinonen et al., 2012), milk (Basset-Mens et al., 2005; Thomassen et al., 2008), fish (Besson et al., 2016; Besson et al., 2017), and pigs products, with different system boundaries, methods and functional units. Due to the focus of this thesis, the studies on pig products are reviewed in the next section.

1.3.2 ***Life cycle assessments applied to pig production***

Life cycle assessments have been applied by the researchers to quantify the environmental impacts of the pig production supply chain, as a whole or partially. In these studies, the entire cradle-to-farm gate pig systems, or partial system boundaries such as feed production and waste management, were assessed. Tables 1 and 2 list some LCA studies on pig products with different scopes and functional units, from the review by McAuliffe et al. (2016) augmented with more recent studies. Most of the early studies allowed to identify the main categories of the environmental impacts of pig production, at the farm level and at the feed production level, GWP, AP, EP and LO, as mentioned in previous sections. Some of these studies related to pig production systems are detailed in this section.

Using LCA, several feeding scenarios including changes in diet composition and feeding plan were investigated. The reduction in crude protein and P of feed is one of the key targets for improvement in environmental impacts related to pig production, achieved through incorporation of specialty feed ingredient in feed, including synthetic AAs and phytase (Kebreab et al., 2016). Using LCA have shown that a partial replacement of soybean meal with synthetic AAs could reduce environmental impacts through reduction of N and associated nitrogen oxide and ammonia emissions (Garcia-Launay et al., 2014; Reckmann et al., 2016). The specific environmental impacts of the supplementary synthetic amino acids were investigated using LCA by several authors (Eriksson, 2005; Garcia-Launay et al., 2014). The potential environmental effects of switching from conventional to precision feeding system in fattening pigs using LCA showed that precision feeding can be effective to improve environmental sustainability in pig production (Monteiro et al. 2016; Andretta et al., 2018; Pomar and Remus 2019).

The pig systems across the globe have often been investigated using LCA on the whole supply chain, including feed production and manure management, rather than partial system boundaries (McAuliffe et al., 2016). For instance, an LCA on three types of pig farming systems in France of good agricultural practices (GAP), organic agriculture (OA) and the red label (RL) was performed, and showed that RL is preferable for AP and EP (Basset-Mens and van der Werf, 2005). Dourmad et al., (2014) conducted an LCA to analyse four scenarios of intensive production (conventional), adapted for more extensive and welfare (adapted conventional), outdoor breeding (traditional) and organic production in Spain, Germany, France, Denmark and the Netherland. They reported lower global (LO, GWP and energy use) and local (AP and EP) impacts for the conventional system per kg live weight (LW) compared to the other systems. Some values of environmental impacts for producing one kg live pig at the farm gate were reported by de Vries and de Boer (2010) for GWP in the range of 2.3 to 5.0 kg CO_2-eq/kg LW; for AP in the range of 8 to 120 g SO_2-eq/kg LW; for EP in the range of 12 to 38 g PO_4-eq/kg LW; and for LO in the range of 4.2 to 6.9 m^2/kg LW, for typical European production farms. Mackenzie et al. (2015) applied LCA to account for uncertainty in the calculation of the environmental impacts of two western and eastern regional pig-farming systems of Canada. Reckmann et al. (2013) applied LCA to investigate the impacts of each life cycle stage of pig including farrowing, weaning and fattening, and showed that the highest environmental impacts came from the fattening stage. Recently, Ottosen et al. (2020), in a first study to incorporate genetics in pig LCA, evaluated the environmental impacts of changes in correlated genetic traits in pigs systems using LCA and showed higher importance for fattening growth rate and body protein-to-lipid ratio, and lesser importance for sow robustness and mortalities in reducing environmental impacts.

The LCA has been also applied at the diet level, as a tool for diet optimisation procedures. Following the integration of a diet formulation algorithm and life cycle inventory by Nguyen et al. (2012) and Moe et al. (2014) in an LCA, Garcia-Launay et al. (2014) utilised InraPorc®

as a module to simulate growth profiles of pigs fed different diets, along with a diet formulation algorithm to formulate diets for pigs with the single objective optimisation of minimizing GWP. To go one step further and predict the nutrient excretion of the diets once fed to the pigs, Mackenzie et al. (2016) developed a nitrogen excretion estimator to integrate to a diet formulation procedure. Moreover, to consider multiple impact categories in diet formulation and environmental optimisation, an environmental impact score was introduced and applied by Mackenzie et al. (2016). Finally, in 2018, Garcia-Launay et al. introduced a multiobjective diet formulation through integrating the diet cost and an environmental impact score of the diet in a unified objective function, which enabled to find the trade-off between diet cost and environmental impacts in the diet formulation.

Study	Scope (system boundary)	Functional unit
Van der Werf et al. (2005)	Raw material extraction and delivery of feed to the pig farm	1000 kg feed for pig consumption
Nielsen and Wenzel (2006)	Raw material extraction to the production of Ronozyme Phytase	1 kg Ronozyme Phytase
Dalgaard et al. (2007)	Crop production to delivery of pork to Port Harwich in Britain	1 kg live weight pig
Perez (2009)	Crop production to pig farm gate	1000 kg live weight pig
Lopez-Ridaura et al. (2009)	Manure storage to utilisation	1 m^3 raw pig slurry
Prapaspongsa et al. (2010)	Manure treatment to land application	1000 kg raw pig slurry
Mosnier et al. (2011)	Raw material extraction to the feed factory	1 kg feed at the feed factory gate
Meul et al. (2012)	Crop production to the production of compound feed	1000 kg compound feed at the feed factory gate
De Vries and Vinken (2012)	Manure storage to utilisation	1000 kg substrate added to the digester
Bayo et al. (2012)	Transport of slurry to receiving lands and subsequent utilisation	1 m^3 pig slurry
De Vries et al. (2013)	Liquid manure storage to manure application	1000 kg pig slurry
Wesnæs et al. (2013)	Storage of pig manure to manure application	1000 kg fattening pig slurry
Brockmann et al. (2014)	Storage of pig manure to manure treatment and/or application	1 m^3 pig slurry
Lijó et al. (2014)	Biomass production to digestate management including pig slurry as co-substrate	100 kWh electricity from biogas in a combined heat and power unit
Luo et al. (2014)	Feed production to slurry treatment and utilisation	1956 pig livestock units (1 livestock units = 500 kg)
Rodriguez-Verde et al. (2014)	Manure and co-substrate storage to treatment and utilisation	110,000 t/year pig manure providing 500 kWe at digester
Ten Hoeve et al. (2014)	Slurry storage to treatment and/or utilisation	1000 kg pig slurry

Table 1. Sample of LCA studies on pig production with different scopes and functional units related to pig feed and feeding products, and pig manure, reviewed by McAuliffe et al. (2016) plus more recent studies

Study	Scope (system boundary)	Functional unit
Cederberg et al. (2005)	Raw material extraction to the pig farm gate	1 kg of bone- and fat-free meat
Eriksson et al. (2005)	Feed production to the pig farm gate	1 kg growth between 29 and 115 kg
Basset-Mens and Van der Werf (2005)	Crop production to pig farm gate	1 kg live weight pig
Williams et al. (2006)	Crop production to pig farm gate	1000 kg carcass weight
Dalgaard et al. (2007)	Crop production to delivery of pork to Port Harwich in Britain	1 kg live weight pig
Perez (2009)	Crop production to pig farm gate	1000 kg live weight pig
Wiedemann et al. (2010)	Crop production to slaughterhouse	1 kg carcass weight at the meat processor gate
Halberg et al. (2010)	Crop production to pig farm gate	1 kg live weight pig
Nguyen et al. (2010)	Crop production to pig farm gate	1 kg live weight pig
Pelletier et al. (2010)	Crop production to pig farm gate	1 kg live weight pig
Nguyen et al. (2010)	Pig farming within the farm gate	1 kg live weight pig
Stone et al. (2011)	Antimicrobial production to manure management	Life cycle of 1 pig (7 kg - 111 kg market weight)
Nguyen et al. (2011)	Crop production to slaughterhouse gate	1 kg pork delivered from the slaughterhouse
Stephen (2012)	Crop production and rearing of the pig to slaughter weight	1 kg live weight pig
Stone et al. (2012)	Raw material extraction to manure management and utilisation	1 grown pig from 29 kg to 118 kg market weight
Devers et al. (2012)	Crop production to delivery of pork to Antwerp in Belgium	1 kg carcass weight
Dolman et al. (2012)	Crop production to pig farm gate	100 kg live weight pig
Ogino et al. (2013)	Feed and amino acid production to manure management	1 kg live weight pig from 1 marketed pig at 115 kg
Jacobsen et al. (2014)	Crop production to meat processor gate	1 kg deboned meat
Reckmann et al. (2013)	Crop production to slaughterhouse gate	1 kg pork slaughter weight
Dourmad et al. (2014)	Crop production to pig farm gate	1 kg live weight pig

Dourmad et al. (2014)	Cradle to farm gate	1 kg live weight pig
Garcia-Launay et al. (2014)	Cradle to farm gate	1 kg live weight pig
Mackenzie et al. (2015)	Cradle to farm gate	1 kg carcass weight
Mackenzie et al. (2016)	Cradle to farm gate	1 kg carcass weight
Monteiro et al. (2016)	Entire pig farming activity	1 kg of body weight gain
McAuliffe et al. (2016)	Cradle to farm gate	1 kg live weight pig
Cadéro et al. (2017)	Fattening unit	Each slaughtered pig
Ottosen et al. (2020)	Cradle to farm gate	1 kg live weight pig

Table 2. Sample of LCA studies on pig production with different scopes and functional units related to pig meat products, reviewed by McAuliffe et al. (2016) plus more recent studies

However, environmental impacts of improvement in feed efficiency of pigs through genetic selection, alone or combined with diet optimisation, has not been evaluated through a comprehensive cradle to farm gate LCA. Rather than performing LCA for an average or a typical representative of a group of pigs, individual LCA would allow to consider the variability of outcomes between pig profiles. Considering the variation of performance traits among individual pigs through performing individual LCA for a pig population could provide insights about the linkage between the traits and the environmental impacts to later define sustainable breeding goals and selection index.

For sustainability assessment, to find out how economic and environmental impacts are compromised in selection for feed efficiency, an economic life cycle assessment would be essential.

1.4 **Economic assessment**

The profitability is the most important aspect of pig farming for the farm owners. For economic assessment at the individual or farm level, an economic model is required. Variety of optimisations on different stages of pig supply chain have been assessed in terms of economy.

Optimisations in feeding and shipping strategies (Niemi, 2006; Davoudkhani et al., 2020), pig delivery weight (Leen et al., 2018; Nadal-Roig et al., 2019), dietary composition (Morel et al., 2012) have addressed some economic improvements in fattening pigs. Modelling for economic assessment of pig farm as a biological system, ie to obtain a bio-economical model, will be described in the next section.

Economic performance of a pig production system, resulting from biological processes, expressed as profit per pig (Houška et al., 2004) or cost per unit per production (de Vries, 1989), can be evaluated with bio-economic models (Kragt, 2012). They simulate the interaction between the economic and biological components and provide a general perspective of a production system (Ali et al., 2018), while biological parameters are at the core of the model (Hanson, 2019). A bio-economic model can be developed and classified according to methodological approaches, type of programing and methods. In the objective approach, a system of equations is applied to represent the internal links between the component of the production system (Kragt, 2012; Michaličková et al., 2016). In the subjective approach, the economic value of a trait is obtained from required genetic gain for that trait (Simm et al., 1987). The normative approach, which is based on actual data, is preferable to the positive approach, which relies on huge amount of historical data (Michaličková et al., 2016). A bio-economic model can also rely on a stochastic approach, in which the input parameters are described by their mean and variability (Jones et al., 2004), a deterministic approach which is based on the average values of the input parameters (Brascamp, 1978), or a combination of stochastic and deterministic approaches (Michaličková et al., 2016). Linear programing (Fisher, 2001) is more popular in bio-economic studies (Berentsen et al., 1997; Acs et al., 2007; Janssen and Ittersum, 2007) than dynamic programing (Veerkamp et al., 1995).

The application of bio-economic models has been expanded to cover farm management and environmental impacts. In the concept of bio-economic model, Janssen et al., (2007) proposed the term of bio-economic farm model (BEFM) to integrate economic, management and biological components of a production system. The BEFM is a useful tool for evaluating ex-post or making ex-ante economic assessments of outcomes of changes in the farm systems in terms of policy, technology or farm plan (Janssen et al., 2010). The BEFMs could be classified as mechanistic or empirical, normative or positive, simple or complex, generic or tailored-made, global or country-based, linear and non-linear programing based (Ivković et al., 2010; Janssen et al., 2010; Calderón Díaz et al., 2019). There, a mechanistic model is developed on exiting theory and knowledge of farms occurring processes, while an empirical model is built based on the patterns found in the historical observed data through extrapolation (Austin et al., 1998).

If the bio-economic model is expressed in a single equation, it is known as a profit function (Quinton et al., 2006; Wolf et al., 2013). Compared to multiple equation bio-economic model, it is simpler in interpretation of the results (Dekkers et al., 2004). A profit function can quantify the relative importance of performance traits for the profit of the production system, which can be used for instance as economic weights to derive a selection index. In this case, the economic weight of the trait, which represents the change in profit due to a change in the performance trait (per unit or per standard deviation) keeping all other traits constant, can be calculated directly from the first derivative of the profit function with respect to the other traits (Moav and Hill, 1966; Brascamp et al., 1985; Houška et al., 2004; Knap, 2005; Besson et al., 2014, 2020). Through this, Hermesch et al., (2003, 2014) and Amer et al. (2014) calculated economic weights of maternal traits of sows and performance and survival traits of fattening pigs.

Generally, to design of breeding goals for genetic selection, the economic weights of the traits affecting profit are derived from profit function, excluding environmental and social costs (Ali et al., 2017). More sustainable pig production farms are expected from the pushing lever of policy regulation (obliged, subsidised, rewarded or punished), and the pulling lever of consumer demand for sustainable pork. Considering a joint economic-environment sustainable breeding goal, rather than a single economic breeding goal, may modify the choice of targeted traits in breeding goals and their weights, as well as the structure of the selection index. In other words, taking into account the environmental costs may re-rank the traits and offer alternative breeding goal and selection direction in favour of traits correlated to sustainable pig production. As another expansion of the application of bio-economic models, beyond being used for economic assessment and genetic index, a bio-economic model can be recruited to assess jointly the economic and environmental impacts (Falconer and Hodge, 2001; Wossink et al., 2001; Quinton et al., 2006; Janssen and Ittersum, 2007). For example, Ali et al., (2018) have considered environmental impacts as costs in a bio-economic model of pig production, by monetising the environmental impact of greenhouses gas (GHG) based on the shadow price of

CO_2. However, due to uncertainty on the cost of all categories of environmental impacts, and lack of universal and standardised guidelines on that matter, monetising of environmental impacts is not a conventional approach.

Accordingly, economic and environmental assessments of pig production should be performed through separate bio-economic and LCA models. To assess the economic impacts of pig selection for feed efficiency, alone or combined with diet optimisation, a bio-economic model should be developed with similar assumptions and flexibility to allow consistent joint evaluations.

1.5 **Thesis aims**

The aim of this thesis was to evaluate breeding strategies for feed efficiency in terms of environmental impacts and economy, to get insights about the consequences of selection for feed efficiency, alone or combined with diet optimisation. The ultimate goal was to identify levers for future sustainable scenarios for pig production. This project was developed in the frame of the SusPig project, an ERANet SusAn project funded in 2017 via the French National Research Agency.

The aim was fulfilled through pursuing the following objectives:

1- Environmental assessment at the individual level to evaluate the genetic selection for feed efficiency. To comply this objective, an individual trait-based LCA model was developed, flexible enough for performing individual LCA (Chapter 2).

2- Environmental optimisation of combinations of genetic line and diets, and corresponding LCA assessment. To fulfil this objective, an approach for diet optimisation for multiple environmental and economic objectives was developed to meet genetic nutritional requirements (Chapter 3).

3- Economic and environmental assessment and optimisation of the combinations of genetic line and diet. For economic assessment at the individual level, an individual trait based bio-economic model was developed based on a profit model (Chapter 4).

These different objectives will be separately developed in each of the three next chapters, followed by a general discussion about results, findings, challenges and conclusions.

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Chapter 2 **Environmental assessment of pig selection for feed efficiency**

2.1 **Introduction**

This chapter aimed to develop an LCA model that could be used for individual assessment, and quantify how pig selection for feed efficiency has been effective in improvement of environmental impacts of pig production. As an alternative index to select for feed efficiency, RFI has been proposed by Koch et al. (1963) and its impacts on different aspects of production performance were reported in several studies (see the literature review for details). However the consequences of selection for reduced RFI on environmental impacts were not investigated through a holistic life cycle environmental assessment. Earlier studies considering feed efficiency mainly evaluated the joint reduction of environmental impacts and FCR, as a main feed efficiency indicator, related to changes in management or feeding practices (Hauschild et al., 2012; Pomar and Remus 2019; Monteiro et al., 2016), and ignored the innate performance individual variability between pigs. The aim was fulfilled through developing an LCA model and running individual LCA on pigs from two genetic lines divergently selected for RFI. Working from individual performances of pigs from divergent lines ensures that most of the differences observed between the groups arise from genetic differences, but also provides references about the variability of the environmental impacts and their correlations with the original performances.

The parametric LCA model was developed with the SimaPro software, in which fattening individual growth performances were used as input parameters to the model, which enabled to perform individual trait based LCA. From this first development step, the InraPorc® software was incorporated as a preliminary module of the full model, for simulating growth performance traits from individual pig nutrient requirement profiles. This step guarantied consistency with using the NE system as the core of the LCA model, and provided flexibility for further combination of genetic and diet optimisation scenarios in next chapters.

This work was communicated at EAAP (2019), in Ghent (Belgium) as a poster (chapter 6, scientific communications), and is published in the journal Animal (2020). The supplementary material associated to the paper is provided at the end of this chapter.

2.2 Paper I. Evaluating environmental impacts of selection for residual feed intake in pigs

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Evaluating environmental impacts of selection for residual feed intake in pigs

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Short title: Environmental impacts in feed efficient pigs

Abstract

To identify a proper strategy for future feed efficient pig farming it is required to evaluate the ongoing selection scenarios. Tools are lacking for the evaluation of pig selection scenarios in terms of environmental impacts to provide selection guidelines for a more sustainable pig production. Selection on residual feed intake (RFI) has been proposed to improve feed efficiency and potentially reduce the associated environmental impacts. The aim of this study was thus to develop a model to account for individual animal performance in life cycle assessment methods to quantify the responses to selection. Experimental data were collected from the fifth generation of pig lines divergently selected for residual feed intake (RFI) (low line, more efficient pigs, LRFI; high line, less efficient pigs HRFI). The average feed conversion ratio (FCR) and daily feed intake of LRFI pigs were 7% lower than the average of HRFI pigs ($P < 0.0001$). A parametric model was developed for life cycle assessment (LCA) based on the dietary net energy fluxes in a pig system. A nutritional pig growth tool, InraPorc®, was included as a module in the model to embed flexibility for changes in feed composition, animal performance traits and housing conditions, and to simulate individual pig performance. The comparative individual based LCA showed that LRFI had an average of 7% lower environmental impacts per kg live pig at farm gate than HRFI ($P < 0.0001$) on climate change (CC), acidification potential (AP), freshwater eutrophication potential (EP), land occupation (LO) and water depletion (WD). High correlations between FCR and all environmental impact categories (> 0.95) confirmed the importance of improvement of feed efficiency to reduce environmental impacts. Significant line differences in all impact categories and moderate correlations with impacts (> 0.51) revealed that RFI is an effective measure to select for improved environmental impacts, despite lower correlations than FCR. Altogether, more

optimal criteria for efficient environmentally friendly selection can then expected through restructuring selection indexes from an environmental point of view.

Keywords: feed efficiency, life cycle assessment, growth performance traits, selection by genetics, net energy flux

Implications

Selection on feed efficiency results in large correlated reductions of the environmental impacts of pig production; with gross feed efficiency having more impact than net feed efficiency. Our pig-based evaluation model will allow definition of selection criteria that result in even larger reductions in environmental impact.

Introduction

Beyond being an economic bottleneck, feed greatly contributes to the environmental impacts of pig farming (McAuliffe *et al*., 2016). Improvement in feed efficiency is a major goal for pig production sustainability, because it reduces environmental fluxes associated with feed production (Nguyen *et al*., 2011) and reduces the amount of effluent per pig as a result of mass balance (Ali *et al*., 2018). Feed efficiency, which is usually inversely expressed as feed conversion ratio (FCR), stands for the body weight gain per unit of feed consumed. Selection for FCR, directly or via increased growth rate or reduced fatness, has been very effective to improve feed efficiency in the past. However, as a ratio, FCR is closely correlated with production traits and selection on this trait has uncontrolled effects on the components of the ratio (Saintilan *et al*., 2013). In 1963, Koch *et al*. introduced a more targeted indicator for net feed efficiency, residual feed intake (RFI). The RFI, which is a linear combination of traits, is moderately heritable in pigs (Saintilan *et al*., 2013) and is defined as the difference between observed feed intake and the feed intake expected from individual maintenance and production requirements. Among the range of approaches for measuring feed efficiency, RFI is increasingly becoming the measure of choice in some species (Kenny *et al*., 2018). Improving animal feed efficiency is possible at two stages. The first stage, which arises from the interaction between feed and animal in the digestive tract, is to improve conversion of the feed gross energy (GE) into metabolizable energy (ME). The second stage is to improve the partitioning of uptaken energy between maintenance and tissue accretion through protein and lipid deposition (Nguyen *et al*., 2005). Improving feed efficiency through selection based on RFI essentially corresponds to the latter (Gilbert *et al*. 2017). Separate selection for RFI has been investigated and impacts on production performance reported (Gilbert *et al*., 2007; Cai *et al*., 2008), as well as on sow reproduction and piglet traits (Gilbert *et al*., 2012; Young *et al*., 2016). However, to date, its impacts have not been thoroughly assessed from an environmental viewpoint due to lack of an appropriate model. To quantify environmental impacts, several studies using life cycle assessment (LCA) examined the environmental burdens of different pig production options (Garcia-Launay *et al*., 2014; Mackenzie *et al*., 2015; McAuliffe *et al*., 2017). The aim of the present study was to develop a model adapted to the evaluation of pig selection strategies and use it to estimate the environmental impacts of selection for RFI, through comparative life cycle assessment of two lines of pigs divergently selected for RFI.

Material and methods

Experimental data

The experimental data were obtained from the fifth generation of Large White pigs divergently selected for RFI. The selection process and results concerning low RFI (LRFI, more efficient pigs) and high RFI (HRFI, less efficient pigs) lines are reviewed in Gilbert *et al*. (2017). The present dataset includes 60 male pigs in the LRFI line and 58 male pigs in the HRFI line. Growing pigs had *ad libitum* access to a one phase conventional diet (Table 1). The experimental data were collected from birth to slaughter. Body weight (BW) was recorded at birth, at weaning (average 28 days of age), at the beginning of the fattening period (10 weeks of age), at 11, 15, 19, 23 weeks of age, and at the end of the test (target BW 115 kg). During the fattening period, data on individual daily feed intake (DFI) recorded on ACEMA 64 automatic feeders (ACEMO, Pontivy, France) were available, and back fat thickness (BFT) was measured by ultrasounds on live animals at 23 weeks of age, using an ALOKA SSD-500 echograph (Aloka, Cergy Pontoise, France). From these records, FCR and RFI were computed as described in Gilbert *et al*. (2007). For LRFI and HRFI sows/litters, the mean values of age at farrowing and weaning, sow BW and BFT before farrowing and at weaning, lactation DFI, number of total born, still born, weaned piglets, piglet BW at birth and at weaning and weaning age, were taken from the experimental data presented in Gilbert *et al*. (2012).

Table 1 Ingredients, chemical composition and nutritional value of the experimental diet of pig lines.

Item	Quantity
Ingredient, g/kg	
Barley	409
Soft wheat	327
Soybean meal (48 % CP)	202
Sunflower oil	23
L-Lysine HCL	3.5
L-Threonine	1.4
L-Tryptophane	0.3
DL-Methionine	0.9
Salt	4.5
Calcium carbonate	11
Dicalcium phosphate	12
Oligo vitamins	5
Chemical composition, g/kg	
Ash	58.5
Dry matter	877.7
Organic matter	819.2
Crude protein	172.3
Starch	411.9
Gross energy (MJ/kg)	16.22
NDF	141.7
ADF	47.4
Crude Fibre	38.1
Residue	163
Calcium	9.97
Phosphorus	6.21
Nutritional value	
NE[1] (MJ/kg)	9.70
ME[1] (MJ/kg)	13.09
Std.dig.Lysine[2] (g/kg)	9.83

[1] were calculated according to the method of Sauvant *et al*. (2004); NE = net energy; ME = metabolisable energy; [2] standardised ileal digestible Lysine.

Goal, scope and framework of the environmental assessment

A ‘cradle-to-farm-gate’ system boundary was chosen, including feed production, manure management and the entire pig production system comprising reproducing sows and their piglets, post-weaning and fattening pigs. One kg of live weight (LW) of pig at the farm gate was used as the functional unit with the goal of comparing the environmental impacts between the HRFI and LRFI lines. To implement LCA, all the materials and energy consumed in the production of one functional unit of the system have to be included in the life cycle inventory (LCI), in addition to all excretions and emissions to the environment. The LCI needs to consider all the processes that take place inside the system boundary. To obtain a flexible and predictive model for daily feed intake, it was required to switch from the mass context of the data recording to the energy context for modelling. Due to the pigs’ ability to adapt their feed intake to the net energy (NE) concentration of different diets (Quiniou and Noblet, 2012), the model was developed based on the daily net energy supply during fattening to allow prediction for different diet compositions and guaranty generality. Our model was consequently developed based on NE for the fattening period and metabolisable energy (ME) for reproducing sows, to estimate the flux of dietary energy which propagates through all individual pigs within the system boundary (Figure 1).

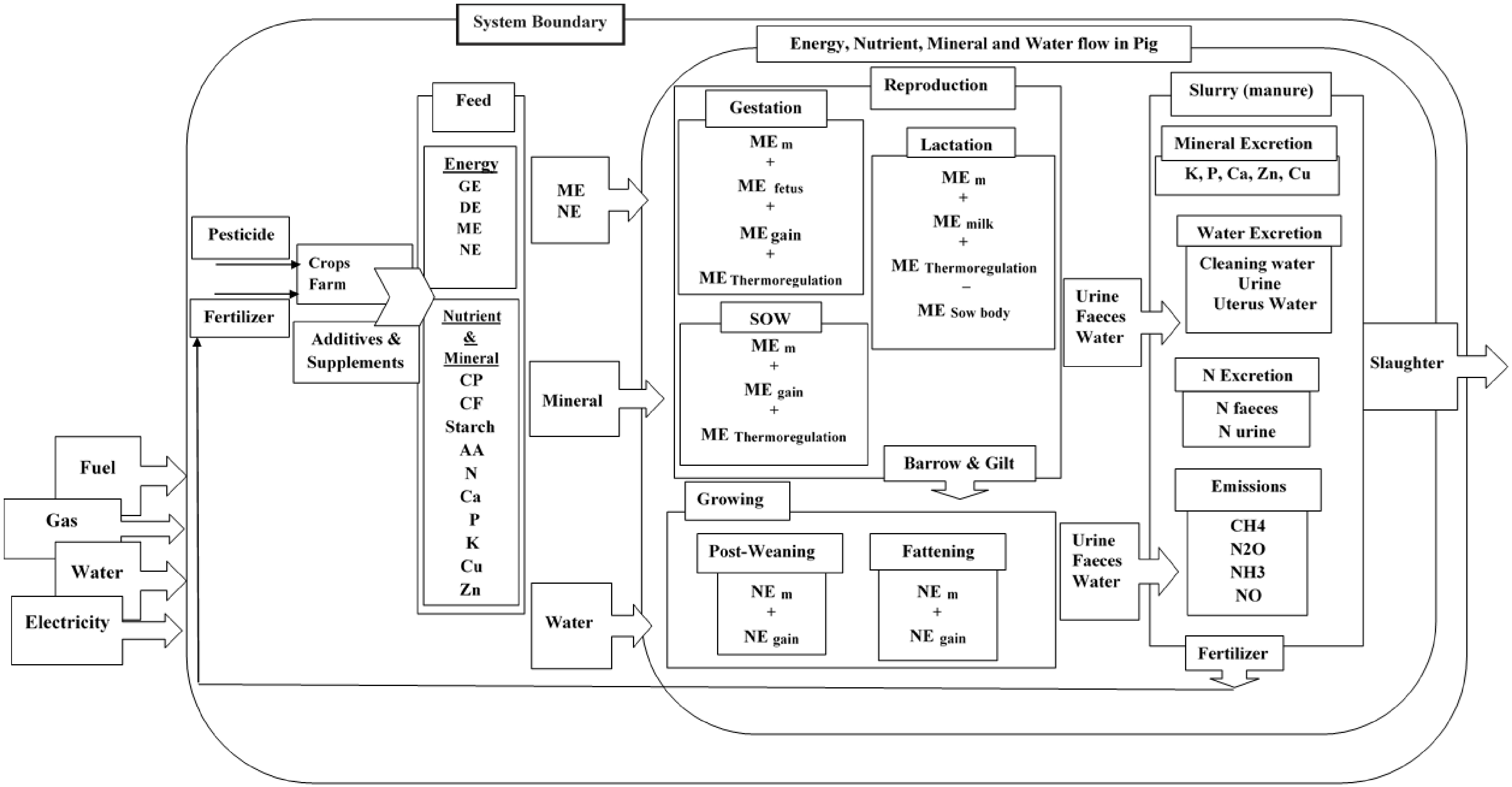

Figure 1 Scheme of the system boundary, which includes the entire pig farm, feed production processes and manure management.

GE = gross energy; DE = digestible energy; ME = metabolisable energy; NE = net energy; ME_m = metabolisable energy required for maintenance; NE_m = net energy required for maintenance; NE_{gain} = net energy required for gain; CP = crude protein; CF = crude fiber; AA = amino acid; N = nitrogen; Ca = calcium; P = phosphorus; K = potassium; Cu = copper; Zn = zinc.

Model structure

The model consists of six modules with distinct functions.

Feeding plan module. InraPorc®, which is a model and software designed to simulate the performance response of pigs to different nutritional strategies (van Milgen *et al*., 2008; Dourmad *et al*., 2008), was incorporated in the LCA model to benefit from its features. It contains the licensed INRA-AFZ database of characterised feed ingredients (Sauvant *et al*., 2004) as an embedded library. This library distinguishes different nutritional values depending on the animal physiological status (sows and growing pigs). In the feeding sub-module, the composition of the diet and the feeding plan (rationing and sequencing plan) during the different periods of the animal's lifetime were defined based on experimental data. The outcome of this sub-module is the chemical compositions and nutritional values of the diets, based on the INRA-AFZ database.

Animal profile module. Each animal profile is the compilation of the feeding plan, housing conditions, experimental data, net energy system, and a final calibration in InraPorc®. The Gamma function was used to express *ad libitum* feed intake because of its flexibility which enables it to adjust to changes in feed intake and body weight (van Milgen *et al*., 2008). The daily *ad libitum* feed intake and NE of the feed characterised the animal daily net energy requirements. InraPorc® was used to establish the individual profiles for each pig separately in the lines during the fattening period (day 68 to day 179), based on the animal's individual data, which were recorded daily, as previously proposed by Saintilan *et al*., 2015. The average profiles for groups of sows and their piglets were defined separately in InraPorc® based on experimental data on the average HRFI and LRFI sows/litters performance summarised in Gilbert *et al*. (2012). The outcome of this module is the predicted growth performance (ADG, ADFI), protein and lipid deposition during fattening (PD and LD, respectively), the protein to lipid ratio of the body (BP/BL ratio), and mineral excretions of the pigs. As InraPorc® was not designed to model the performance of animals during post-weaning, a calculation module was developed in R to estimate the excretions and emissions during the post-weaning period (28 days to 10 weeks of age) according to Rigolot *et al*. (2010a and 2010b).

Emission and excretion module. To calculate the emissions and excretions, and the slurry composition, three sub-modules were developed in R for the sow-litter, post-weaning and fattening stages. The average performance data was used for the sow-litter stage and the individual performance data were used for the post weaning and fattening stages. The components of the excreta (dry matter (DM), organic matter (OM), nitrogen (N), phosphorus (P), potassium (K), copper (Cu), and zinc (Zn)) were calculated using the mass-balance approach, as the difference between nutrients taken up from the feed and the nutrients retained in the body. Emissions of enteric methane (CH_4), nitrogen mono oxide (NO), nitrous oxide (N_2O), ammonia (NH_3), and carbon dioxide (CO_2) during housing were calculated according to Rigolot *et al*. (2010a and 2010b). Subtraction of N excretion and gaseous N lost in housing determined the quantity of N at the beginning of manure storage (Garcia-Launay *et al*., 2014).

A sub-module was developed to estimate emissions, leaching, and runoff during manure storage and application in the field. The NH_3 emissions during outside storage were calculated according to the emission factors recommended by Rigolot *et al*. (2010b). The NO_x emissions were calculated according to Nemecek *et al*. (2004). Methane emissions from manure during storage were calculated using guidelines by the intergovernmental panel on climate change IPCC (2006). Direct and indirect emissions of N_2O and NH_3 during spreading of slurry were calculated according to IPCC (2006).The value of the manure as a replacement for synthetic fertiliser was considered according to the mineral fertiliser equivalency of 75% for N (Nguyen *et al*., 2010) and 100% for P and K (Nguyen *et al*., 2011).

Water, energy expenditure and transport modules. The model linked drinking water to feed intake according to the Institut de la Filière porcine (IFIP) report on typical French farms (IFIP, 2014), with water to feed ratios of 4.5, 4.0, 2.5, and 2.7 for lactating, gestating, post weaning, and fattening pigs, respectively. Cleaning water was estimated at 2 300 litres per sow and 30 litres per fattening pig according to IFIP (2014) and Rigolot *et al*. (2010a). In addition, the energy expenditure link to the functional unit was 0.42 kWh per kg live weight, and was broken down into electricity, oil, and gas components, according to IFIP (2014). Transport of feed was calculated as a coefficient of feed intake. Linking water and transport to feed intake made the model sensitive to feed efficiency for further sensitivity and uncertainty analyses.

Life cycle impact assessment

An individual LCA was conducted for each pig in the LRFI and HRFI lines through incorporating its own experimental recorded traits and the traits obtained from InraPorc® in the LCA model. The outputs of the LCA model were the impact categories of climate change (CC), terrestrial acidification potential (AP), freshwater eutrophication potential (EP), land occupation (LO), and water depletion (WD). For impact analyses, the ReCiPe Midpoint 2016 (H) V1.13 (Huijbregts et al., 2016), one of the most recently updated life cycle impact assessment methods, accompanied with the Ecoalim (Wilfart *et al*., 2016) and Ecoinvent (Wernet *et al*., 2016) inventory databases, were used. The equivalency factors for the impact categories were assigned according to the factors recommended in the ReCiPe method. All environmental impact assessments were implemented in the SimaPro V8.5.4.0 on the MEANS (MulticritEria AssessmeNt of Sustainability) platform (http://www.inra.fr/means).

The line impact differences were tested with a T-test, and impacts were declared significantly different for $P < 0.05$. In addition, correlations between performances and environmental impacts were calculated within lines, for a better understanding of the relationships between the components.

Uncertainty analysis

Monte Carlo simulations is an approach, available in SimaPro V8.5.4.0, to quantify the effects of the uncertainties in the model parameters on the estimated environmental impacts: by resampling the parameter values based on assumptions about their uncertainties, a confidence interval for each impact can be obtained. In addition, the Ecoinvent LCA databases, which are embedded in SimaPro V8.5.4.0, provide quantitative uncertainties for parameters in most of its processes, mainly with lognormal distributions (Ivanov *et al*., 2019). To incorporate the intended traits in the LCA, a trait based model was developed based on the growth performances equations presented by van Milgen *et al*. (2008) (also applied in InraPorc®) and linked to the emissions and excretions according to Rigolot *et al*. (2010a and 2010b). The quantities of all feed ingredients were linked to the related traits, such as ADFI and fattening duration, by considering their incorporation rate in the diet. This integrated and connected model made it possible to perform uncertainty and sensitivity analyses in SimaPro. To evaluate the impact of the LCA model parameter uncertainty on the results, the line mean values of the performance traits (ADFI, FCR, ADG, BP/BL ratio, PD, fattening duration, BP and BL at slaughter, and BFT) were extracted from experimental data and InraPorc® outputs, and used as inputs for the uncertainty analysis. Then, parallel Monte Carlo simulations were run on the two lines jointly to evaluate the sensitivity of the impact categories to the model parameter uncertainties.

Sensitivity analysis

Sensitivity analysis is the study of the relative importance of the different input parameters in the model outputs. To perform a sensitivity analysis, it is necessary to have a parametric model in which all the parameters are mathematically interlinked (supplementary material S1). To perform the sensitivity analysis on animal performance traits, related traits had to be incorporated in the model as direct input parameters, accompanied by their distributions. In this way, any change in animal traits propagates through the model and affects the appropriate material, process, emission and excretion sub-inventories in the LCI.

A one-at-a-time (OAT) sensitivity analysis, an appropriate approach for limited parameter and linear LCA models, was conducted based on the upper and lower bounds of the 95% confidence interval (CI) (±2SD) of the main production trait distributions. The LCA model was considered sensitive to a trait if a change in any impact value was greater than 5% after a change to the upper and lower bounds of the intended trait compared to the initial impact value (Mackenzie *et al*., 2015). The OAT sensitivity analysis of the traits made it possible to identify the best candidate traits for improvement in the corresponding environmental impact categories.

Results

Traits comparison between lines

Prior to LCA, a statistical review of the experimental data provided a general overview on the variation of growth performance traits between the two lines. The mean growth performance traits in the two lines were compared with a Student's t test (Table 2), as well as the trait predictions from InraPorc®. The feed conversion ratio differed significantly between the lines (-130 g/kg gain for LRFI compared to HRFI pigs, $P < 0.001$), as did the average daily feed intake ($P < 0.0001$), and RFI ($P < 0.01$). The lines also differed in their average daily gain ($P < 0.05$), age at slaughter ($P < 0.05$), fattening duration ($P < 0.05$), but not in body weight at slaughter ($P = 0.43$). The two lines had similar protein content at slaughter ($P = 0.32$), but not lipid content, backfat thickness and LMP ($P < 0.0001$), leading to a difference in the BP to BL ratio ($P < 0.0001$).

Table 2 Growth performance traits and InraPorc® estimations of body composition of pigs in low residual feed intake (LRFI) and high residual feed intake (HRFI) lines.

	Mean LRFI	Mean HRFI	Mean differences (%)	SD LRFI	SD HRFI	*P*[3]
Traits records[1]						
BW birth (kg)	1.50	1.53	1.98	0.20	0.33	0.63
BW weaning (kg)	8.51	9.12	6.92	1.18	1.22	0.007
BW initial-fattening (kg)	28.7	29.9	4.09	4.06	4.70	0.14
ADG fattening (kg/d)	0.80	0.83	3.68	0.080	0.071	0.047
ADFI fattening (kg/d)	1.97	2.15	8.73	0.21	0.19	<0.0001
FI fattening (kg)	214.3	225.5	5.09	18.3	28.1	0.011
FCR fattening (kg /kg gain)	2.45	2.58	5.16	0.16	0.18	<0.0001
RFI (g/d)	-36.1	35.1	197.1	130.8	104.8	<0.01
ECR fattening (MJ /kg gain)	23.78	25.03	5.45	1.63	1.77	<0.0001
Fattening duration (days)	109.6	104.9	4.38	12.00	9.34	0.02
Age at slaughter (days)	181.1	177.0	2.28	10.00	7.44	0.011
BW slaughter (kg)	116.3	117.4	0.94	7.04	8.30	0.43
InraPorc® estimations[2]						

PD fattening (g/day)	133.0	136.9	2.88	13.9	15.4	0.38
Carcass weight (kg)	91.9	92.7	0.86	5.56	6.55	0.43
Lipid weight at slaughter (kg)	22.4	25.7	13.72	3.28	4.11	<0.0001
BFT slaughter (mm)	15.3	16.5	7.54	1.20	1.49	<0.0001
Protein weight at slaughter (kg)	18.6	18.4	1.08	1.31	1.34	0.32
LMP (%)	60.9	58.8	3.50	2.00	2.01	<0.0001
LMC (kg)	55.9	54.5	2.53	3.93	3.72	0.042
BP/BL at slaughter	0.85	0.73	15.18	0.13	0.13	<0.0001

[1] Traits recorded in pigs; BW = body weight; ADG = average daily gain; ADFI = average daily feed intake; FI = total feed intake; FCR = feed conversion ratio; RFI = residual feed intake; ECR = energy conversion ratio

[2] Outcomes from InraPorc®; PD = protein deposition; BFT = back fat thickness; LMP = lean meat percentage; LMC = Lean meat content; BP/BL = ratio of body protein weight/ Body lipid weight at slaughter

[3] *P* were calculated via a t-test on the line effect.

Individual life cycle assessment on the low and high residual feed intake lines

The five impact categories were calculated for 116 pigs through individual LCA. The outcomes of individual LCA on the LRFI and HRFI lines in the five impact categories are summarised in Table 3. The values in all impact categories were lower in the LRFI line than in the HRFI pigs (P < 0.0001): CC (2.60 vs 2.77 kg CO_2-eq), AP (44.5 vs 48.1 gr SO_2-eq), EP (3.35 vs 3.63 g P-eq), LO (4.19 vs 4.45 m^2a), and WD (0.044 vs 0.047 m^3). The minimum and the maximum difference between HRFI and LRFI were in land occupation (6.01%) and eutrophication (8.02%), respectively, and the average difference for the five impact categories was 7%. To test the relative contributions of the different processes involved in the LCA, the impact categories were segmented into feed, housing and manure, and on-farm water and energy (electricity, gas…) use. Their percentage contribution to each segment is shown in Figure 2 for the two lines combined, as there were limited line differences. Feed had the maximum share in the impact categories of CC (72%), LO (100%) and WD (79%), whereas housing and manure had the biggest share in EP (66%) and AP (60%). On-farm water and energy had relevant impacts only in WD (28%).

Table 3 Five impact categories calculated per kg pig weight at farm gate by the life cycle assessment (LCA) model based on ReCiPe 2016 Midpoint (H) V1.13 method for low residual feed intake (LRFI) and high residual feed intake (HRFI) lines.

Impact category	Unit	Mean HRFI	Mean LRFI	Difference (%)	SD LRFI	SD HRFI	*P*[1]
Climate change	kg CO_2 eq	2.77	2.60	6.33	0.12	0.11	<0.0001
Acidification	g SO_2 eq	48.1	44.5	7.77	2.91	2.61	<0.0001
Eutrophication	g P eq	3.63	3.35	8.02	0.22	0.20	<0.0001
Land occupation	m^2a	4.45	4.19	6.01	0.19	0.18	<0.0001
Water depletion	m^3	0.047	0.044	6.59	0.0018	0.0017	<0.0001

P = phosphorous; m^2a = area time; m^3 = cubic meter;

[1] *P* were calculated via a t-test on the line effect.

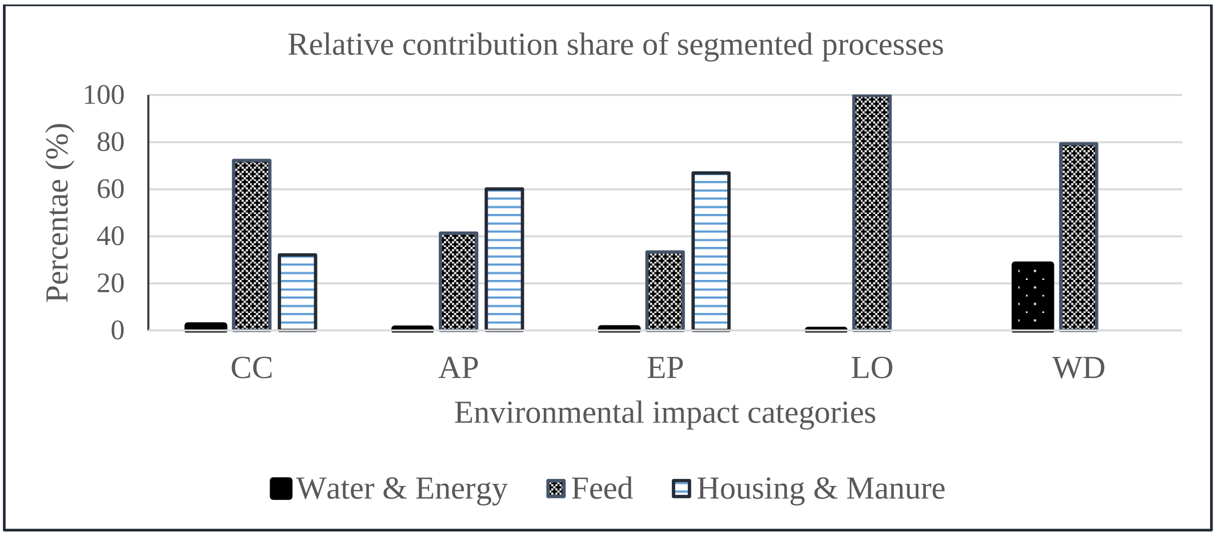

Figure 2 Relative contribution of the segmented pig farming processes within the system boundary of life cycle assessment (LCA), in the five impact categories. Feed ingredients are clustered as 1. feed; 2. emissions and excretion during housing, manure storage and spreading are clustered as housing & manure; 3. On-farm consumption of water and energy are clustered as on-farm water & energy. CC = climate change; AP = acidification potential; EP = freshwater eutrophication potential; LO = land occupation; WD = water depletion.

The correlations between impact categories and performance traits, obtained from experimental data (ADG, FCR, ADFI and RFI) and traits simulated by InraPorc® (BP/BL ratio, BFT, PD, BL, BP) are reported in Table 4. Based on the 95% confidence interval of the correlation estimations, no line differences were evident, except for BP with EP and AP, with a higher negative correlation in LRFI line. All impact categories were highly correlated to FCR, with values higher than 0.96 for both lines. All impact categories had also moderate to high correlations with RFI (from 0.51 in HRFI pigs to 0.74 in LRFI pigs), and BP/BL ratio (values between -0.68 and -0.85). All impact categories are highly correlated to BFT, BP, BL and PD, with the absolute values higher than 0.48 for both lines except BP for HRFI line which correlations had lower magnitude with AP and EP.

Table 4. Phenotypic correlations (95% confidence interval) of five environmental impact categories with the recorded traits in the low residual feed intake (LRFI) and high residual feed intake (HRFI) pig lines.

Trait[1]	CC	AP	EP	LO	WD
LRFI line					
ADG Fattening	-0.32	-0.35	-0.35	-0.31	-0.30
	(-0.53;-0.07)	(-0.56;-0.1)	(-0.56;-0.11)	(-0.52;-0.06)	(-0.52;-0.05)
FCR Fattening	0.97	0.96	0.96	0.98	0.97
	(0.95;0.98)	(0.94;0.98)	(0.93;0.98)	(0.96;0.99)	(0.95;0.98)
RFI (g/d)	0.73	0.74	0.75	0.71	0.71
	(0.58;0.83)	(0.6;0.84)	(0.61;0.84)	(0.56;0.82)	(0.55;0.82)
ADFI Fattening	0.29	0.26	0.25	0.30	0.31
	(0.03;0.51)	(0.00;0.48)	(0.00;0.48)	(0.05;0.52)	(0.06;0.52)
BP/BL ratio	-0.68	-0.68	-0.68	-0.68	-0.68
	(-0.80;-0.51)	(-0.80;-0.51)	(-0.79;-0.51)	(-0.80;-0.51)	(-0.80;-0.51)
BFT	0.58	0.59	0.58	0.61	0.60
	(0.39;0.73)	(0.39;0.73)	(0.38;0.73)	(0.42;0.75)	(0.41;0.74)
PD	-0.58	-0.61	-0.62	-0.57	-0.56
	(-0.73;-0.38)	(-0.75;-0.42)	(-0.75;-0.43)	(-0.72;-0.36)	(-0.71;-0.35)
BL	0.58	0.59	0.58	0.61	0.60
	(0.39;0.73)	(0.39;0.73)	(0.38;0.73)	(0.42;0.75)	(0.41;0.74)
BP	-0.56	-0.55	-0.55	-0.51	-0.52
	(-0.71;-0.36)	(-0.7;-0.34)	(-0.71;-0.34)	(-0.68;-0.29)	(-0.69;-0.31)
HRFI line					
ADG Fattening	-0.47	-0.37	-0.36	-0.41	-0.44
	(-0.65;-0.23)	(-0.57;-0.12)	(-0.57;-0.11)	(-0.61;-0.17)	(-0.63;-0.21)
FCR Fattening	0.98	0.99	0.98	0.99	0.98
	(0.97;0.99)	(0.98;0.99)	(0.97;0.99)	(0.99;1.00)	(0.97;0.99)
RFI (g/d)	0.51	0.55	0.55	0.53	0.51
	(0.29;0.68)	(0.34;0.71)	(0.34;0.71)	(0.31;0.69)	(0.29;0.68)
ADFI Fattening	0.21	0.31	0.32	0.27	0.23

	(-0.06;0.44)	(0.06;0.53)	(0.06;0.53)	(0.01;0.49)	(-0.03;0.46)
BP/BL ratio	-0.74	-0.83	-0.83	-0.77	-0.74
	(-0.84;-0.59)	(-0.90;-0.72)	(-0.9;-0.73)	(-0.86;-0.64)	(-0.84;-0.59)
BFT	0.48	0.62	0.62	0.55	0.51
	(0.26;0.66)	(0.42;0.75)	(0.43;0.76)	(0.34;0.71)	(0.28;0.68)
PD	-0.66	-0.59	-0.58	-0.61	-0.63
	(-0.79;-0.48)	(-0.73;-0.38)	(-0.73;-0.38)	(-0.75;-0.42)	(-0.77;-0.45)
BL	0.48	0.62	0.62	0.55	0.51
	(0.26;0.66)	(0.42;0.75)	(0.43;0.76)	(0.34;0.71)	(0.28;0.68)
BP	-0.16	-0.03	-0.03	-0.07	-0.11
	(-0.40;0.11)	(-0.29;0.23)	(-0.28;0.24)	(-0.32;0.20)	(-0.36;0.15)

[1]Traits recorded in pigs; ADG = average daily gain; ADFI = average daily feed intake; FCR = feed conversion ratio; RFI = residual feed intake; Outcomes from InraPorc®: PD = protein deposition; BFT = back fat thickness; BP/BL = ratio of body protein weight/ Body lipid weight; Outcomes from life cycle assessment: CC = climate change; AP = acidification potential; EP = freshwater eutrophication potential; LO = land occupation; WD = water depletion

Uncertainty analysis

A parallel Monte Carlo simulation study based on the mean values of the traits was run on both lines. The results are graphically represented in Figure 3 in five impact categories. In 100% of the simulations for CC, AP, EP, LO, and 61% for WD, the LRFI line had less impacts than the HRFI line, indicating that the line differences are not sensitive to the uncertainty of the model parameters imbedded in SimaPro, except for WD.

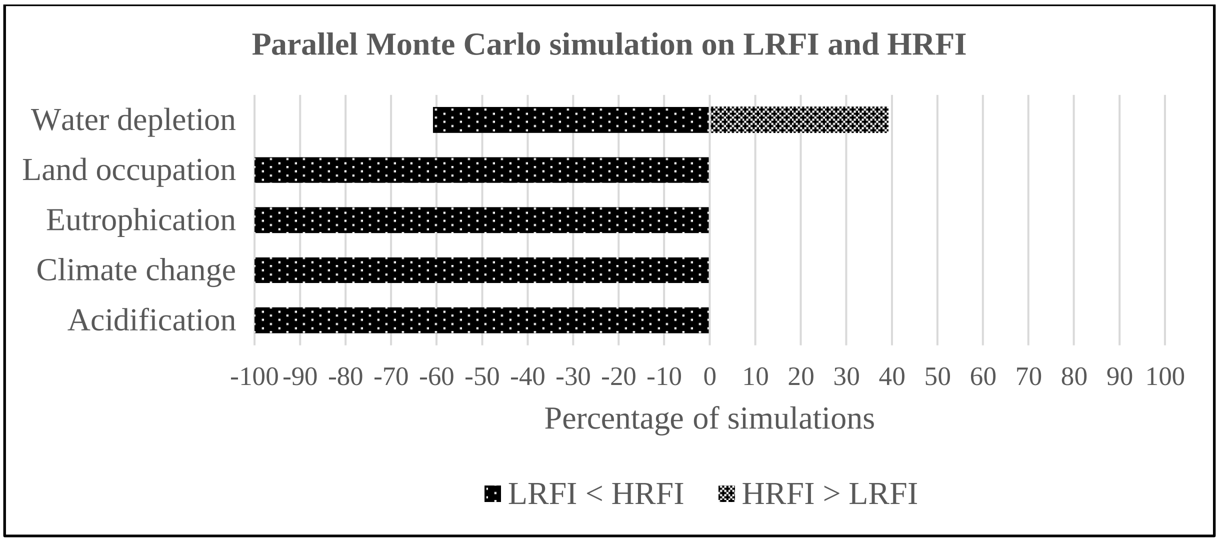

Figure 3 Life cycle assessment (LCA) applied to parallel Monte Carlo simulations for the high residual feed intake (HRFI) and low residual feed intake (LRFI) lines. The figure shows the percentage of scenarios from 1000 Monte Carlo simulations in which each line outperformed the other. Parallel Monte Carlo simulations use identical values from shared uncertainties to calculate environmental impacts. Therefore the percentage difference in the results can be referred to as the difference between the lines. Positive values are associated with simulations in which the high residual feed intake (HRFI) line has more favourable impacts than low residual feed intake (LRFI) pigs, and negative values, the reverse.

Sensitivity analysis

To perform the OAT sensitivity analysis, all incorporated production traits were kept constant but the value of one trait was changed by ±2SD based on the distributions listed in Table 2. The focus traits BP, ADG, ADFI, PD, BL, FCR and BP/BL were changed one at a time.

The percentage change in the environmental impact categories compared to the initial impact values due to the changes in any trait are presented in Figure 4. For all categories, the environmental impacts were sensitive to ADFI, ADG, FCR, BP and PD, which corresponded to more than 5% changes in the impacts compared to the initial values. The maximum and the minimum sensitivity for ADFI (+20.6% and -10.7%) were related to EP and WD, for ADG (+17.6% and -10.5%) to LO and WD, for FCR (+13% and - 8%) to EP and WD, for BP (+17.7% and - 9%) to EP and WD, and for PD (+21% and -16%) both maximum and the minimum sensitivity were related to EP.

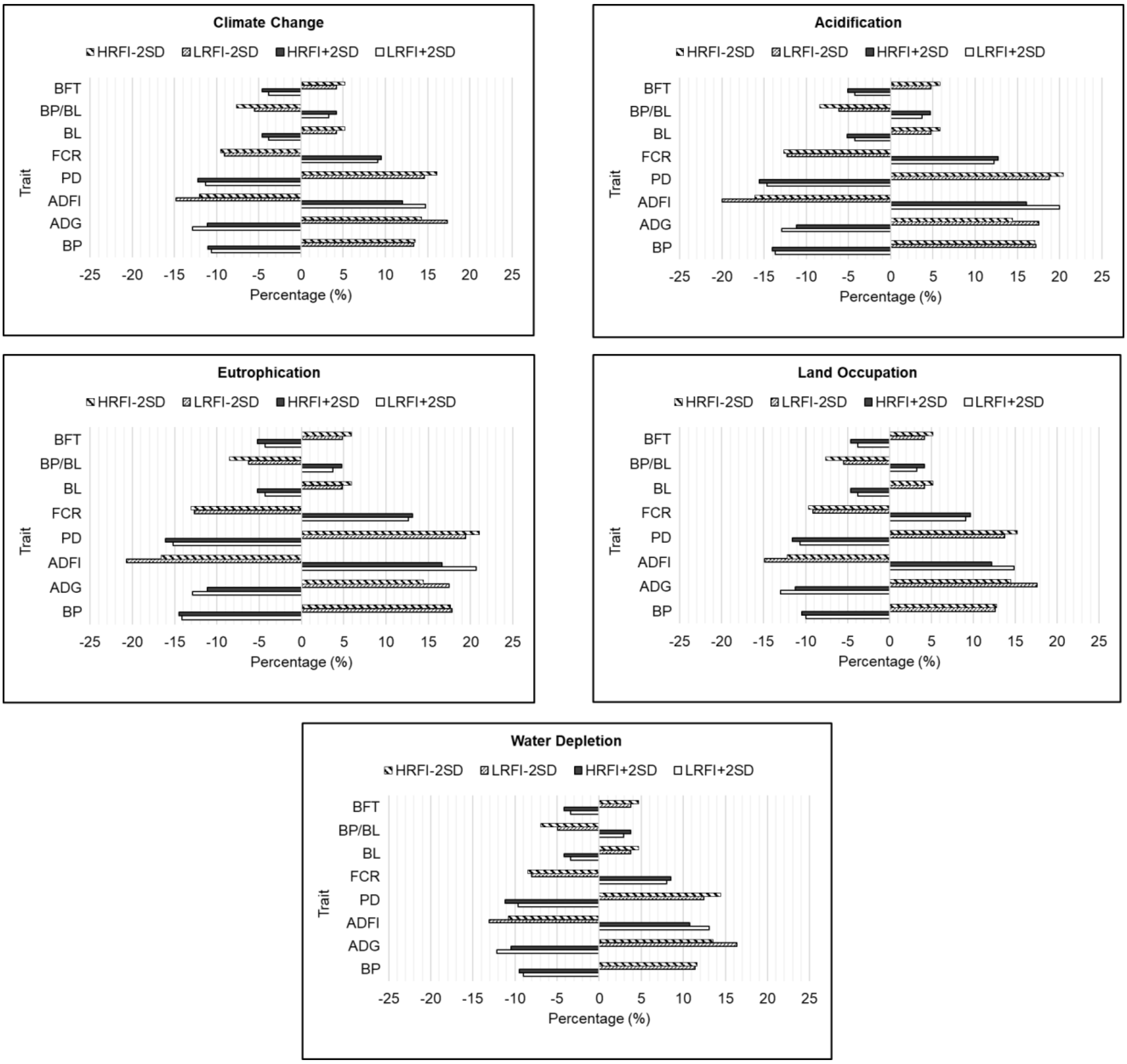

Figure 4 One-at-a-time sensitivity analysis based on performance traits for the low residual feed intake (LRFI) and high residual feed intake (HRFI) pig lines. Percentage of changes in environmental impacts compared to the mean values due to changes in ±2SD in each trait. ADFI = average daily feed intake; ADG = Average daily gain; BP = Body protein at slaughter; BP/BL = Ratio of body protein-to-body lipid at slaughter; PD = average daily protein deposition; BFT= back fat thickness; FCR= Feed conversion ratio; BL= Body lipid content at slaughter.

Discussion

The aim of this study was to develop a model to evaluate the environmental impacts of selection for feed efficiency using comparative life cycle assessment, and to apply the model to individual records of two divergent pig lines after five generations of selection for RFI. Feed conversion ratio is correlated with RFI, and selection for reduced RFI has been shown to also reduce FCR in these lines (Gilbert *et al.*, 2017). Lower FCR is generally due to lower feed intake, higher body weight gain, or both. Major differences in ADFI in the two lines and minor differences in ADG indicated that lower FCR in LRFI was mostly due to lower ADFI, which matches the objectives of selecting for RFI and agrees with earlier results in the same lines at that stage of the selection experiment (Gilbert *et al.*, 2007).

Studies have reported a negative (favourable) correlation between RFI and body leanness (e.g. Cai *et al.*, 2008). On the other hand, energy partitioning between protein and fat deposition can be modified by improving feed efficiency (Noblet and van Milgen, 2004). If the general weight gain was little affected by selection, the InraPorc® model showed that the protein to lipid ratio differed significantly between the lines, mainly due to significant differences in lipid content at slaughter, meaning that selection for LRFI improved the protein to lipid ratio mainly through reduced lipid deposition and back fat thickness, in agreement with the hypothesis stated by Dekkers and Gilbert (2010) concerning the switch of more efficient pigs to a more oxidative metabolism.

Inferring from the differences between LRFI and HRFI feed intake, we hypothesised that the lines would have different environmental impacts. Indeed, the LRFI impacts were on average 7% lower than HRFI impacts in all categories, in agreement with the positive genetic correlation between FCR and RFI with excretion traits (nitrogen and phosphorus) reported by Saintilan *et al*. (2013) and Shirali *et al*. (2012), who used models at the level of the animal only to predict individual excretion of pigs.

Differences in the level of environmental impact categories between different LCA studies may be due to differences in the methods, inventories, assumptions, emission factors, and system boundaries. To guarantee consistency in the calculation model, LCA method, inventories and system boundary, when comparing the lines, we applied the same model to both. By changing the method to the CML-IA baseline V3.04 (Center of Environmental Science of Leiden University, http://cml.leiden.edu/software/datacmlia.html) with the same inventories, the impact values decreased to 2.56 kg CO_2-eq for LRFI and to 2.70 kg CO_2-eq for HRFI, confirming the importance of the model for comparing impacts. Thus, although it may not be reasonable to compare the results of two different studies, one can reasonably compare their orders of magnitude and range. The values of the CC impact for LRFI and HRFI were in the same ranges as the values reported by Dourmad *et al*. (2014) (2.3 to 3.5 kg CO_2-eq/kg LW) and de Vries and de Boer (2010) (2.3 to 5.0 kg CO_2-eq/kg LW) for typical European production farms. The impacts of LRFI and HRFI on AP were also in the range of values reported by de Vries and de Boer (2010) (8 to 120 g SO_2-eq/kg LW). The impact on EP for LRFI and HRFI differed from the impacts reported in the literature. These variations were due to the use of ReCiPe midpoint 2016, which accounts for the impact of freshwater eutrophication based on P-eq rather than PO_4-eq. When EP was calculated based on PO_4-eq (according to the CML-IA baseline method) the values changed to 25 g PO_4-eq for LRFI and 27 g PO_4-eq for HRFI, which is in the same range of values reported by de Vries and de Boer (2010) (12 to 38 g PO_4-eq/kg LW). The LO values were also in the range reported by de Vries and de Boer (2010) (4.2 to 6.9 m^2/kg LW).

Clustering the different processes involved in the system boundary provided further insights into the relative contributions of each segment to the impact categories, with limited differences between lines. The relative importance of feed and manure were in accordance with results published by Garcia-Launay *et al*. (2014). The higher feed contribution to three impact categories of CC, LO and WD is certainly the main driver of the higher environmental impacts of HRFI compared to LRFI. Moreover, as HRFI pigs consume more feed with limited difference in digestibility (Barea *et al*., 2010; Montagne *et al*., 2014), they excrete more nutrients and produce more manure because of the mass balance. Considering manure as organic fertiliser partly compensated for the higher environmental impacts of HRFI associated with higher excretion and emission rates. Relative contribution of the segmented process confirmed that improving feed efficiency and manure management present the main opportunities for improvement in pig farming.

According to the average values of the traits, the RFI lines only marginally differ in BP and PD ($P = 0.32$). The protein deposition plays a role in affecting the environmental impacts in two ways. On one hand, body weight is strongly dependent on protein accretion and lipid deposition (Noblet and Etienne, 1987), which could affect FCR. On the other hand, changes in protein content influence nitrogen retention and subsequent excretion. Excreted nitrogen is at the origin of the emissions of N-gas as nitrous oxide and ammonia during animal housing, outdoor storage of manure and application of manure in the field. A change in body protein, on one hand, alters FCR through a change in body weight, and on the other hand, may - due to a domino effect - influence all downstream nitrogen associated excretions and emissions. While all impact categories are moderately correlated to PD (-0.58), the marginal difference of the lines in BP suggest that selection for RFI would have only limited effects on protein deposition, and thus nitrogen excretion, which is one of the main sources of environmental impacts. However, the RFI correlations with impacts were of similar magnitude as PD, which could indicate that these two criteria would reduce the environment impacts partly via different levers. Thus, it could be inferred that selection for RFI could be combined with other criteria to target protein deposition. In that respect, the close genetic correlation between FCR and lean meat growth rate (Clutter *et al*., 2011) makes this trait a more promising criterion for environmental improvement, which from a practical perspective is interesting, as it has been for decades the main criterion used on pig farms to improve feed efficiency. The very high correlation between FCR and all impact categories confirmed FCR as a key trait to reduce the environmental burdens of pig production. However, selecting for FCR has major impacts on decreasing leanness, which might no more be desirable for some commercial lines in the future. Our study shows that RFI would be a valid alternative to select for feed efficiency with positive environmental impacts.

The statistical analysis of the results of individual LCA, performed on all pigs, revealed that the lines are significantly different for the five categories of environmental impacts. The results of parallel Monte Carlo simulations confirmed these differences and showed that the line difference is not sensitive to the model parameter uncertainties. The OAT sensitivity analysis showed that the impact categories are highly sensitive to ADFI, PD, ADG and FCR, and less sensitive to BFT, BL and BP/BL. On the other hand, the correlations between the impacts and the traits show that the impacts are highly correlated to FCR, BP/BL, BFT and BL. This discrepancy between the OAT results and the correlations obtained from individual LCA could be due to not considering the correlations between the traits in the OAT sensitivity analysis, as proposed by Ottosen *et al*. (2019). Consequently, further global sensitivity analyses accounting for trait dependencies should enable a more global understanding of the influence of genetic trait changes on the environmental impacts. Ultimately, this could be used to propose new selection indexes optimising the economic and environmental components jointly, as explored recently by Besson *et al*. (2020).

Conclusion

The feed efficiency concept arose from an economic incentive as the ratio of gain (pig weight gain) to cost (feed). To date, emissions associated to pig farming have not been accounted for in selection strategies, neither as a cost nor as an income. In the environmental context, phosphorus and nitrogen excretions, associated emissions and other fluxes emerge as main sources of the environmental burden of pig farming. Ignoring that economic drivers influence the main sources of environmental costs was pointed out, and we suggest that including environmentally optimised criteria could alleviate the environmental burden of pig production, while still satisfying economic requirements. Consequently, our study shows that more optimal selection criteria could emerge through restructuring the trait weights from an environmental point of view.

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Declaration of interest

None.

Ethics statement

None.

Software and data repository resources

The model was not deposited in an official repository.

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2.3 **Supplementary material of the paper**

Supplementary material. The following formulations have been applied to calculate the emissions and excretions using the mass-balance approach.

$eBW = 5.969*BP^{0.944} + 0.854 * BL^{0.944}$ (van Milgen et al., 2008)

Lean meat percentage $= 72.58 – 43.49 * BL / eBW$ (van Milgen et al., 2008)

$N_{Body} = e^{(-0.9892 – 0.0145 Lean\%)} * eBW^{(0.7518 + 0.0044 Lean\%)} / 6.25$ (Dourmad et al., 1992)

$N_{Intake} = Feed_{Intake} * N_{Feed}$

$N_{Excreted} = N_{Intake} – N_{Retained}$

P_{Body} (g) $= 5.39*eBW$ (Rigolot et al., 2010a)

Ca_{Body} (g) $= 8.56*eBW$ (Rigolot et al., 2010a)

K_{Body} (g) $= - 0.0041*eBW^2 + 2.68*eBW$ (Rigolot et al., 2010a)

Cu_{Body} (mg) $= 1.1*eBW$ (Rigolot et al., 2010a)

Zn_{Body} (mg) $= 20.6*eBW$ (Rigolot et al., 2010a)

$N_20 = 0.002*N_{Excreted}$ (Rigolot et al., 2010b)

$N_2 = 5*N_20$ (Rigolot et al., 2010b)

$NH_{3\ Building}$ (kg) $= 17/14*0.24*N_{Excreted}$ (Rigolot et al., 2010b)

$ResD = Feed_{intake} *residue\ feed$

$ECH_{4\ growing} = ResD*670$ J/g (Rigolot et al., 2010a)

$CH_{4\ Emitted} = ECH_4 / 56.65$ MJ/kg (Rigolot et al., 2010a)

$CH_{4\ Housing}$ (kg) $= VS*B_0*MCF$ (Rigolot et al., 2010b)

$OM_{Faeces} = Feed*OM_{feed} *(1 – dCOM)$ (Rigolot et al., 2010a)

$dCOM_{Grow} = (0.744 + (14.69\ DE – 0.50\ NDF – 1.54\ MM) / DM) / (OM / DM)$ (Rigolot et al., 2010a)

eBW = empty body weight ; BP = body protein ; L = body lipid; N Body = nitrogen content of body; N Intake = total uptaken nitrogen; N Feed = nitrogen content of 1kg feed; N Excreted = total excreted nitrogen; NRetained = nitrogen retained in the body; OM = organic matter; MM = mineral mater; DM = dry matter; dCOM = feed organic matter digestibility coefficient; NDF = Neutral detergent fiber; B0 = maximum CH4 producing capacity; MCF = methane conversion factor; ResD = digested fibre ingested.CH4 = methane; N = nitrogen; Ca = calcium; P = phosphorus; K = potassium; Cu = copper; Zn = zinc.

2.4 **Main messages from Chapter 2**

A first LCA evaluation tool adapted for the environmental evaluation of pig selection scenarios has been proposed. It relies on **a parametric LCA model** based on the dietary net energy fluxes in a pig system, and incorporates **a nutritional pig growth tool**, InraPorc® as a module to embed flexibility for changes in feed composition, animal performance traits and housing conditions (Figure 10).

The model was applied to quantify the environmental impacts of pigs from the fifth generation of pig lines divergently selected for RFI on five major environmental impacts of pig production. The comparative individual-based LCA showed that **LRFI had an average of 7% lower environmental impacts per kilogram live pig at farm gate compared to HRFI** ($P < 0.0001$) on climate change, acidification potential, freshwater eutrophication potential, land occupation and water depletion. Using individual assessment allowed to consider the covariance between the performance traits as well as their variations among individuals, in the LCA, while providing means for statistical analysis.

Thanks to the individual assessment, correlations between performance and environmental impact categories can be estimated. High correlations between FCR and all environmental impact categories (>0.95) and moderate correlations with RFI (>0.51) **confirmed the importance of improvement in feed efficiency to reduce environmental impacts**. This result revealed that **RFI is an effective measure to select for improved environmental impacts**, with the potential advantage of lower correlated impacts of other production traits.

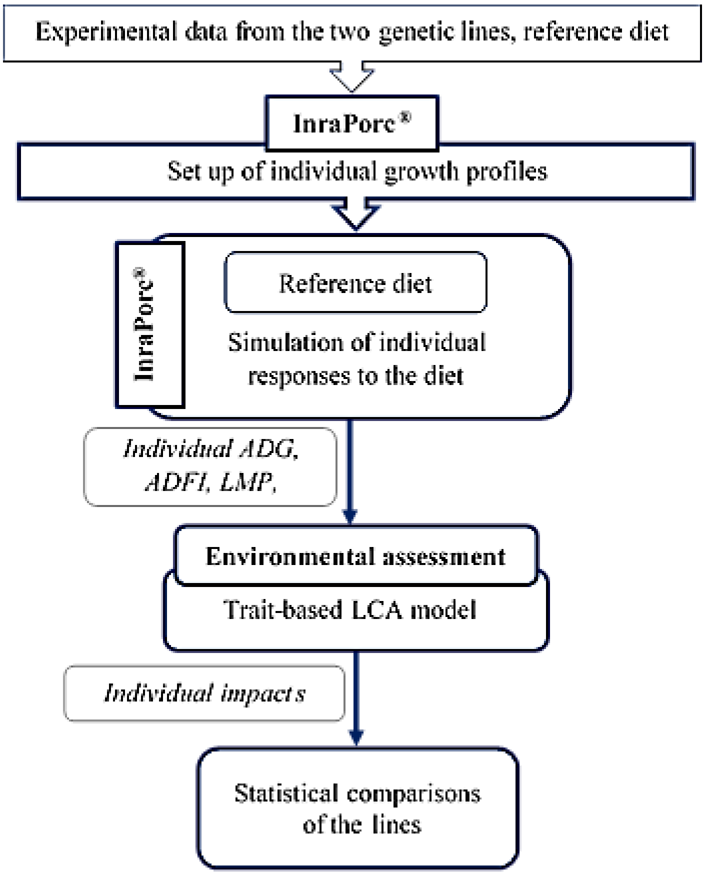

Figure 10. Schematic representation of the base-LCA individual model developed in this first study.

Chapter 3 **Environmental assessment of combinations of nutritional approaches: towards overall farm feed efficiency**

3.1 **Introduction**

This chapter aimed to propose the concept of overall farm feed efficiency, and environmentally assessed combinations of selection for feed efficiency and tailored diets environmentally optimised embedded in this concept. A preliminary analysis of the lines selected for feed efficiency unveiled that their nutritional requirements were significantly different during the full growing period (Figure 11).

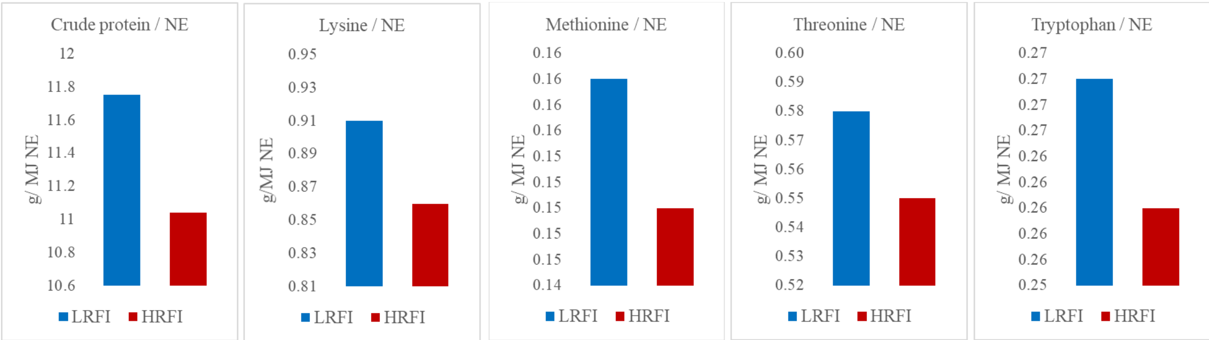

Figure 6. Differences between line representative requirements
All differed by $P < 0.05$, and the low residual feed intake line (LRFI) had on average 5.3% higher average density of nutritional requirements to the high RFI (HRFI) pigs

In practice, the LRFI pigs had higher digestible AA requirements per unit of net energy than HRFI pigs, which is a classical pattern when comparing pigs based on RFI or FCR (Saintilan et al., 2015). However, in spite of this difference, during the course of the selection the diet composition was not modified to be adjusted to the line requirements, and all pigs were fed the same conventional growing-finishing commercial diet.

The approach presented in this chapter was developed to improve the balance between the supplied and the required nutrients for each line, and jointly optimise the diet composition for multiple environmental impacts. To achieve this, a diet optimisation module was added to the model developed in the previous chapter that combined nutritional constraints and environmental optimisation. To keep consistency with the LCA model, this step was also based on the net energy system. In addition, an environmental score was defined to convert the multiple environmental objective problem into a single environmental objective. Finally, the environmental impacts of combinations of lines and optimised diets were assessed through an individual-based comparative LCA.

This work was orally presented at the virtual EAAP in 2020 (awarded by one of the EAAP scholarships 2020) and during a postgraduate conference at New England University Armidale (Australia) (Chapter 6, scientific communications). It is accepted for publication in International Journal of Life Cycle Assessment (2020). The supplementary material is provided after the paper.

3.2 Paper II. An approach to achieve overall farm feed efficiency in pig production: environmental evaluation through individual life cycle assessment

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An approach to achieve overall farm feed efficiency in pig production: environmental evaluation through individual life cycle assessment

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Abstract

Purpose Use a holistic individual life cycle assessment (LCA) to investigate possible mitigation of environmental impacts through optimisation of overall farm feed efficiency by combining animal selection for feed efficiency and formulation of diets with minimum environmental impacts tailored to pig nutritional requirements.

Methods A linear multi-objective optimisation method was used to combine diet optimisation tailored to meet the representative nutritional requirements of genetic lines with environmental optimisation of the environmental impacts of the diet. Environmental optimisation was obtained by weighting the environmental impacts of the diet in a single environmental impact score. An individual trait based LCA model with a cradle-to-farm-gate system boundary and functional unit of 1 kg live pig at the farm gate was applied to genetic lines selected for high (LRFI, high feed efficient line) and low (HRFI, low feed efficient line) feed efficiency data. The production traits of each individual animal in response to the optimised diets were simulated with InraPorc®, and imported into the individual LCA model to assess global warming potential (GWP), terrestrial acidification potential (AP), freshwater eutrophication potential (EP), and land occupation (LO) of the overall farm feed efficiency approach.

Results and discussion Integrating selection for feed efficiency, nutritional requirements of genetic lines (HRFI and LRFI) and environmental diet optimisation resulted in overall mitigation of environmental impacts. Compared to the conventional diet, the environmental score of the optimised tailored diets was reduced by 5.8% and 5.2% for LRFI and HRFI lines, respectively. At the general production system level, the environmental impacts decreased by an average of 4.2% for LRFI and 3.8% for HRFI lines compared to environmental impacts of the lines fed the conventional diet ($P < 0.05$). The HRFI line with its optimised tailored diet had fewer impacts than the LRFI line with the conventional diet, except for EP. Individual LCA revealed high correlations between environmental impacts and feed efficiency and protein deposition traits.

Conclusions Implementation of overall farm feed efficiency would effectively mitigate environmental impacts. A holistic economic evaluation of the resulting trade-off between diet costs and pig performances is now needed to design a comprehensive tool to orientate selection and formulation decisions for sustainable pig production systems.

Keywords: Environmental impact. Life cycle assessment. Residual feed intake. Feed efficiency. Nutrient tailored diet. Diet environmental optimisation. Pig

1 Introduction

Improving feed efficiency is a major objective to enhance pig production sustainability in terms of economy and environment. The main environmental impacts of pig production originate from feed production (Opio et al. 2013) and from manure excretion and emissions during pig farming (Dourmad and Jondreville 2007; Mackenzie el al. 2016). The improvement in the main environmental burden sources can be obtained through reduction in feed intakes, and supply of nutrients tailored to the animal requirements, to achieve better use of lower quantities of feed by the animals. Feed efficiency, which is usually expressed as its inverse, feed conversion ratio (FCR), stands for the body weight gain per unit of feed consumed. Selecting pigs based on feed conversion ratio (FCR) or residual feed intake (RFI) has been shown to be effective to improve feed efficiency in growing pigs (Gilbert et al. 2007 and 2017; Cai et al. 2008; Rothschild and Ruvinsky 2011). Unbalanced dietary nutrients and energy in the feed ration can result in unnecessary high excretion rate. Thus, a diet tailored to nutritional requirements is an important aspect for the environmental optimisation of pig production (Hauschild et al. 2012; Pomar and Remus 2019). Improving feed efficiency by adjusting the composition of the diet to the nutritional requirements of a group or an individual animal (precision feeding) has also been investigated (Pomar et al. 2009; Remus et al. 2019; Monteiro et al. 2016), and some related methods, decision support tools and systems are under development (Brossard et al. 2017 and 2019). Other methods are available for environmental diet optimisation either by accounting for the choice of ingredients to be incorporated (Garcia-Launay et al. 2018; Tallentire et al. 2017) or combining diet optimisation with minimum nutrient excretion impacts (Mackenzie et al. 2016). Life cycle assessment (LCA) has already been used for environmental assessment of various aspects of pig production systems (Lammers. 2011; Garcia-Launay et al. 2014; Mackenzie et al. 2015; McAuliffe et al. 2016 and 2017; Ottosen et al. 2020). We assessed the environmental impacts of pig selection for feed efficiency in a previous study by using individual LCA (Soleimani and Gilbert 2020), which made it possible to link individual genetic profiles to individual environmental impacts. Here we propose an overall environmental optimisation approach for pig production which combines "pig selection for feed efficiency", "formulation of a nutritionally tailored diet", and "environmental optimisation of the diet" as a strategy to achieve an overall farm feed efficiency. To achieve overall farm feed efficiency, diets were formulated according to the nutritional requirements of lines selected for different feed efficiency levels. Given these constraints, diets with minimum environmental impacts were determined, and the resulting environmental impacts of a system combining selected lines fed their optimised tailored diet were quantified to assess overall farm feed efficiency. The aim of this study was to establish the optimisation model and assess the total environmental impacts of improvements in overall farm feed efficiency on pig production, by performing individual LCA. The performance traits correlated with the environmental impacts could then used for further pig selection choices for environmental objectives.

2 Materials and methods

2.1 Life cycle assessment (LCA)

Environmental impacts were evaluated using LCA, which is most frequently used to assess the environmental impacts of products and services (Itskos et al. 2016). The marked contribution of emissions during animal farming, manure storage and application, quantified as global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP) (de Vries and de Boer. 2010), have massive implications on human health and ecosystems. Thus, these three impact categories are the most common in LCA studies of pig production (McAuliffe et al. 2016). In addition, since vast land areas are required for producing ingredients for feed, relatively to those for vegetable protein and oil (Basset-Mens et al. 2005), some being located in sensitive ecosystems exposed to high land conversion rate, the land occupation impact category is important for an environmental impact assessment of pig production. Consequently, the impact categories GWP (kg CO_2-eq), AP (kg SO_2 eq), EP (kg P eq) and LO (m^2a crop eq) were used to assess the environmental impacts in our study. ReCiPe Midpoint 2016 (H) V1.02 (Huijbregts et al., 2017), was used together with Ecoalim (Wilfart et al. 2016) and Ecoinvent (Wernet et al. 2016) inventory databases for the impact assessment. Individual environmental assessments for each pig were implemented in SimaPro V8.5.4.0 on the MEANS (MulticritEria AssessmeNt of Sustainability) platform (http://www.inra.fr/means), following the approach we proposed in a previous study (Soleimani and Gilbert 2020).

2.1.1 Goal and scope

The goal of the present study was to develop an approach to achieve overall farm efficiency in pig farms, and to investigate the resulting environmental impacts using a trait-based individual LCA model (Soleimani and Gilbert 2020). A 'cradle-to-farm-gate' system boundary including feed production, sow-litter, post-weaning, fattening pigs and manure management, was taken from conventional French pig farming systems. A simplified process flow diagram of the system is shown in Figure 1. One kg of pig live weight (LW) at the farm gate was chosen as the functional unit, and used as a reference to compare the environmental impacts of the different scenarios.

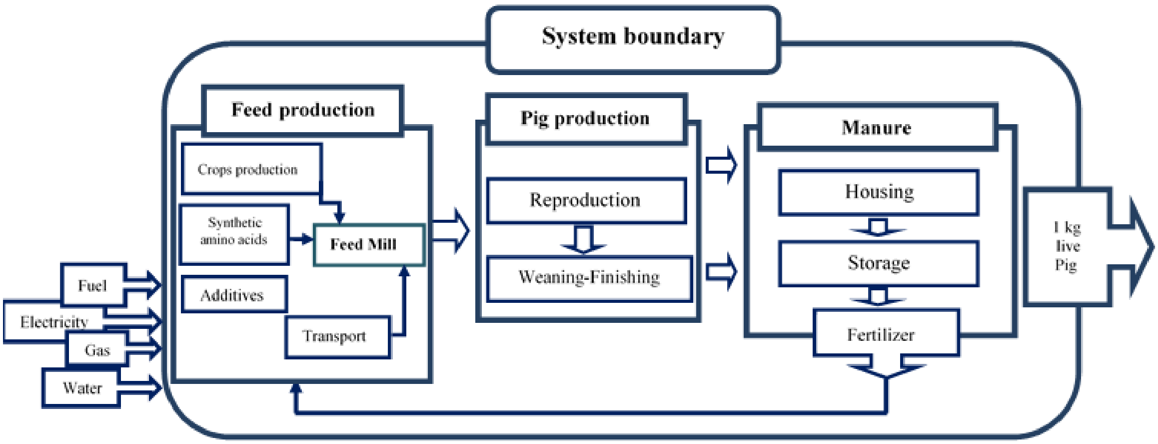

Fig 1. Scheme of the system boundary, which includes the entire pig farm, feed production processes and manure management.

2.1.2 The LCA model

The LCA model was developed in six separate modules: feeding plan, animal profile, emissions, excretion, water expenditure, and energy expenditure (Soleimani and Gilbert, 2020). Briefly, the model was developed based on pig net energy (NE) requirements, with a focus on the fattening period to allow prediction of the different performance profiles resulting from the composition of the tested diet. InraPorc® software, designed to simulate the performance pigs' response to different nutritional strategies (van Milgen et al. 2008; Dourmad et al. 2008), was incorporated in the LCA model to obtain sow-litter profiles (identical in all scenarios), feeding plans and corresponding simulated growth performance during fattening. Water and energy expenditures were calculated based on the IFIP report on typical French farms (IFIP - Institut de la Filière porcine 2014). The individual fattening performance traits were used as input parameters in the life cycle inventory (LCI) in SimaPro to perform individual LCAs. The components of excreta (dry matter (DM), organic matter (OM), nitrogen (N), phosphorus (P), and potassium (K)) were calculated using the mass-balance approach, as the difference between nutrient intake in the feed and the nutrients retained in the body (Supplementary material S1). A typical French slatted floor type of housing and slurry storage was adopted, along with system expansion approach considering that the manure produced replaced a certain percentage of mineral fertilisers (Garcia-Launay et al., 2014). Average performance data were used for the sow-litter stage, and individual performance data were used for the post weaning and fattening stages. Emissions of enteric methane (CH4), nitrous oxide (N2O), nitrogen (N2) and ammonia (NH3) in the building and during outside storage were calculated according to the IPCC guidelines (Tier I and Tier II) using model and emission factors developed by Rigolot et al. (2010a and 2010b) for French pig systems. Methane emissions from manure during storage, emissions of N2O, were calculated using the guidelines provided by the intergovernmental panel on climate change IPCC (2006, Tier 2) and the potential leaching rate of PO4 and NO3 during spreading of slurry were adopted from Nguyen et al. (2012). NO_x emissions were calculated according to Nemecek et al. (2004). The fertiliser equivalence value of the manure as a replacement for synthetic fertiliser was considered to be 100% for P and K (Nguyen et al. 2011) and 75% for N (Nguyen et al. 2010). To ensure the results were comparable, the inventories, methods and calculations were kept the same in all the LCA runs. The environmental impacts of the diet ingredients were obtained from the Ecoalim dataset (Wilfart et al. 2016) of the AGRIBALYSE® database using the Recipe method 2016, applying the attributional approach. Values of 500 km for cereals and 100 km for meals were used for the transport of ingredients from the farm to the feed factory (Garcia-Launay et al. 2018), and a value of 30 km (Cadéro et al. 2018) was used for the distance from the feed factory to the pig farm, taken from the attributional life cycle inventories of the ecoinvent version 3.1 database.

2.2 Experimental data

Experimental data (body weights, feed intakes, body composition) were available from birth to slaughter weight for two lines of Large White pigs divergently selected for RFI under ad-libitum feeding with the conventional diet. The composition of the conventional diet is reported in the supplementary material S2. The selection process concerning low RFI (LRFI, more efficient pigs) and high RFI (HRFI, less efficient pigs) lines are reviewed in Gilbert et al. (2017). The dataset used in the present study included data from 57 male pigs of the fifth generation of each line fed a conventional diet formulated to cover pig requirements. Growing pigs had ad libitum access to a one-phase conventional diet from 10 weeks of age to slaughter (at about 115 kg body weight). The data on individual daily feed intake (DFI) for the whole fattening period were recorded on automatic feeders (ACEMO, Pontivy, France), and back fat thickness (BFT) was measured via ultrasounds on live animals at 23 weeks of age, using an echograph (ALOKA SSD-500, Cergy Pontoise, France). Average daily gain (ADG), feed conversion ratio (FCR) and RFI were then computed as reported in Gilbert et al. (2007). The experimental data for reproductive sows and litters of the same lines (LRFI and HRFI) including the mean sow and piglet BW at weaning and farrowing, sow BFT before farrowing, sow lactation DFI, number of total born, still born and weaned piglets, piglet BW at birth and at weaning, and farrowing and weaning age, were adopted from Gilbert et al. (2012).

2.3 Line diet optimisation

In this study, the diet formulation was optimised to obtain diets with minimum environmental impacts but covering the specific nutritional requirements of the different genetic lines. To diversify the sources of energy and protein available for the diet formulation, six ingredients, oats, triticale, corn, peas, rapeseed meal, and sunflower meal were added to the eight ingredients of the conventional diet (barley, wheat, soybean meal, sunflower oil, and synthetic AA L_lysine (LLY), L_threonine (LTH), L_tryptophan (LTR), DL_methionine (DLM)), to formulate new diets. The new ingredients were selected based on their availability at the market and on the accessibility of their characterization data in the embedded database of InraPorc®. The net energy (NE) density and digestible CP and AAs of the ingredients were extracted from the INRA-AFZ database (Sauvant et al. 2004) of feed ingredients (Table 1). Ingredients like salt, carbonate calcium and vitamins, which do not have digestible energy, CP or AAs, were considered as additives and excluded from the formulation step, so in total Q = 14 ingredients were retained for formulation. Some common industrial rules and recommendations for commercial diet formulation, such as storage availability, are beyond the scope of this study and are not accounted for.

Table 1. Digestible crude protein (CP) and amino acids, and net energy (NE) of the ingredients retained for diet formulation, and their environmental impacts.

Ingredients	Quantity notation	CP (g/kg_{feed})	Lysine (g/kg_{feed})	Threonine (g/kg_{feed})	Tryptophan (g/kg_{feed})	Methionine (g/kg_{feed})	NE (MJ/kg)	GWP (kg) CO_2 eq	AP (gr) SO_2 eq	EP (gr) P eq	LO (m^2a crop)
Barley	b	80.5	2.85	2.62	1.03	1.43	9.56	0.46	5.60	0.16	1.371
Oat	o	74.2	2.99	2.36	0.94	1.51	8.06	0.50	7.95	0.20	2.079
Triticale	T	83.4	3.24	2.71	1.06	1.53	10.40	0.48	5.43	0.19	1.837
Corn	c	69.8	1.92	2.49	0.40	1.55	11.20	0.33	7.11	0.12	1.033
Pea	p	165.8	12.45	5.93	1.31	1.60	9.75	0.37	3.65	0.57	2.663
Rapeseed meal	r	254.7	13.5	10.87	3.28	6.00	6.26	0.40	5.36	0.10	1.211
Sunflower meal	sm	273.5	9.68	9.72	3.44	6.99	5.50	0.25	2.94	0.25	1.975
Wheat soft	w	92.8	2.51	2.66	1.14	1.51	10.54	0.42	7.96	0.129	1.330
Soybean meal	s	391	25.02	15.4	5.25	5.89	7.86	1.52	5.64	0.385	2.086
Sunflower oil	f	0	0	0	0	0	29.76	1.17	15.51	1.12	8.701
L-Lysine HCL	LLY	954	798	0	0	0	11.88	10.55	76.60	37.85	3.118
L-Threonine	LTH	731	0	990	0	0	11.11	10.62	84.23	37.16	3.109
L-Tryptophan	LTR	853	0	0	985	0	11.53	21.24	168.47	74.32	6.219
DL-Methionine	DLM	584	0	0	0	990	10.61	2.99	8.86	0.270	0.016

CP = crude protein; LO = land occupation; EP= freshwater eutrophication potential; AP = acidification potential; GWP= global warming potential; NE = net energy; P = phosphorous; m^2a crop= area time; NE density and digestible CP and amino acids (lysine, threonine, tryptophan, and methionine) of the ingredients were extracted from the INRA-AFZ database of feed ingredients. The environmental impacts of diet ingredients (GWP, AP, EP, LO) were obtained from the Ecoalim dataset of the AGRIBALYSE® database with the Recipe method 2016.

2.3.1 Choice of nutritional requirements for diet formulation

To formulate a diet tailored to animal dietary requirements, the nutritional constraints which should be satisfied by the diet have to be identified. Pigs adjust their ad-libitum feed intake to the net energy density (NE) of the diet (Quinion and Noblet 2012). Consequently, dietary nutrients are up taken proportionally to the NE of the diet. In cereal-based diets, essential amino acids (AA) lysine, threonine, tryptophan, and methionine are the most limiting AA (D'Mello. 1993), which turned out to be mostly added as synthetic AA to cereals to achieve balanced nutritional composition, as in the conventional diet used to obtain the pig performances in our previous study (see Table 1, Soleimani and Gilbert 2020, for details). Thus, to avoid AA deficiency, these four amino acids were set as target constraints in the formulation. In addition, to satisfy the dietary requirements of all amino acids, crude protein (CP) was also set as a target constraint to ensure coverage of the remaining essential and non-essential amino acids. Finally, digestible CP and AA requirements were standardised to the NE content of the diet, to account for the feed intake regulation by NE density. Therefore digestible crude protein (CP), digestible lysine, digestible threonine, digestible tryptophan and digestible methionine, expressed as standardised requirements to the diet NE (g/MJ NE), were retained as the target constraints to be satisfied by the diets tailored to the pig requirements.

2.3.2 Determination of the representative nutritional requirements of the lines

The experimental data were imported into InraPorc® to calibrate a growth performance profile for each individual pig. The profiles were calibrated using the recorded daily ad-libitum feed intake during the fattening period with the conventional diet, expressed relative to the NE of the diet. The individual digestible CP and AA requirement profiles of the pigs were then obtained as InraPorc® outputs. Pigs are usually fed in groups with a single diet adjusted to the nutrient requirements of a representative pig in the group (Remus et al. 2019). Accordingly, the five targeted daily requirements for the whole fattening period were extracted from InraPorc® for each individual to identify the representative pig for each line in our dataset. For all individuals, the maximum requirement for these five indicators were observed in the early stages of the growing period. From these individual maxima, the mean maximum requirement for each line was computed for each indicator as the representative requirement of each line. In the following, *Alpha* is the digestible crude protein requirement (g per MJ NE), *Beta* the digestible lysine requirement (g per MJ NE), *Gamma* the digestible threonine requirement (g per MJ NE), *Lambda* the digestible methionine requirement (g per MJ NE), and *Delta* the digestible tryptophan requirement (g per MJ NE).

2.3.3 Diet formulation tailored to each line

To consider the representative requirement of each line in the tailored diet formulation, linear equations (1-6) were retained as constraints for each line l (l = 2 in our study) and Q possible ingredients (Q = 14 in our study). Since the diet would be formulated for one kg of feed, the first equation ensures the prospective diet plus the additives does not exceed one kg, and the rest of the equations ensure the dietary nutrients correspond to the representative requirements of each line.

$$\text{1kg} - \text{additives (kg)} = \sum_{i=1}^{Q} q_{i_l} \tag{1}$$

$$Alpha_l = \sum_{i=1}^{Q} q_{i_l}\, CP_i \Big/ \sum_{i=1}^{Q} q_{i_l}\, NE_i \tag{2}$$

$$Beta_l = \sum_{i=1}^{Q} q_{i_l}\, LLY_i / \sum_{i=1}^{Q} q_{i_l}\, NE_i \tag{3}$$

$$Gamma_l = \sum_{i=1}^{Q} q_{i_l}\, LTH_i / \sum_{i=1}^{Q} q_{i_l}\, NE_i \tag{4}$$

$$Delta_l = \sum_{i=1}^{Q} q_{i_l}\, LTR_i / \sum_{i=1}^{Q} q_{i_l}\, NE_i \tag{5}$$

$$Lambda_l = \sum_{i=1}^{Q} q_{i_l}\, DLM_i / \sum_{i=1}^{Q} q_{i_l}\, NE_i \tag{6}$$

2.3.4 Formulating tailored diets with minimum environmental impacts for each line

The least environmental impact formulation approach implemented in this study involves two steps (1) formulating a least cost (LC) diet as the baseline reference for environmental impacts and cost, and (2) formulating a diet with the lowest environmental impact score in an acceptable cost interval compared to the least cost diet. In step 1, the objective function of the optimisation is the cost, which should be minimised conditionally to the nutritional constraints in equations (1) to (6). For the nutritional constraints, the cost constraint was normalized to the ingredient NE to compute the diet cost to minimise:

$$min\,cost = \sum_{i=1}^{Q} q_{i_l}\, p_i / NE_i \tag{7}$$

where q_{i_l}, p_i and NE_i are the rate of incorporation of the i^{th} ingredient in line *l*, the price and net energy of i^{th} ingredient, respectively, with $i = 1,\ldots, Q$. The least cost diet for each line was obtained through an evolutionary optimisation algorithm of NSGA-II from equations (1) to (7) with library of mco in R version 3.6.3 (population size of 340 and 3,500 generations). This algorithm identifies the non-dominated solutions on the Pareto-optimal front curve that best satisfy the nutritional and cost constraints. The price of each ingredient was obtained from the monthly average of the market price of ingredients in France reported by IFIP (IFIP, Mensuel d'information aliment, May 2020). The environmental impacts of the least cost diet (GWP_{LC}, AP_{LC}, EP_{LC}, LO_{LC},) for each line *l* were calculated by summing the environmental impacts of each ingredient (Table 1) in proportion to its rate of corporation in the diet:

$$impact_{LC_l} = \sum_{i=1}^{Q} q_{i_l}\, impact_i \tag{8}$$

where $impact_i$ is the environmental impact of ingredient *i*, and *impact* is GWP, AP, EP or LO.

For step 2, the first task was to define an environmental impact score to minimise. The environmental impacts of the least cost diet were used for each line as normalization factors for each impact, as proposed by Garcia-Launay et al. (2018). Then, weights were applied to obtain an environmental impact score (EI score) to minimise as a new objective function:

$$\mathrm{EI}_{score\_l} = \sum_{impact=1}^{4} w_{impact}((\sum_{i=1}^{Q} q'_{i_l}\ impact_i\ /NE_i)/(impact_{LC_l})) \quad (9)$$

where q'_{i_l} is the quantity of i^{th} ingredient in the diet with the lowest environmental impact score for line *l*. In our study, an equal weighting of one was first used for w_{GWP}, w_{EP}, w_{AP} and w_{LO} to avoid unbalanced impacts of the environmentally optimised tailored diet. Finally, the costs of the least environmental score diets were limited to avoid exceeding the cost of the least cost diet by more than 10%. The NSGA- II algorithm was applied to obtain the diets with the lowest environmental impact score under the dietary requirement constraints for each line, from equations (1) to (6) and (9) with cost < 110% least cost.

2.3.5 Sensitivity analysis of the environmental impacts of the diets to the representative requirements of the lines and environmental score weights

To define an approach to assess the sensitivity of the environmental impacts of the diets to changes in the representative requirements of the lines, first the correlations between the individual maximum requirements of the pigs in each line were computed. All the representative requirements were highly correlated (> 0.99). To consider these high correlations in a sensitivity analysis, an all-at-once sensitivity analysis was conducted based on changes in all the requirements combined, first for +1SD, and then for -1SD, separately for the two lines. Then the full diet optimisation process described above was applied again, and the differences in the environmental impacts of the new optimised tailored diet relative to the initial optimised tailored diet were used for within-line sensitivity analysis. An impact category was considered to be sensitive to changes in the representative requirements of the line if the change in that impact category was greater than 5% (Mackenzie et al. 2016) due to changing by +1SD or -1SD all the representative requirements of the lines at once. In addition, in the environmental score used for optimisation, the environmental impact weights (w_{GWP}, w_{EP}, w_{AP} and w_{LO}) were equal to one. To assess the sensitivity of optimised tailored diet environmental impacts to the choice of weight, a one-at-a-time sensitivity analysis was performed based on successive changes of +0.5 and -0.5 for each weight in each diet optimisation run, separately for the two lines.

2.4 Environmental evaluations of overall farm feed efficiency

The growth performance traits, including average daily feed intake, average daily gain, back fat thickness, body protein and body lipid at slaughter (120 kg) and length of the fattening period, were simulated with InraPorc® for each pig in response to its line optimised tailored diet. These performances were then used as input parameters for the individual trait-based LCA mode (Soleimani and Gilbert 2020) to assess the environmental impacts of the overall farm feed efficiency approach. Statistical analyses were applied to the outputs of the different steps of this evaluation, based on calculation of the line means and standard deviations (SD) of growth performance traits and their environmental impacts. T-tests were used to test the line differences, and environmental impacts were declared significantly different between scenarios when $P < 0.05$. Correlations between traits and environmental impacts were performed to identify the traits with maximum environmental impact. In addition, a principal component analysis was also performed for a better understanding of the relationships between the components (using fviz function from library of factoextera in R).

Results

3.1 Representative requirements of the lines based on individual requirements

Table 2 lists the means and standard deviations of the five representative requirements of the two genetic lines (digestive CP, lysine, threonine, methionine, and tryptophan). On average, the LRFI line had +5% requirements in g/MJ NE compared to the HRFI line ($P < 0.05$), with the crude protein requirements showing the largest difference (6.4%) between lines.

Table 2. Mean maximum individual standardised requirements for the low residual feed intake (LRFI) line and the high residual feed intake **(**HRFI) line and their standard deviations (N=57 pigs per line)

	LRFI	**HRFI**	***P***
Alpha: digestible crude protein requirement (g/MJ NE)	11.75 (2.46)	11.04 (2.33)	<0.05
Beta: digestible lysine requirement (g/MJ NE)	0.91 (0.20)	0.86 (0.18)	<0.05
Gamma: digestible threonine requirement (g/MJ NE)	0.58 (0.12)	0.55 (0.11)	<0.05
Lambda: digestible methionine requirement (g/MJ NE)	0.27 (0.03)	0.26 (0.05)	<0.05
Delta: digestible tryptophan requirement (g/MJ NE)	0.16 (0.06)	0.15 (0.03)	<0.05

3.2 Environmentally optimised diets tailored to the nutritional requirements of each line

The least environmental impact score diet which satisfies the representative requirements of each line at a cost less than 110% of that of the least cost diet was retained as the optimised tailored diet for the corresponding line. The LRFI optimised tailored diet had 9.38 MJ NE/kg, and the HRFI optimised tailored diet had 9.75 MJ NE/kg, with triticale, in which the proportions of sunflower meal and soybean meal were highest in the LRFI optimised tailored diet, whereas pea and sunflower oil were incorporated only in the HRFI optimised tailored diet (supplementary material S3). In addition, smaller quantities of synthetic AA were incorporated in the LRFI optimised tailored diet (L-Tryptophan and DL-Methionine), whereas L-Lysine was higher in this diet. Compared to their respective least cost diets with the 9.27 MJ NE/kg for LRFI and 10.01 MJ NE/kg for HRFI, the main differences in composition were in triticale, wheat, sunflower meal and corn along with less incorporation of L-Lysine in HRFI optimised tailored diet. Table 3 lists the environmental impacts and cost of the line optimised tailored diets and least cost diets, together with the conventional diet. The environmental impact score of the optimised tailored diets decreased of -5.2% for HRFI and -5.8% for LRFI compared to the score of conventional diet, as the feed cost per MJ NE (-11.5% and -12.0%). When considering the detailed E environmental impacts, the optimised tailored diets showed reductions per MJ NE of feed for GWP (-12.8% and -4.5% for the HRFI optimised tailored diet and LRFI optimised tailored diet, respectively), LO (-18.6% and -27.4%), AP (-5.2% for HRFI), and increased in EP (+3.1% for LRFI) and EP (+40.7% and +8.4 %). The price of optimised tailored diets (0.199 €/kg for LRFI and 0.208 €/kg HRFI) was lower than the price of the conventional diet (0.234 €/kg) per kg of feed and per MJ of NE. These feed prices were less than 110% of the least cost diets prices of each line.

Table 3 Environmental impacts of 1 kg of the conventional, optimised tailored diet (OTD) and least cost diets for the low residual feed intake (LRFI) line and the high RFI (HRFI) line.

	GWP kg CO_2 eq	AP g SO_2 eq	EP g P eq	LO m^2a crop eq	EI_{score}	Price €	NE MJ
/kg feed							
LRFI OTD	0.456	6.64	0.43	1.27	3.68	0.199	9.38
LRFI least cost diet	0.504	5.71	0.49	1.69	4.00	0.187	9.30
HRFI OTD	0.433	6.34	0.58	1.48	3.85	0.208	9.78
HRFI least cost diet	0.484	6.84	0.60	1.42	4.00	0.204	10.01
Conventional diet	0.494	6.66	0.41	1.81	4.04	0.234	9.70
/MJ NE							
LRFI OTD	0.0486	0.707	0.0458	0.135	0.392	0.0212	
LRFI least cost diet	0.0541	0.613	0.0526	0.181	0.430	0.0201	
HRFI OTD	0.0442	0.648	0.0593	0.151	0.393	0.0213	
HRFI least cost diet	0.0483	0.683	0.0599	0.141	0.399	0.0203	
Conventional diet	0.0509	0.686	0.0422	0.186	0.416	0.0241	

P = phosphorous; m^2a crop eq= area time; EI_{score} = environmental impact score obtained from normalized impacts to the least cost diet combined additively with a weigh of one. The difference in percentage between the low residual feed intake line (LRFI) and the high RFI (HRFI) line optimised tailored diets (OTDs) with conventional diet standardised to their net energy (NE).

3.3 Sensitivity analysis of the environmental impacts of the diets to the representative requirements of the lines and weighting factors

To evaluate the sensitivity of the optimised tailored diet environmental impacts to the changes in representative requirements of the lines, a sensitivity analysis was performed by changing all the requirements by +1 or -1 SD at once. The percentage changes in the environmental impacts and the environmental score of the new optimised tailored diets (details on composition are provided in supplementary material (S3) are shown in fig 2. All environmental impacts increased after increasing the representative requirements of the lines by +1SD in the two lines, except AP for LRFI line and EP for HRFI. Changes in the HRFI line were more than 5% for all environmental impacts with the exception of AP (+4%), whereas sensitivity was much higher for the LRFI optimised tailored diet, with marked increases in LO and EP (> +35%). On the other hand, decreasing all the representative requirements of the lines by 1SD led to moderate changes in the environmental impact of the line optimised tailored diets. HRFI optimised tailored diet had increased GWP and LO after reduction of the requirements (> +11%), and decreased EP (-25%), whereas all environmental impacts were reduced for the LRFI optimised tailored diet when -1SD was applied to the requirements, from 6% (EP) to 10% (LO), with very limited change in AP. Based on these sensitivity results, GWP, EP and LO were most sensitive to the changes in requirements. The environmental scores were affected by the changes in requirements mainly in the LRFI line, with a decrease of 6.2% when the requirements were reduced and an increase by 18% when they were increased.

To evaluate the sensitivity of the optimised tailored diet score to variations of environmental impact weights, a one-at-a-time sensitivity analysis was performed (fig 3). Altogether, the sensitivity of the optimised tailored diet environmental score to the score weight changes was relatively low, and only found for LRFI optimised tailored diet: the main sensitivity was found for increases in the LRFI optimised tailored diet scores in relation to LO, EP and AP reduced weights (increases > 6%), and LRFI optimised tailored diet scores when the weights for AP and GWP were increased.

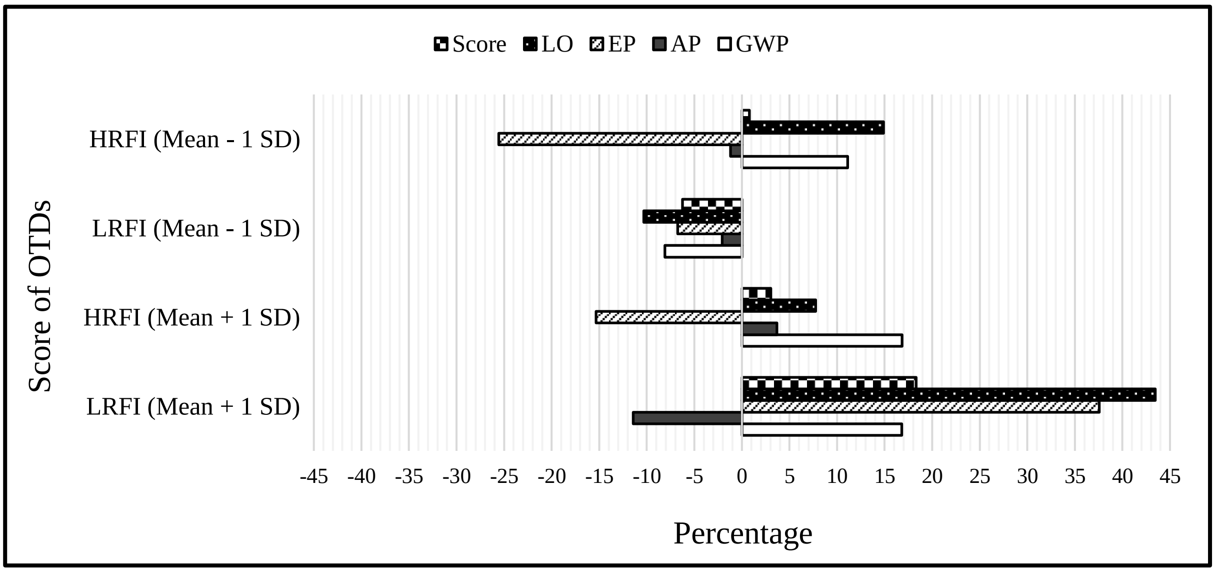

Fig 2. Percentage changes in the environmental impacts and score of the optimised tailored diets for the high residual feed intake (HRFI) line and the low residual feed intake (LRFI) line when the representative requirements of the lines are changed by ±1SD all-at-once in the diet-

optimised formulation. GWP = global warming potential; AP = acidification potential; EP = freshwater eutrophication potential; LO = land occupation.

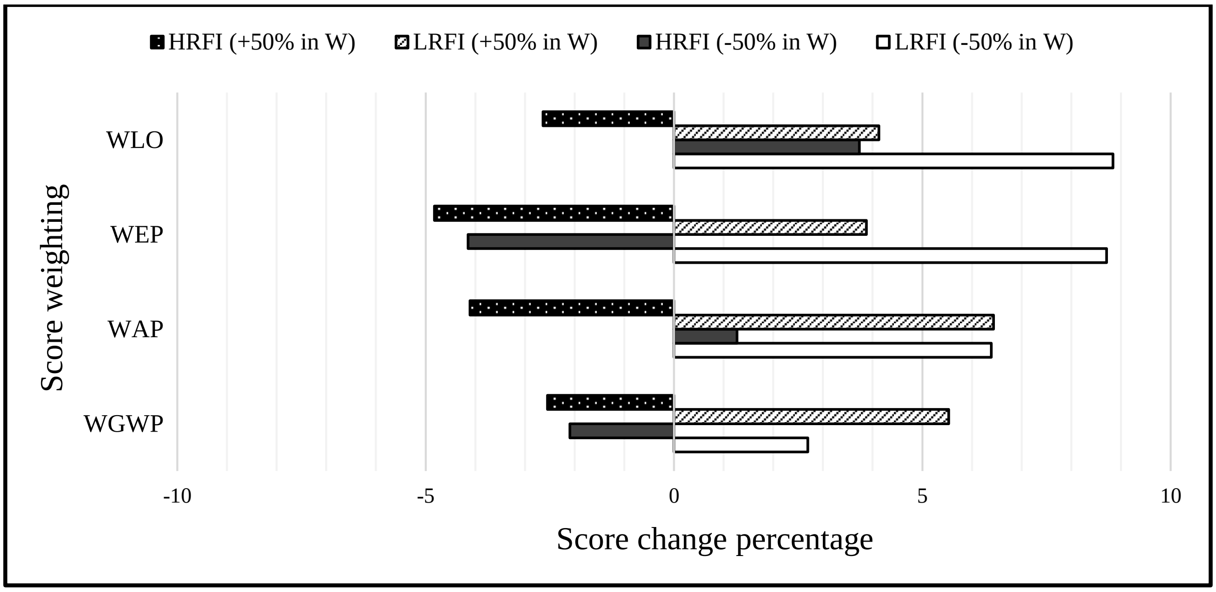

Fig 3. Percentage changes in the environmental score of the optimised tailored diets of the high residual feed intake (HRFI) line and the low residual feed intake (LRFI) line when the weights (w_{GWP}, w_{EP}, w_{AP} and w_{LO}) were changed by ±50% one-at-a-time for the diet-optimised formulation. w_{GWP} = weight for global warming potential; w_{EP} = weight acidification potential; w_{EP} = weight freshwater eutrophication potential; w_{LO} = weight land occupation.

3.4 Simulated individual trait responses to the line optimised tailored diets

The performance responses of all individual pigs to the line optimised tailored diets were simulated with InraPorc® up to the 120 kg BW. Table 4 gives the resulting mean and SD of the performance traits for each line. Significant differences between the lines were observed for feed intake ($P < 0.05$), energy conversion ratio ($P < 0.001$), protein weight at slaughter ($P < 0.0001$), backfat thickness ($P < 0.0001$), body lipids at slaughter ($P < 0.0001$), with lower average values in the LRFI line, and age at slaughter ($P < 0.05$) and ratio body proteins/body lipids at slaughter ($P < 0.0001$), with higher values in the LRFI line.

Table 4 Mean and standard deviation (SD) of growth performance traits and body composition for the low residual feed intake (LRFI) line and high residual feed intake (HRFI) line fed their corresponding optimised tailored diet, simulated by InraPorc®.

	Mean LRFI	**Mean HRFI**	**SD LRFI**	**SD HRFI**	***P*[1]**
Traits					
ADG fattening (kg/d)	0.78	0.81	0.09	0.07	0.061
ADFI fattening (kg/d)	2.04	2.13	0.21	0.16	<0.05
FCR fattening (kg /kg gain)	2.61	2.64	0.19	0.18	0.55
ECR fattening (MJ /kg gain)	24.56	25.84	1.81	1.77	<0.001
Fattening duration (days)	119.5	112.9	16.3	11.8	<0.05
BW slaughter (kg)	121.37	121.26	0.43	0.43	0.34
Age slaughter (days)	191.05	185.12	15.26	11.36	<0.05
PD fattening (g/day)	127.8	128.2	14.0	11.3	0.76
BL (kg)	24.70	28.08	3.09	2.65	<0.0001
BFT slaughter (mm)	16.20	17.50	1.15	0.99	<0.0001
BP (kg)	19.38	18.89	0.44	0.37	<0.0001
BP/BL at slaughter	0.79	0.68	0.11	0.07	<0.0001

BW = body weight; ADG = average daily gain; ADFI = average daily feed intake; FCR = feed conversion ratio; ECR = energy conversion ratio; PD = protein deposition; BFT = back fat thickness; BP/BL = ratio of body protein weight/ body lipid weight at slaughter. BP = body protein content; BL = body lipid content.

[1]*P* were calculated via a t-test on the line effect.

3.5 Environmental assessment of the overall farm feed efficiency approach

To assess the environmental impacts of producing 1 kg of live pig through feeding the line optimised tailored diets, an individual LCA was performed in SimaPro for each pig fed its line optimised tailored diet, based on the performance traits simulated with InraPorc®. Table 5 lists the resulting four impact categories for the two lines. In response to their optimised tailored diet, all impact categories differed significantly ($P < 0.05$) between lines, the HRFI line having systematically larger impacts than the LRFI line (from +2.04 for GWP to +18.13 % for LO).

The lines with the conventional diet differed significantly in all impact categories ($P < 0.0001$), with a minimum difference in LO (+6.5%) and maximum difference in AP (+8.7%) in HRFI relative to LRFI (Table 5). The environmental impacts of the lines fed their optimised tailored diets are shown together with their environmental impacts with the conventional diet in Fig 4, with reference to the scenario with least environmental impacts (LRFI line fed its optimised tailored diet). Feeding the lines with their optimised tailored diets reduced all environmental impacts compared to when fed the conventional diet ($P < 0.0001$), with the exception of EP which increased ($P < 0.0001$). For all environmental impact categories, a bigger decrease was found with the line optimised tailored diet for the HRFI genetic line than the LRFI genetic line, with the exception of LO, which remained quite high. Altogether, feeding the HRFI line its optimised tailored diet led to a scenario with less environmental impacts than the LRFI line fed the conventional diet, with the exception of EP.

Table 5. Mean and standard deviation (SD) of four environmental impact categories calculated per kg of body weight of pig at the farm gate (120 kg body weight) through individual LCA using the ReCiPe 2016 Midpoint (H) V1.13 method for the low residual feed intake (LRFI) line and the high residual feed intake (HRFI) line fed their optimised tailored diet (OTDs) and conventional diet (Con).

Impact category	Unit	Mean LRFI OTD	Mean HRFI OTD	SD LRFI OTD	SD HRFI OTD	P^{1} OTDS	Mean LRFI Con	Mean HRFI Con	SD LRFI Con	SD HRFI Con	P^{1} Con
Global warming potential	kg CO_2 eq	1.96	2.00	0.098	0.092	<0.05	2.07	2.21	0.124	0.124	<0.0001
Acidification	g SO_2 eq	35.6	36.5	2.37	2.22	<0.05	36.8	40.0	2.783	2.797	<0.0001
Eutrophication	g P eq	1.27	1.39	0.077	0.081	<0.0001	1.16	1.24	0.077	0.077	<0.0001
Land occupation	m^2a crop eq	3.53	4.17	0.21	0.24	<0.0001	4.30	4.58	0.30	0.30	<0.0001

P = phosphorous; m^2a crop eq = area time;

[1] *P* were calculated via a t-test on the line effect.

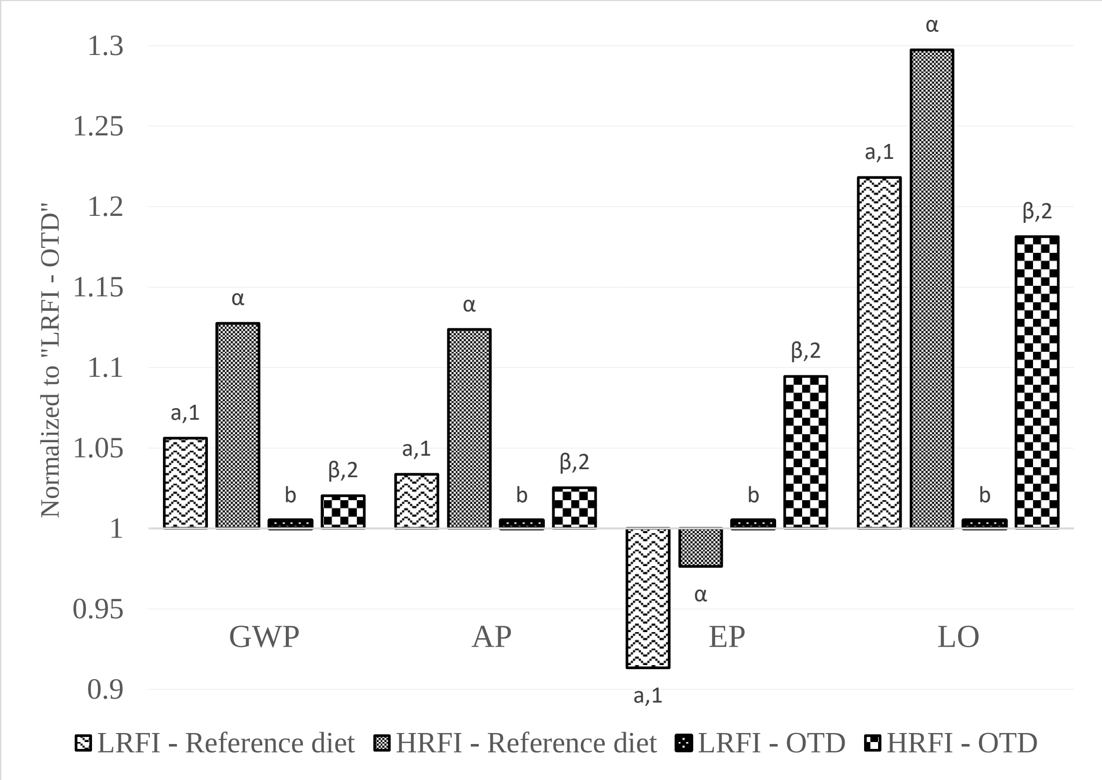

Fig 4. Four environmental impact categories for the low residual feed intake (LRFI) line and high residual feed intake (HRFI) line fed their optimised tailored diet (OTD) and the conventional diet, presented relative to the impacts of the LRFI line fed its OTD. GWP = global warming potential; AP = acidification potential; EP = freshwater eutrophication potential; LO = land occupation.

[1] for each impact category, different superscripts in Latin letters indicate significant differences at $P < 0.05$ for pairwise T test comparisons of impacts of the LRFI line fed different diets; different superscripts in Greek letters indicate significant differences at $P < 0.05$ for pairwise T test comparisons of impacts of the HRFI line fed different diets; different number superscripts indicate significant differences at $P < 0.05$ for pairwise T test comparisons of impacts of the LRFI line fed the conventional diet and the HRFI line fed the OTD.

3.6 Correlations between growth performance traits and impact categories

To gain more insight into the relationships between growth performance traits and environmental impacts when the lines where fed their optimised tailored diet, phenotypic correlations were computed between the individual performances and the individual LCA results in each line fed its own optimised tailored diet (supplementary material S4). According to the 95% confidence interval of the correlation estimations, no difference between lines could be inferred for these correlations, except for RFI whose correlation with environmental impacts was 0.49 in the LRFI line, whereas it was 0.11 in the HRFI line. A principal component analysis (PCA) was performed to illustrate these correlations between traits and environmental impacts. Figure 5 shows the projection of the traits and EIs on the two first dimensions. All the impact categories were highly correlated with FCR, with correlations higher than 0.82, driving the first dimension of the PCA. Impact categories also had moderate to high negative correlations with traits related to protein deposition BP/BL ratio, BP, PD and ADG, with the absolute values higher than 0.42 for both lines.

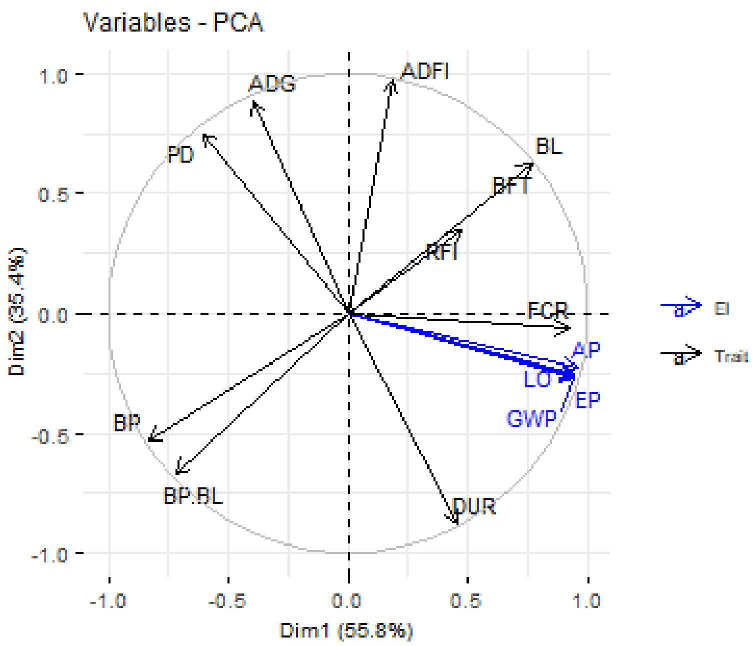

Fig 5. Projection of the traits and environmental impacts (EI) on the two first dimensions of a principal component analysis applied to the correlation matrix between and the environmental impacts and the traits after adjustment for the line effect (N=114 pigs with data). DUR = duration; ADFI = average daily feed intake; ADG = Average daily gain; BP = Body protein at slaughter; BP.BL = Ratio of body protein-to-body lipid at slaughter; PD = average daily protein deposition; BFT= back fat thickness; FCR= Feed conversion ratio; RFI = residual feed intake; BL= Body lipid content at slaughter; GWP = global warming potential; AP = acidification potential; EP = freshwater eutrophication potential; LO = land occupation.

4 Discussion

In this study, the reduction of environmental impacts of pig production due to improvement in overall farm feed efficiency was assessed through LCA. Genetic selection for feed efficiency, formulation of diet tailored to each line, and environmental diet optimisation were combined to achieve better production efficiency with reduced environmental impacts.

4.1 Environmental assessment of overall farm feed efficiency

Performing individual LCA on the two genetic lines of pigs fed their optimised tailored diet markedly improved the environmental score, demonstrating the value of the overall farm feed efficiency approach for environmental optimisation of pig production. In this study, the objective was to demonstrate that optimised combinations of genetics and diets is a path to reduce the environmental burden of pig production. From this simulation study, changes in the assumptions and conditions of the model could affect the outcomes of each scenario. However, most deviations from the current assumptions would have a similar effect for all the compared scenarios. For instance, it is expected that variations in the supply chain of the ingredients (e.g. origin), database inventories, manure management and application, farm operations, pig survival rate, and other methodological choices would modify the magnitude of the impacts for all scenarios, while the general conclusions about the scenario differences would hold robust. The results of this study are limited to the simulation tools and further field studies will be required to confirm these outcomes. With weights of 1 for the four impact categories in the environmental score and our list of ingredients, the lines fed their optimised tailored diet had lower GWP, AP and LO than the lines fed a single conventional diet, but not higher EP. Since the phosphorous content of the optimised tailored diets was lower than in the conventional diet, the increased EP in the two lines could be explained by the higher EP of the optimised tailored diet, via higher EP of their ingredients, rather than by increased excretion and leaching of phosphorous during manure storage and spreading. The substitution of the synthetic fertilisers by the N, P and K of the manure has partly alleviated the environmental burdens of the pig production. The differences in environmental impacts between the LRFI and HRFI lines fed their optimised tailored diet were smaller than the differences when they were fed the conventional diet, even if only a limited list of ingredients to be incorporated was considered in our study. Including a larger variety of ingredients, for instance with lower environmental impacts and lower amino acid concentrations relative to NE, as HRFI pigs had lower representative requirements, could further limit the environmental impacts of the less efficient pigs in a population. Furthermore, as previously reported by Soleimani and Gilbert (2020) with the same model applied to the lines fed the conventional diet, correlations between performance traits and environmental impacts appear to be robust to changes in the animals' genetic potential, and the present study shows that they are also robust to the diet. Thus, the high correlations between all environmental impacts and FCR and protein deposition related traits make them good candidates for the definition of an environmentally oriented selection index.

4.2 Formulation of diets tailored to each line and environmental multiobjective optimisation

A number of studies have been dedicated to optimise diets to achieve different objective functions. Pomar et al. (2012) considered the reduction in N and P excretions as the objective function, Nguyen et al. (2013) targeted cost as the objective function, and GWP and EP as the constraints. Tallentire et al. (2017) minimised a single impact as the objective function along with the constraint of limiting the increase in the cost of the diet compared to a least cost diet. Mackenzie et al. (2016) included four environmental impact categories in their objective function, and combined predictions of excretion corresponding to each dietary nutrient. Finally, Garcia-Launay et al. (2018) presented a multiobjective formulation method to include feed costs and environmental impacts in the objective function using weighting factors. In our study, we capitalised on these approaches to implement a multi-objective diet formulation combining environment, cost and line nutritional requirements. More specifically, the choice of an environmental score is critical, along with the choice of which environmental impacts to include, the choice of normalization factors to standardise the magnitude of the environmental impacts in the score, and the choice of weights to combine them. First, the four highest environmental impacts at the pig production level were retained. Energy demand for instance, as one of the main impacts of diet productions, could be added to the model later (Basset-Mens et al. 2005; Leinonen et al. 2012). Second, we normalized the diet impacts to the environmental impacts of the least cost diet for each line (Garcia-Launay et al. 2018), so all environmental scores can be interpreted with respect to this reference. Third, equal weights were considered for all impact categories in the definition of the environmental score to minimise (Mackenzie et al. 2016). Diet optimisation for a single environmental impact may increase other impact categories (Tallentire et al. 2017). Giving equal weights is an arbitrary choice, and, depending on the societal context and on the load of the different impacts on the territory, different weights could be applied. However, the sensitivity analysis results showed that changes in the environmental impact score are difficult to predict when the weights are modified, as previously reported by Garcia-Launay et al. (2018): a higher value for a given weighting factor does not ensure a major reduction in the intended impact, and may increase other impacts. Finally, rather than considering the estimated emissions and excretions after diet consumption in the diet optimisation (Mackenzie et al. 2016), our formulation approach was constrained to the NE content of the resulting diet. This choice ensures consistency with the expected intakes, and hence related emissions and excretions at the pig farm level. Simultaneously minimising the environmental impacts and constraining cost is a multi-objective optimisation problem, with the issue of having a different scale for each objective. Different approaches have been proposed to solve this problem in the context of combining environmental impacts and costs, such as monetising the environmental impacts to combine all objectives in a cost function (Eldh et al. 2006), or normalizing the impacts, and weighting them in a single score (Mackenzie et al. 2016). To avoid assumptions on the costs of the different environmental impacts, we chose the second option in this study, and combined it with a constraint on the increase in cost. Environmental diet optimisation can increase the cost of the diet, which is the biggest production cost for owners of pig farms. Relative to the conventional diet, the optimised tailored diets cost less and had lower environmental impact scores, per kg of feed and per unit of NE. However, minimising the environmental impacts had a cost at the level of the diet, which in our study was higher for the HRFI optimised tailored diet than for the LRFI optimised tailored diet. Increasing the number of ingredients, and diversifying them towards incorporation of by-products, would certainly provide more flexibility in the diet optimisation and minimisation of environmental impacts. However since the main concern of the study was to develop and demonstrate the approach towards overall farm feed efficiency, a limited number of new ingredients was tested. In addition to the environmental assessment of overall farm feed efficiency strategies proposed in this study, further economic assessments would be needed to provide complementary insights into their sustainability.

4.3 Choice of nutritional requirements for each line and performance responses of individual pigs to their optimised tailored diet

The representative requirements of the LRFI were higher than those of the HRFI, as previously reported by Gilbert et al. (2017) for the same genetic lines. Respecting the high correlations between the five representative requirements, the all-at-once sensitivity analysis showed that environmental impacts were quite sensitive to representative requirements, especially when they were increased by +1SD. Due to switches between ingredients to respond to the new requirements, the effects on the environmental impacts were quite varied, both in direction and magnitude. However, when summed in the environmental score, the main changes were changes in LRFI representative requirements. The higher baseline requirements for LRFI might reflect the higher sensitivity of impacts to higher requirements and underlines the need to adequately capture the nutritional requirements of the targeted animals.

The performance traits showed a decrease in growth rate in both lines with the optimised tailored diets compared to the conventional diet (Soleimani and Gilbert, 2020), leading to approximately three more days required for the pigs to reach 120 kg BW. This is certainly related to the choice of representative requirements to formulate the line constraints: considering the average maximum nutritional requirements in each line would lead to the nonsatisfaction of the requirements in about half the animals in the early stage of the growing phase. In our dataset, this was limited to the very first days of the growing period, but could create a longer delay in reaching slaughter body weight. In an environmental perspective, the reduction in growth rate could be considered to be offset by the reduction in the environmental impacts to produce 1 kg of live pig in both lines. One possible way to alleviate this reduction in growth performance would be to increase the representative requirements, considering the 75% quantile of the maximum pig requirements per line, rather than the average maximum. Increased environmental impacts would certainly result from this strategy, especially in the more efficient genetic line, as shown by the sensitivity analysis. However, this could be reduced by formulating optimised tailored diets for different growth stages using multiphase feeding. In addition, individually tailored diet formulation and optimisation would certainly offer higher overall farm feed efficiency through precision feeding of individual pigs (Pomar and Remus 2019) selected for feed efficiency. However, a further economic assessment would reveal to what extent cost is compromised by switching from a conventional diet to optimised tailored diets at the farm level.

5 Conclusion

Animal selection for feed efficiency, formulation of diets tailored to the requirements of a genetic line, and environmental optimisation of the diet have separate potential for improving farm feed efficiency to reduce environmental impacts. Our study shows that combining these levers in an overall farm feed efficiency approach would remarkably reduce the environmental impacts of pig production systems. The real time diet formulation tailored to the requirements of each individual selected for feed efficiency, integrated in real time optimisation according to an objective or multi-objective environmental function, would be a complementary tool to mitigate the environmental impacts of pig production. Although environmental optimisation of the production system was achieved in our study, economic evaluations of the full production system including different ranges of genetic and dietary options will be necessary to achieve selection and formulation decisions that tackle the necessary trade-offs between economic and environmental objectives of a sustainable pig production system.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest.

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3.3 **Supplementary material of the paper**

Supplementary material 1. The following formulations have been applied to calculate the emissions and excretions using the mass-balance approach.

eBW= 5.969 * BP 0.944 + 0.854 * BL 0.944	(van Milgen et al., 2008)
Lean meat percentage = 72.58 – 43.49 * BL/ eBW	(van Milgen et al., 2008)
N Body = e^(-0.9892 – 0.0145 * Lean%) * eBW^(0.7518 + 0.0044 Lean%) / 6.25	(Dourmad et al., 1992)
N Intake = Feed Intake * N Feed	
N Excreted = N Intake – N Retained	
P_{Body} (g) = 5.39 * eBW	(Rigolot et al., 2010a)
Ca_{Body} (g) = 8.56 * eBW	(Rigolot et al., 2010a)
K_{Body} (g) = -0.0041 * eBW^2 + 2.68 * eBW	(Rigolot et al., 2010a)
Cu_{Body} (mg) = 1.1 * eBW	(Rigolot et al., 2010a)
Zn_{Body} (mg) = 20.6 * eBW	(Rigolot et al., 2010a)
N_20 = 0.002 * N Excreted	(Rigolot et al., 2010b)
N_2 = 5 * N_20	(Rigolot et al., 2010b)
$NH_{3\ Building}$ (kg) = 17 / 14 * 0.24 * N Excreted	(Rigolot et al., 2010b)
ResD = Feed Intake * Residue Feed	(Rigolot et al., 2010b)
$ECH_{4\ growing}$ = ResD * 670	(Rigolot et al., 2010a)
$CH_{4\ Emitted}$ = ECH_4 / 56.65	(Rigolot et al., 2010a)
$CH_{4\ Housing}$ (kg) = VS * B_0 * MCF	(Rigolot et al., 2010b)
OM_{Faeces} = Feed * OM_{feed} * (1 – dCOM)	(Rigolot et al., 2010a)
dCOM = (0.744 + (14.69 DE – 0.50 NDF – 1.54 MM) / DM) / (OM / DM)	(Rigolot et al., 2010a)

eBW = empty body weight ; BP = body protein ; L = body lipid; N Body = nitrogen content of body; N Intake = total uptaken nitrogen; N Feed = nitrogen content of 1kg feed; N Excreted = total excreted nitrogen; NRetained = nitrogen retained in the body; OM = organic matter; MM = mineral mater; DM = dry matter; dCOM = feed organic matter digestibility coefficient; NDF = Neutral detergent fiber; B0 = maximum CH4 producing capacity; MCF = methane conversion factor; ResD = digested fibre ingested.CH4 = methane; N = nitrogen; Ca = calcium; P = phosphorus; K = potassium; Cu = copper; Zn = zinc.

Supplementary material 2. Compositions of the conventional, optimised tailored diets (OTD) and least cost diets of the low residual feed intake (LRFI) and high RFI (HRFI) lines.

Ingredients	Conventional diet	LRFI OTD	HRFI OTD	LRFI Least Cost	HRFI Least Cost
	(NE = 9.70 MJ)	(NE = 9.38 MJ)	(NE= 9.78 MJ)	(NE = 9.30 MJ)	(NE = 10.01 MJ)
Ingredient, g/kg					
Oat	0	0	0	0	0
Triticale	0	53	1	545	170
Corn	0	319	316	7	501
Pea	0	0	160	28	38
Rapeseed meal	0	155	82	34	1
Sunflower meal	0	0	0	80	24
Barley	409	354	347	263	153
Wheat	327	73	44	1	2
Soybean meal 48	202	3.83	0	0	67
Sunflower oil	23	0	9	0	0
L-Lysine HCL	3.5	5.6	4.5	5.5	7.7
L-Threonine	1.4	1.7	1.8	2.0	1.9
L-Tryptophan	0.3	0.4	0.5	0.2	0.5
DL-Methionine	0.9	0.5	0.8	0.6	0.7
Salt (Sodium Chloride)	4.5	4.5	4.5	4.5	4.5
Calcium carbonate	11	11	11	11	11
Dicalcium phosphate	12	12	12	12	12
Vitamins and minerals	5	5	5	5	5
Nutrient composition, g/kg					
Ash	58.5	54.3	52.1	54.3	49.1
Dry matter	877.7	873.0	871.8	876.6	871.6
Organic matter	819.2	818.6	819.8	822.4	822.5
Crude protein	172.3	135.9	132.6	131.1	128.9
Crude fiber	38.1	45.8	42.4	47.6	33.3
Starch	411.5	465.4	482.4	481.5	521.2
Gross energy (MJ/kg)	16.22	15.70	15.86	15.56	15.74
NDF	141.7	159.9	145.8	161.2	124.3
ADF	47.4	62.6	45.4	60.4	40.3
Residue	163.0	165.6	147.0	165.9	122.2
Calcium	9.97	9.63	9.12	9.08	8.67
Phosphorus	6.21	6.01	5.47	5.95	5.02

Supplementary material 3. The compositions of optimised tailored diets (OTDs) obtained from ±1 standard deviation (SD) changes in line representative requirements (LRRs) of the low residual feed intake (LRFI) and high residual feed intake (HRFI) lines.

Ingredients	HRFI +1SD	HRFI -1SD	LRFI +1SD	LRFI -1SD
Oat	0	63	6	0
Triticale	290	173	491	5
Corn	268	68	1	454
Pea	6	65	25	3
Rapeseed meal	16	4	2	29
Sunflower meal	0	2	189	0
Barley	180	397	194	234
Wheat	60	157	49	215
Soybean meal 48	137	0	2	19
Sunflower oil	0	32	0	0
L-Lysine HCL	5.5	4.5	7.0	5.4
L-Threonine	2.1	1.7	2.4	1.7
L-Tryptophan	0.4	0.3	0.3	0.4
DL-Methionine	1.9	0.7	0.5	1.7
Salt (Sodium Chloride)	4.5	4.5	4.5	4.5
Calcium carbonate	11	11	11	11
Dicalcium phosphate	12	12	12	12
Vitamins and minerals	5	5	5	5

Supplementary material 4. Phenotypic correlations (95% confidence interval) of four environmental impact categories with the performances in the LRFI and HRFI lines fed the tailored diets.

Trait	GWP	AP	EP	LO
LRFI line				
ADG Fattening	-0.60 (-0.75;-0.41)	-0.57 (-0.72;-0.37)	-0.60 (-0.74;-0.41)	-0.60 (-0.74;-0.41)
FCR Fattening	0.84 (0.74;0.9)	0.85 (0.76;0.91)	0.84 (0.74;0.9)	0.84 (0.74;0.9)
RFI (g/d)	0.49 (0.26;0.66)	0.50 (0.29;0.67)	0.49 (0.26;0.66)	0.49 (0.27;0.66)
Duration Fattening (d)	0.66 (0.49;0.79)	0.63 (0.44;0.76)	0.66 (0.49;0.78)	0.66 (0.48;0.78)
ADFI Fattening	-0.13 (-0.38;0.13)	-0.09 (-0.34;0.17)	-0.13 (-0.37;0.13)	-0.13 (-0.37;0.13)
BP/BL ratio	-0.42 (-0.61;-0.19)	-0.47 (-0.65;-0.24)	-0.43 (-0.62;-0.19)	-0.43 (-0.62;-0.2)
BFT	0.44 (0.21;0.63)	0.48 (0.26;0.66)	0.45 (0.22;0.63)	0.45 (0.22;0.63)
PD	-0.76 (-0.85;-0.63)	-0.74 (-0.84;-0.59)	-0.76 (-0.85;-0.62)	-0.76 (-0.85;-0.62)
BL	0.44 (0.21;0.63)	0.48 (0.26;0.66)	0.45 (0.22;0.63)	0.45 (0.22;0.63)
BP	-0.56 (-0.71;-0.35)	-0.59 (-0.74;-0.4)	-0.56 (-0.71;-0.35)	-0.56 (-0.71;-0.36)
HRFI line				
ADG Fattening	-0.51 (-0.68;-0.29)	-0.49 (-0.67;-0.27)	-0.51 (-0.68;-0.29)	-0.51 (-0.68;-0.28)
FCR Fattening	0.82 (0.71;0.89)	0.83 (0.72;0.89)	0.82 (0.71;0.89)	0.82 (0.71;0.89)
RFI (g/d)	0.11 (-0.16;0.36)	0.12 (-0.14;0.37)	0.11 (-0.15;0.36)	0.11 (-0.15;0.36)
ADFI Fattening	0.73 (0.58;0.83)	0.71 (0.55;0.82)	0.73 (0.57;0.83)	0.72 (0.57;0.83)
BP/BL ratio	-0.01 (-0.27;0.25)	0.02 (-0.24;0.28)	0 (-0.26;0.26)	0 (-0.26;0.26)
BFT	-0.63 (-0.76;-0.44)	-0.65 (-0.78;-0.47)	-0.63 (-0.77;-0.45)	-0.63 (-0.77;-0.45)
PD	0.68 (0.51;0.8)	0.7 (0.54;0.81)	0.68 (0.51;0.8)	0.68 (0.51;0.8)
BL	-0.69	-0.68	-0.69	-0.69

	(-0.81;-0.53)	(-0.8;-0.51)	(-0.81;-0.52)	(-0.81;-0.52)
BP	0.68 (0.51;0.8)	0.70 (0.54;0.81)	0.68 (0.51;0.8)	0.68 (0.51;0.8)

ADG = average daily gain; ADFI = average daily feed intake; FCR = feed conversion ratio; PD = protein deposition; BFT = back fat thickness; BP/BL = ratio of body protein weight/ Body lipid weight; CC = climate change; AP = acidification potential; EP = freshwater eutrophication potential; LO = land occupation.

3.4 **Main messages from Chapter 3**

A linear multi-objective optimisation method allowed to combine diet optimisation tailored to meet the line nutritional requirements with environmental optimisation of the diet (Figure 12). The environmental optimisation was obtained by weighting the environmental impacts of the diet in a **single environmental impact score**.

Thanks to the inclusion of InraPorc® in the LCA model, the **production traits of each individual animal in response to the optimised diets were simulated**, and used for individual assessment of the overall farm feed efficiency approach.

Integrating selection for feed efficiency, nutritional requirements of genetic lines and environmental diet optimisation resulted in overall mitigation of environmental impacts. Environmental impacts decreased compared to environmental impacts of the lines fed the conventional diet, by an average of 4.2% for LRFI and 3.8% for HRFI lines ($P < 0.05$). This outcome is consistent with previous results about the advantage of precision feeding for lowering environmental impacts on one hand, and opportunities to formulate environmentally optimised diets, but quantifies the improvement brought by their combination.

Opportunities to lower impacts of particularly low efficient individuals were identified, as the HRFI line with its optimised tailored diet had fewer impacts than the LRFI line with the conventional diet, except for EP. The high correlations between environmental impacts and feed efficiency reported in the previous chapter were confirmed, and were not affected by the change of diets.

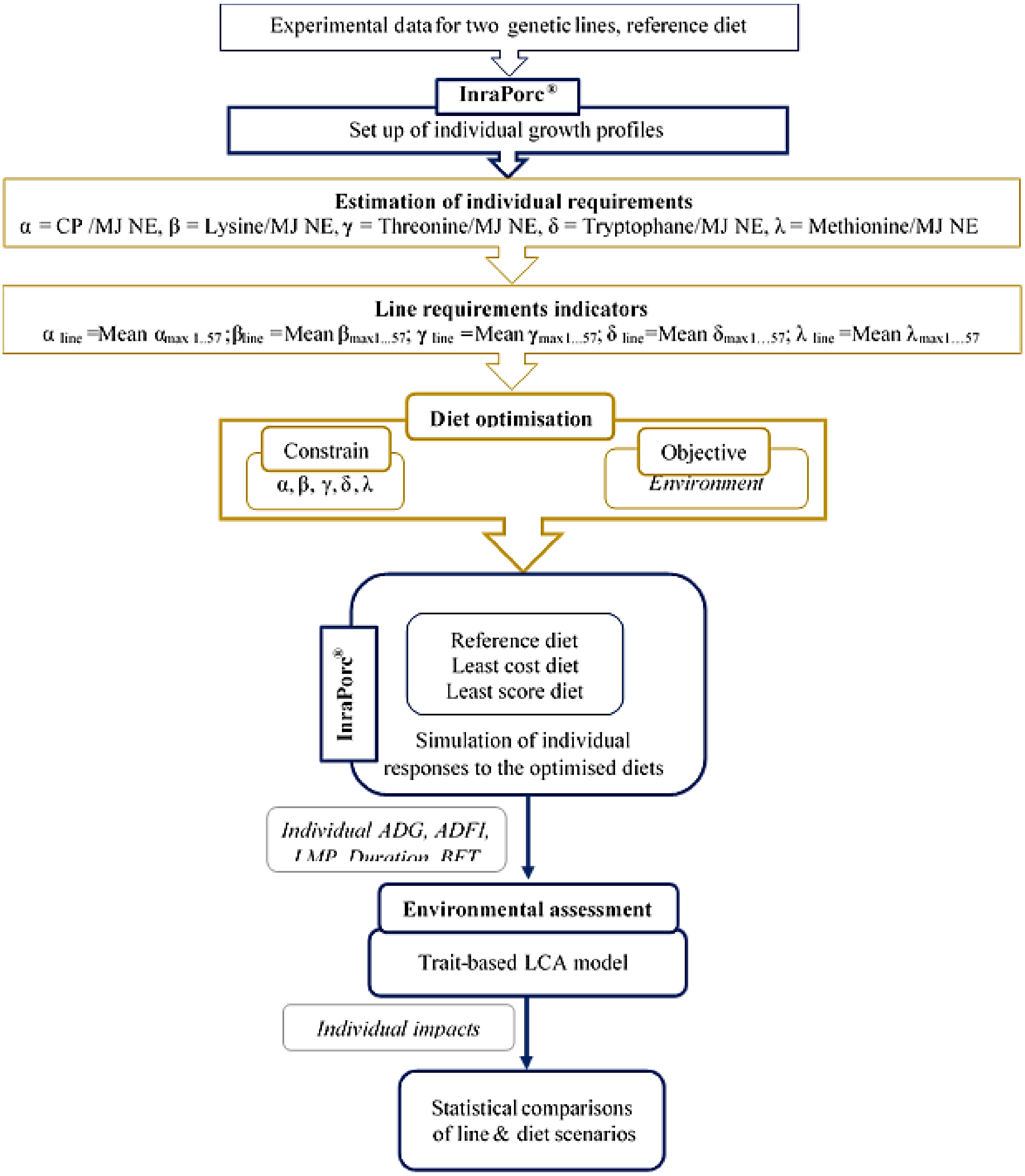

Figure 7. Schematic representation of the base-LCA individual model developments in this second study. The yellow parts show the additions compared to chapter 2

Chapter 4 **Economic and environmental assessments of combined genetic and nutritional strategies: towards a sustainable optimisation of pig production**

4.1 **Introduction**

This chapter aimed to investigate more globally the sustainability of selection for feed efficiency, alone or combined with further diet optimisations, by adding an economical assessment to the developed LCA model. Indeed, sustainability comprises the joint optimisation of its three pillars, so the cost of environmental optimisation needed to be quantified. In addition, the potential for combined optimisations on the two pillars was examined: a joint economic and environmental diet optimisation was added to the diet formulation step to determine a trade-off between economy and environment for the diets.

To fulfil this aim, a trait based bio-economic model was developed from a profit approach. Incorporating the appropriate traits as input parameters to the model enabled performing individually economic assessment. This development was carried out during a four months internship from Nov 2019 to Feb 2020 at AGBU (Armidale, Australia), visiting Prof. Susanne Hermesch. The bio-economic model and previously developed LCA model were applied in parallel to individually assess the economic and environmental impacts of selection for feed efficiency combined to the tailored diets optimised for least cost, least environmental score, and joint economy-environment objectives.

This work has been accepted for oral communication in the French Porcine Days, Feb 2021, *53èmes Journées de la Recherche Porcine* (chapter 6, scientific communications), and is published in the Journal of Animal Science (2021). The supplementary material is provided at the end of the paper.

4.2 Paper III Combined economic and environmental assessments of pig production systems to improve pork production sustainability

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Combined economic and environmental assessments of pig production systems to improve pork production sustainability[1]

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ABSTRACT

We evaluated the economic and environmental impacts of strategies that incorporated selection for pig feed:gain and dietary optimization based on a single or multiple objectives tailored to meet the population's nutritional requirements, with the goal to optimize sustainable *farm feed efficiency.* The economic and environmental features of the strategy were evaluated using life cycle assessment (**LCA**) and bio-economic models. An individual trait-based LCA model was applied to evaluate global warming potential (**GWP**), terrestrial acidification potential (**AP**), freshwater eutrophication potential (**EP**), and land occupation (**LO**) of the combined genetics and nutrition optimization to produce 1kg of live pig weighing 120kg at the farm gate. A parametric individual trait-based bio-economic model was developed and applied to determine the cost breakdown, revenue and profit to be gained from a 120kg live pig at the farm gate. Applying the combined genetics and nutrition optimization, the individual performance traits of pigs from two genetic lines with contrasted levels of feed efficiency were simulated with InraPorc in response to diets formulated for least cost, least environmental impacts, or minimum combination of cost and environmental impacts objectives, and accounting for the nutritional requirements of each line. Significant differences in the environmental impacts ($P < 0.0001$) and profit ($P < 0.05$) between lines predicted the same reference diet showed that selection for feed efficiency (residual feed intake, **RFI**) in pigs improves pig production sustainability. When pig responses were simulated with their line optimized diets, except for EP, all the line environmental impacts were less ($P < 0.05$) than with the reference diet. The high correlations of feed conversion ratio (**FCR**) with the environmental impacts (> 0.82) and the profit (< -0.88) in both lines underline the importance of feed efficiency as a lever for the sustainability of pig production systems. Implementing combined genetics and nutrition optimization, the inherent profit and environmental differences between the genetic lines was predicted to be reduced from 23.4% with the reference diet to 7.6% with the diet optimized jointly for economic and environmental objectives (joint diet). Consequently, for increased pig sustainability, diet optimization for sustainability objectives should be applied to cover the specific nutritional requirements arising in the herd from the pigs' genetic level.

Key words: bio-economic model, feed efficiency, residual feed intake, genetic, environmental assessment, pig.

LIST OF ABBREVIATIONS

LCA, life cycle assessment

GWP, global warming potential

AP, terrestrial acidification potential

EP, freshwater eutrophication potential

LO, land occupation

RFI, residual feed intake

FCR, feed conversion ratio

LRFI, low residual feed intake

HRFI, high residual feed intake

BFT, back fat thickness

LMP, lean meat percentage

EI, environmental impact

PD, protein deposition

w_t, weighting factor

BP, body protein content

BL, body lipid content

BP/BL, body protein content / body lipid content at slaughter

LC, least cost

LLY, L_lysine

LTH, L_threonine

LTR, L_tryptophan

DLM, DL_methionine

INTRODUCTION

Improvement in feed efficiency in pigs can be achieved through genetic selection for feed efficiency as feed efficiency itself (gain:feed), feed: gain, its inverse, or residual feed intake (RFI), diet formulation tailored to the animal's requirements, and optimized to achieve additional objectives. These approaches, alone or combined, have led to the emergence of different feed efficiency scenarios for better production sustainability, some of which have been the subject of separate investigations. Selection for feed efficiency based on the measurement of residual feed intake (**RFI**) and feed conversion ratio (**FCR,** feed:gain) have been successfully implemented in pigs (Clutter , 2011; Gilbert et al., 2007; Cai et al., 2008; Gilbert et al., 2017). The environmental impacts of selection for feed efficiency based on RFI were investigated, for instance by Soleimani and Gilbert (2020a). Improving feed efficiency and reducing environmental impacts by feeding animals with diets tailored to their nutritional requirements based on the precision feeding concept, have also been investigated (Pomar et al., 2009; Monteiro et al., 2016; Remus et al., 2019), and appropriate methods, decision support tools, and systems are currently under development (Brossard et al., 2017; Brossard et al., 2019). Mackenzie et al., (2016); Tallentire et al., (2017), and Garcia-Launay et al., (2018) proposed a variety of diet optimization protocols based on single or multiple objectives. The environmental impacts of feed efficiency improvement scenarios combining genetics, tailored diet formulation, and environmental optimization were investigated by Soleimani and Gilbert, (2020b). However, a joint evaluation of economic and environmental impacts of these approaches is still needed to examine how these two pillars of sustainability can best be combined. It will then be possible to perform animal selection and multi-objective diet optimization tailored to the nutritional requirements of each line, to improve sustainable farm feed efficiency. The economics of a biological process can be evaluated using bio-economic models (Kragt, 2012), which translate biological components into economic indicators through a system of equations (Dekkers et al., 2004). Bio-economic models can be based on either a deterministic approach, in which mean values are input parameters (Brascamp, 1978), a stochastic approach, in which the mean and variances of the input parameters are used (Jones et al., 2004), or a combination of stochastic and deterministic approaches (Michaličková et al., 2016). For environmental assessment, life cycle assessment (**LCA**) has become the standard framework to assess the different aspects of pig production systems (Lammers, 2011; McAuliffe et al., 2016; McAuliffe et al., 2017). In this study, a trait-based bio-economic model was designed and developed to simulate the profit to be made from each individual pig directly using its own traits. When applied to a set of different individuals, it enabled estimation of the relative variability of the profit at farm level. This model was used jointly with our previously developed LCA model, which incorporates the individual performance traits of fattening pigs, to perform LCA of individual pigs (Soleimani and Gilbert, 2020a). The aim of the present study was thus to evaluate the sustainability of several combined genetics and nutrition optimization scenarios in terms of economy and environment, using individual deterministic bio-economic and LCA models to quantify the economic and environmental costs of different optimization options combining diets and pig genetics. Performing individual assessments also provides insights into the correlations between production traits, profit, and environmental impacts, which can then be used for further optimization of selection and management of pig production systems.

MATERIAL AND METHODS

Animal Data

All procedures involving animal data collection were in accordance with the national regulations for humane care and use of animals in research. This section provides an overview on the origin of the experimental data, collection procedures, and tools, and of the application to set up the growth performance profile of the individual pigs. A scheme of the procedure implemented for economic and environmental assessment of combined genetics and nutrition optimization scenarios is presented in supplementary material 1.

Experimental Data. Experimental data were collected from birth to slaughter from the fifth generation of Large White pigs divergently selected for RFI (Gilbert et al., 2017) in the experimental facilities at INRAE (Surgères, France, https://doi.org/10.15454/1.5572415481185847E12). Residual feed intake is defined as the difference between observed feed intake and feed intake predicted from maintenance and production requirements. The present dataset included 57 male pigs from each of the low RFI (**LRFI**, more efficient pigs) and high RFI (**HRFI**, less efficient pigs) lines. Fattening pigs had ad-libitum access to a one phase conventional diet. The daily feed intake of each individual was recorded by ACEMA 64 automatic feeders (ACEMO, Pontivy, France) from 11 weeks of age to 110 kg live weight. Body weight was recorded at birth, at weaning (at average 28 days of age), at the beginning of the growing period (10 weeks of age), and at least once a month during fattening until slaughter (average BW at slaughter 110 kg), and ADG and ADFI for the fattening period were computed. Back fat thickness (**BFT**) was measured using an ALOKA SSD-500 echograph on live animals at 23 weeks of age (Aloka, Cergy Pontoise, France). The selection procedure and results are reviewed in Gilbert et al., 2017 for both LRFI and HRFI lines.

Growth Model and Individual Profiles. The recorded experimental data for all fattening pigs were imported into the population version of InraPorc (Brossard et al., 2014), which simulates the performance of pigs in response to different nutritional strategies (van Milgen et al., 2008). The imported data were first used to calibrate an individual growth performance profile based on the Gompertz growth function for each pig. The profiles for the fattening period were calibrated according to the daily ad-libitum NE uptake using the Gamma function. The calibrated profiles were then used to estimate the feed intake of pigs when offered different optimized diets, to simulate the individual performance responses of pigs up to slaughter weight. A fixed live weight of 120 kg at slaughter was applied to facilitate comparison of the economic and environmental outcomes of the different scenarios. The resulting traits and animal indicators (ADFI, ADG, BFT, lean meat percentage (**LMP**), carcass weight, age at slaughter, and fattening duration) for each individual were used as input parameters for economic and environmental assessment with the bio-economic and LCA models described in the following section.

Bio-economic Model

General Structure. The bio-economic model was developed in R using a typical linear profit model (Janssen and Ittersum, 2007). The linear profit model calculates profit as sales revenue minus costs. In this model, the life cycle of a market pig is assumed to be divided into three periods: up to weaning (~28 days of age), post weaning (~28 to 75 days of age), and growing-finishing (~ 75 days of age to reach 120 kg BW).

Costs (120 kg live pig) = weaned piglet market price + post-weaning costs + growing-finishing costs

All costs related to reproduction (sow plus litter), including artificial insemination and replacement costs, health costs, energy, feed, maintenance, labor force, manure disposal, and capital depreciation were included in the market price of a weaned piglet. Since LRFI sows produced more weaned piglets than HRFI sows (10.2 LRFI vs. 9.6 HRFI, Gilbert et al., 2012) and the lactation feed intake of LRFI sows was lower than that of HRFI sows (4.54 kg/d for LRFI vs. 4.82 kg/d for HRFI, Gilbert et al., 2012), using the same weaning costs for the two lines resulted in a conservative hypothesis for LRFI pigs. Post-weaning costs were calculated using the experimental data collected from the beginning to the end of post-weaning in the two lines. The required data including ADFI, ADG, diet types, and feeding duration are reported in (Gilbert et al., 2019). The fattening costs were calculated based on individual traits. The revenue from each pig was only that obtained from the sale of live pigs at the farm gate, which is equal to the market price of the pig. The cost of manure treatment and application from weaning to finishing was assumed to be offset by its revenue. The values and market prices of the services and raw materials were taken from French and European references. The output of the model is the profit made on an individual 120 kg live pig at the farm gate.

***Breakdown of Costs*.** The costs of fattening including feed and water, building and capital, and energy and labor costs were parametrized individually with performance traits. Other costs including insurance, veterinary care, health, maintenance, and repairs were considered as fixed costs. The cost of each component is summarized in supplementary material 2.

Feed and water costs. Feed and water costs were assumed to be the cost of uptaken feed and water. The cost of feed after weaning was calculated based on a conventional two feed phase dietary sequence, with a starter diet from weaning to day 12 and a post-weaning diet until the end of the post-weaning period. The average daily feed intake (ADFI, kg/d) of the two diets in each line under ad-libitum access to feed is reported in (Gilbert et al., 2019). The cost of feed was calculated by multiplying the average quantity of feed consumed at each stage by the price of the feed in France. During fattening, the cost of feed for each individual pig was obtained by multiplying the price of 1 kg fattening diet (€/kg) by ADFI (kg/d) and the duration the fattening period (d) of the pig concerned. The price of each ingredients was calculated from the monthly average market price of the ingredients in France reported in the monthly information pamphlet on feed published by the pig industry (IFIP - *Institut de la Filière Porcine*, *Mensuel d'information aliment*, May 2020). The cost of drinking water was considered to be proportional to feed consumption, multiplied by the price of drinking water (€/liter). The water to feed ratio was considered to be 2.5 liter/kg of feed in the post-weaning stage (IFIP, 2014). The water to feed ratio was 2.7 liter/kg of feed during the fattening period (IFIP, 2014). The price of water was obtained from the water industry's information center in France (https://www.cieau.com/le-metier-de-leau/prix-des-services-deau/).

Cost of energy. The cost of energy during the post-weaning period in each line was calculated by multiplying the individual ADG and the duration of the post-weaning stage by the energy consumption per kg of weight gain (0.42 kWh/kg of gain, IFIP, 2014) and the cost of energy (€/kWh) in France. The cost of energy during the fattening period was calculated by multiplying individual ADG and fattening duration (d) by 0.42 (kWh/kg of gain) by the price of energy (€/kWh) in France.

Cost of labor. The cost of labor was calculated based on the French reference, which is of 2.3 farm workers for a farm with 200 sows, with 25 weaned piglets per sow per year, 1,600 working hours per year, and the cost per hour of a labor earning the minimum wage (1.5 * min. wage/hour, min. wage = 10.03 €/hour). The cost of labor was broken down into the cost of labor per pig and per day (€/pig/day), and then multiplied by the duration of the post-weaning and fattening to compute the cost of labor for an individual pig at the farm gate.

Buildings and capital costs. Building and capital costs were calculated as the investment required per sow, assuming 25 weaned piglets per sow per year on average and interest rate of 6% per year. Annual depreciation was included in the sales price of a weaned piglet. The capital cost for an individual pig was estimated by multiplying the capital cost per pig and per day (€/pig/day) by the duration of the post-weaning and fattening periods.

Revenue. Revenues are represented by the finishing pig market price. The revenue from selling the cull sows was assumed to be included in the market price of a weaned piglet. In the French market pricing system, the price of a finishing pig is a multivariate function of quantity (carcass weight), quality of the carcass (LMP), and a bonus or penalty per kg carcass depending on the combined values of these two parameters (Supplementary material 3, Lopez et al., 2016). The individual market prices were estimated based on the pig carcass traits simulated by InraPorc for each diet. The base market price of the carcass was calculated using the market price of a 100-kg carcass and LMP of 56% (https://rnm.franceagrimer.fr/prix?PORC).

Profit. The profit per pig (€/pig) was obtained by subtracting the individual production costs from the revenue obtained by the sale of the finished pig. The formulations were used to calculate the individual profit, see supplementary material 4.

Environmental Assessment

LCA Choices. A 'cradle-to-farm-gate' system boundary was built using typical French pig farming systems including sow-litter, post-weaning, fattening pigs, feed production, and manure management, schematically depicted in Soleimani and Gilbert (2020a). One kg live weight (LW) of pig at the farm gate was chosen as the functional unit to enable reliable comparison of the environmental impacts of the different assessments. The impact categories that contributed most to emissions during housing of the animals, manure storage and application (de Vries and de Boer, 2010) were selected for analyses first: global warming potential (**GWP**, kg CO_2-eq), acidification potential (**AP**, kg SO_2 eq), and eutrophication potential (**EP**, kg P eq), which are also the most conventional impact categories in LCA of pig production systems (McAuliffe et al., 2016). Moreover, in pig farming, feed production accounts for almost 100% of the land occupation (**LO**, m^2a crop eq) impact category (Basset-Mens and van der Werf, 2005), and was thus included in our analysis. The method of ReCiPe Midpoint 2016 (H) V1.02 (Huijbregts et al., 2017), the Ecoinvent inventory (Wernet et al., 2016), and Ecoalim (Wilfart et al., 2016) databases were used to assess environmental impacts. Based on the same approach as in a previous study using this model (Soleimani and Gilbert, 2020a), the individual environmental impacts of each pig in the two lines were assessed on the MEANS (MulticritEria AssessmeNt of Sustainability) platform using SimaPro V8.5.4.0 (http://www.inra.fr/means).

The LCA Model. Briefly, the LCA model was developed in six modules based on net energy: animal profile, feeding plan, emissions, excretion, water expenditure, and energy expenditure (Soleimani and Gilbert, 2020a). In addition to the R and InraPorc module to decipher individual profiles during the post-weaning and fattening stages described previously, we also used the sow version of the InraPorc software (Dourmad et al., 2008) to set up a single sow-litter profile per line for all assessments. Energy and water expenditure were calculated based on a report on typical French farms by the IFIP (*Institut de la Filière porcine*, (IFIP, 2014). For individual LCAs, the fattening performance traits of each pig were used as input parameters in the life cycle inventory in SimaPro. Using the mass-balance approach, the composition of the excreta (DM, OM, potassium, phosphorus, and nitrogen) was calculated as the difference between nutrient intake and the nutrients retained in the body (Supplementary material 5). Individual performance data were used for the post-weaning and fattening stages, and average performance data were used for the sow-litter stage. The building emissions of ammonia, nitrogen monoxide, enteric methane, nitrous oxide, and nitrogen were calculated following (Rigolot et al., 2010a; Rigolot et al., 2010b). The guidelines provided by the intergovernmental panel on climate change (IPCC, 2006) were used to calculate emissions of methane, direct and indirect emissions of nitrous oxide, and leaching of phosphate and nitrate during the spreading of slurry. Emissions of ammonia during outside storage were calculated based on the emission factors recommended by Rigolot et al. (2010b). Emissions of nitrogen oxides were calculated following Nemecek et al. (2004). As a replacement for synthetic fertilizer, the fertilizer equivalence value of the manure was considered to be 75% for nitrogen (Nguyen et al., 2010) and 100% for phosphorus and potassium (Nguyen et al., 2011). To be sure the results were consistent and comparable, the same inventories, methods and calculations were used in all the LCA runs. Using the Ecoalim dataset (Wilfart et al., 2016) of the AGRIBALYSE database, the environmental impacts of the diet ingredients were estimated by applying the *ReCiPe Method (2016).* A distance of 100 km was assumed for the transport of the ingredients of the diets from the farm to the feed factory, a distance of 500 km for cereals (Garcia-Launay et al., 2018), and a distance of 30 km (Cadero et al., 2018) for transport from the feed factory to the pig farm, using the Ecoinvent version 3.1 database (attributional life cycle inventories).

Diet Optimization

Choice of Ingredients. Six new ingredients (corn, oats, peas, triticale, rapeseed meal, and sunflower meal) were added to the eight ingredients of the reference commercial diet (wheat, barley, soybean meal, sunflower oil, and synthetic L_lysine (**LLY**), L_threonine (**LTH**), L_tryptophan (**LTR**), DL_methionine (**DLM**), giving a total of Q = 14 ingredients incorporated in the diet formulation. The reference diet was a commercial French conventional experimental diet offered to the animals during the experimental data collection (as fed in 2005). It was thus formulated to allow the expression of the genetic potential of all pigs, with a low cost constraint. The new ingredients were chosen to extend the choice of protein and energy resources based on the availability of data on their impacts, cost, and their market availability. Information concerning digestible CP, AAs, and net NE density of the ingredients was obtained from the feed ingredients database INRA-AFZ (Sauvant et al., 2004). Considered as additives, ingredients that have no digestible CP or AAs or energy (e.g. salt, calcium carbonate, and vitamins) were not included in diet formulation. Although the additives were excluded from diet optimization procedure, their properties, and potential shortcomings created by the inclusion of new ingredients, in the optimized diet was picked up in the simulation of responses to the optimized diets with the InraPorc software. Some commercial and industrial limitations for diet optimization, like the possible incompatibility of the list of ingredients to feed milling and processing constraints were not accounted for in this study either, but in practice, may represent notable constraints.

Definition of the Nutritional Requirements of Each Line. To be able to identify the nutritional constraints to tailored diet formulation, the dietary requirements of the species concerned have to be known. Pigs adjust their ad-libitum feed intake to the dietary NE density (Quiniou and Noblet, 2012), so the nutrients in the diet are taken up in proportion to the NE of the diet. In addition, balanced nutritional composition relies on certain essential AAs lysine, threonine, tryptophan, and methionine, which are usually added to cereals as they are most limiting AA in cereal-based diets (D'Mello, 1993). To avoid AA deficiency, the four above-mentioned amino acids were considered as constraints in the formulation of the diets tested in the present study. To ensure the remaining essential and non-essential amino acids were covered, the requirements for digestible CP per MJ NE were also obtained for each individual from InraPorc and considered among the constraints. Finally, to account for the fact feed intake is regulated by NE density, digestible crude protein, digestible lysine, digestible threonine, digestible tryptophan, and digestible methionine requirements were standardized to the dietary NE (kg/MJ NE), and considered as constraints to be met by diets that are tailored to pig requirements. From the calibrated nutritional profiles of the individual pigs obtained with InraPorc with the experimental data, the digestible CP and four AAs requirement per MJ NE, for each individual pig were obtained from InraPorc. The individual requirement indicators were at maximum in the early stages of growing. The following requirements were averaged to obtain the representative requirement of each line l: digestible crude protein requirement ($Alpha_l$), digestible lysine requirement ($Beta_l$), digestible threonine requirement ($Gamma_l$), digestible methionine requirement ($Lambda_l$), and digestible tryptophan requirement ($Delta_l$).

Nutritional Objective for Diet Formulation. For diet formulation tailored to nutritional requirements, the linear equations 1-6 were defined as constraints for each line *l* (*l* = 2 in our study) and Q as possible ingredients (Q = 14 in our study). The first equation ensures the prospective diet does not exceed one kg, and the remainders of the equations guarantee the dietary nutrient requirements are satisfied based on the representative requirements of each line.

$$\text{1kg – additives (kg)} = \sum_{i=1}^{Q} q_{i_l} \quad (1)$$

$$Alpha_l = \sum_{i=1}^{Q} q_{i_l}\, CP_i \Big/ \sum_{i=1}^{Q} q_{i_l}\, NE_i \quad (2)$$

$$Beta_l = \sum_{i=1}^{Q} q_{i_l}\, LLY_i / \sum_{i=1}^{Q} q_{i_l}\, NE_i \quad (3)$$

$$Gamma_l = \sum_{i=1}^{Q} q_{i_l}\, LTH_i / \sum_{i=1}^{Q} q_{i_l}\, NE_i \quad (4)$$

$$Delta_l = \sum_{i=1}^{Q} q_{i_l}\, LTR_i / \sum_{i=1}^{Q} q_{i_l}\, NE_i \quad (5)$$

$$Lambda_l = \sum_{i=1}^{Q} q_{i_l}\, DLM_i / \sum_{i=1}^{Q} q_{i_l}\, NE_i \quad (6)$$

where q_{i_l} (kg) is the rate of incorporation of the ^{i}th ingredient in the diet in line l, and NE_i (MJ), CP_i (kg/MJ NE), LLY_i(kg/MJ NE), LTH_i (kg/MJ NE), LTR_i (kg/MJ NE), and DLM_i (kg/MJ NE), are, respectively, the net energy, crude protein, lysine, threonine, tryptophan, and methionine contents of ith ingredient as defined above.

Line Tailored Diet Formulation with the Least Cost, Least Environmental Score, and Joint Cost-Environment Optimization Objectives. In addition to covering the requirements of the genetic line selected, for each line, three optimization scenarios were considered: (1) a least cost (**LC**) diet, (2) a diet with the least environmental impact score within an acceptable cost interval compared to the least cost diet, and (3) a joint cost-environment optimized diet. First, the price normalized to the NE of the ingredient was applied to avoid formulating diets with insufficient energy content that would subsequently increase feed intake (Quiniou and Noblet, 2012).

$$min\ cost = \sum_{i=1}^{Q} q_{i_l}\, p_i /\ NE_i \quad (7)$$

where q_{i_l}, p_i, and NE_i are the rate of incorporation of the i^{th} ingredient in the diet targeting line l, the price, and net energy of i^{th} ingredient, respectively, with $i = 1,\ldots, Q$. The least cost diets for each line were obtained by applying the optimization algorithm NSGA-II from the mco library in R version 3.6.3 (with a population size of 340 and 3,500 generations) to the objective function and constraints. This algorithm identifies the non-dominated solutions on the Pareto-optimal front curve that minimize the objective function while best satisfying the constraints.

The environmental impacts (GWP_{LCl}, AP_{LCl}, EP_{LCl}, LO_{LCl}) of the least cost diet for each line l were calculated by summing the environmental impacts of each ingredient (supplementary material 6) in proportion to their rate of incorporation in the diet:

$$impact_{LC_l} = \sum_{i=1}^{Q} q_{i_l}\, impact_i \quad (8)$$

where $impact_i$ is the environmental impact of ingredient i, and *impact* is GWP, AP, EP or LO.

Second, the environmental objective to be minimized was computed. The environmental impacts of the least cost diet of each line were used as normalization factors for each impact of the new line formulated diet (Garcia-Launay et al., 2018). Then, the impacts in an environmental impact score (**EI** score) were combined linearly to obtain the objective function to be minimized:

$$\mathrm{EI}_{score\_l} = \textstyle\sum_{impact=1}^{4} w_{impact}((\sum_{i=1}^{Q} q'_{i_l}\, impact_i\ /NE_i)/(impact_{LC_l}/NE_{LC_l})) \quad (9)$$

where q'_{i_l} and NE_i are the quantity and net energy of i^{th} ingredient in the diet for line l. To avoid unbalanced environmental impacts of the optimized tailored diets, an equal weighting of one was used for w_{GWP}, w_{EP}, w_{AP}, and w_{LO}. The NSGA- II optimization algorithm was applied to the objective function (Eq 9) to obtain the diets with the least environmental impact score under constraints (Eq.1) to (Eq.6), plus the additional constraint that the costs of the least environmental score diets were limited to 110% of the cost of the least cost diet for each line.

Third, the environmental and economic objectives were linearly integrated into one multi-objective function with normalization of each component to their counterparts for the least cost diet used as a baseline, considering a weighting factor **(w_t)** for EI score and its complement of 1-w_t for the cost:

$$\text{Joint Score}_l = w_t\left(\sum_{impact=1}^{4} w_{impact}\left(\left(\sum_{i=1}^{Q} q''_{i_l}\, impact_i\, /NE_i\right)/\left(impact_{LC_l}/NE_{LC_l}\right)\right)\right) + (1-w_t)\left(\left(\sum_{i=1}^{Q} q''_{i_l}\, p_i/\, NE_i\right)/\left(price_{LC_l}\, /NE_{LC_l}\right)\right) \tag{10}$$

where q''_{i_l} and NE_i are the quantity and net energy of i^{th} ingredient in the new formulated diet for line *l*.

Environmental impacts and costs were expressed relative to the net energy of the ingredients. The joint diet was obtained for each line by applying the NSGA- II optimization algorithm on the objective function (Eq. 10) for each w_t from 0 to 1 with a step of 0.01, which made it possible for us to investigate the impact of trade-offs between the economic and environmental objective. The best-optimized diet was when the reduction in the environmental score relative to the environmental score of the least cost diet versus the increase in price relative to the price of the least cost diet became the maximum. This w_t point identified the optimum trade-off between the economic and environmental objectives of the formulation of feed for each line.

Assessment of Profit Sensitivity of Each Line to Market Price Volatility

The profit sensitivity of each line with each diet was evaluated as the percentage change in market prices that would reduce the profit of the line concerned to zero. Since the market price of pig is the only source of revenue in this study and we were focusing on feed efficiency during fattening, the sensitivities of the line were assessed only relative to an increase in the cost of the fattening diets or to a decrease in pig price. Analyzing the sensitivity of the ingredients to price volatility would require re-simulating the responses of individual pigs to the new optimized diets due to changes in the price of the ingredients. Changing the price of an ingredient one at a time could lead to an unpredictable outcome due to the relative prices, CP, and AA content of each ingredient, while the characteristics of each ingredient are beyond the scope of this study.

Statistical Analyses

The performance traits for each pig were simulated with InraPorc in response to the reference and the optimized diets in each line, and then used as input parameters for the individual trait-based bio-economic and LCA models to assess the economic and environmental impacts of the combined genetics and nutrition optimization scenarios. Statistical analyses were performed of the individual profit, environmental impacts, and the performance traits. The line average (SD) of the growth performance traits and their corresponding profits and environmental impacts were computed per line, and Student's t tests were used to test the differences in all variables between the two lines (differences were considered significant at $P < 0.05$). The correlations between profit, environmental impacts, and performance traits were calculated, together with their 95% confidence intervals using the cor.test function in R.

RESULTS

Characteristics of Optimised Diets

Genetic differences were found between the requirements representative of the lines. The averages (SD) requirements for digestible crude protein, digestible lysine, digestible threonine, digestible methionine, and digestible tryptophan were greater for LRFI pigs [11.75 (2.46), 0.91 (0.20), 0.58 (0.12), 0.27 (0.03), 0.16 (0.06) g/MJ NE, respectively] compared to HRFI pigs [11.04 (2.33), 0.86 (0.18), 0.55(0.11), 0.26 (0.05), 0.15 (0.03) g/MJ NE, respectively]. The diets with the least cost and with the least environmental scores tailored to the representative requirements of each line were obtained by minimizing the corresponding objective functions. The joint optimized diet for each line was obtained from an optimum trade-off between least cost and least environmental score objectives using a weighting factor of w_t. The joint diets were obtained for $w_t = 0.24$ for LRFI and $w_t = 0.44$ for HRFI, at the point where the decrease in the environmental score (standardized to the score of the least cost diet) relative to the increase in price (standardized to the price of the least cost diet) was the highest. The composition of the optimized diets are provided in Table 1. The resulting environmental impacts, score, and price of 1 MJ NE of the optimized and reference diets are provided in Table

2. Expressing the environmental impacts, score, and price per MJ NE of the diet made them comparable within and between lines. In both lines, all the optimized diets had lower prices and lower environmental scores than the reference diet, with the exception of the environmental score of the least cost diet in LRFI (0.430 vs. 0.416) due to greater GWP and EP. The joint diet in both lines had a greater environmental score than the least score diet of the line (0.394 vs. 0.392 for LRFI and 0.395 vs. 0.393 for HRFI), and a greater price than the least cost diet of the line (0.0210 vs. 0.0201 for LRFI and 0.0206 vs. 0.0203 for HRFI). In all the optimized diets, EP increased compared to the reference diet. Finally, no systematic difference in the environmental impacts or prices was found between diets formulated for the LRFI and the HRFI pigs.

Table 1 Diet compositions of the reference, least environmental score, least cost and joint cost-environmental diets of the low residual feed intake (LRFI) and high residual feed intake (HRFI) lines

Ingredients	Reference	LRFI Least cost	HRFI Least cost	LRFI Least score	HRFI Least score	LRFI Joint	HRFI Joint
Net energy (MJ/kg)	9.70	9.27	10.01	9.38	9.75	9.69	9.66
Oat	0	0	0	0	0	20	0.4
Triticale	0	545	170	53	1	217	158
Corn	0	7	501	319	316	379	170
Pea	0	28	38	0	160	47.2	89
Rapeseed meal	0	34	1	155	82	52	12
Sunflower meal	0	80	24	0	0	60	40
Barley	409.4	264.0	153.0	354.4	347.9	121.0	361.4
Wheat	327	1.2	2.7	74	44	33.7	107
Soybean meal 48	202	0	67	3.9	0	25.6	17
Sunflower oil	23	0	0	0	9	3.4	4.6
L-Lysine HCL	3.5	5.5	7.7	5.6	4.5	5.6	5.1
L-Threonine	1.4	2	1.9	1.7	1.8	1.9	1.9
L-Tryptophan	0.3	0.2	0.5	0.4	0.5	0.5	0.4
DL-Methionine	0.9	0.6	0.7	0.5	0.8	0.6	0.7
Salt	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Calcium carbonate	11	11	11	11	11	11	11
Dicalcium phosphate	12	12	12	12	12	12	12
Vitamins and minerals	5	5	5	5	5	5	5

Table 2 Environmental impacts[1], environmental impact score, and price per unit of net energy (/MJ NE) of the reference, least score, least cost, and joint cost-environment diets for the low residual feed intake (LRFI) line and the high RFI (HRFI) line

/MJ NE	**GWP**, g CO_2 eq	**AP**, g SO_2 eq	**EP**, g P eq	**LO**, m^2a crop eq	**Environmental impact score**	**Price,** €	**NE,** MJ
Reference diet	509	0.686	0.0422	0.186	0.416	0.0241	9.70
LRFI diets							
Least cost	541	0.613	0.0526	0.181	0.430	0.0201	9.27
Least score	486	0.707	0.0458	0.135	0.392	0.0212	9.38
Joint	486	0.663	0.0505	0.152	0.394	0.0210	9.69
HRFI diets							
Least cost	483	0.683	0.0599	0.141	0.399	0.0203	10.01
Least score	442	0.648	0.0593	0.151	0.393	0.0213	9.75
Joint	490	0.643	0.0496	0.163	0.395	0.0206	9.66

[1]GWP: global warming potential, AP: acidification potential, EP: freshwater eutrophication potential, LO: land occupation

Simulated Individual Trait Responses to the Diets

The average (SD) of the performance traits predicted responses to the line-optimized diets simulated with InraPorc up to 120-kg BW are listed in Table 3. With the same reference diet, the LRFI line had lower predicted ADFI, total feed intake, FCR, RFI, energy conversion ratio, lipid weight, and BFT at slaughter, a longer fattening period, increased protein weight, LMP, and protein/lipid ratio at slaughter ($P < 0.05$). The ADG, BW, and carcass weight at slaughter, and protein deposition during growth did not differ between lines ($P > 0.14$). With the optimized diets, almost the same differences were obtained, except for FCR and feed intake traits when expressed in kilogram of feed due to the differences in NE / kg of optimized diets between the lines. However, expressing conversion ratio in MJ (ECR) returned the original differences. An increase in the duration of the fattening period was observed when pigs performances were predicted from the optimized diets compared to the reference diet. For ADG and duration of fattening, the differences between the lines increased slightly with the optimized diets, especially with the joint diet.

Table 3 Mean (SD) and *P*-values of differences between the lines in growth performance and body composition traits[1] in the low residual feed intake (LRFI) line and high residual feed intake (HRFI) line fed the reference, least cost, least score, and joint optimised diets, as simulated by InraPorc

	Reference			**Least Cost**			**Least Score**			**Joint**		
	LRFI	HRFI	*P*-value[2]	LRFI	HRFI	*P*-value	LRFI	HRFI	*P*-value	LRFI	HRFI	*P*-value
ADG fattening, kg/d	0.80 (0.091)	0.83 (0.080)	0.14	0.77 (0.089)	0.80 (0.071)	<0.05	0.78 (0.089)	0.81 (0.072)	0.06	0.78 (0.090)	0.82 (0.074)	<0.05
ADFI fattening, kg/d	1.99 (0.20)	2.17 (0.16)	<0.0001	2.06 (0.21)	2.08 (0.15)	0.54	2.04 (0.21)	2.13 (0.16)	<0.05	1.98 (0.20)	2.16 (0.16)	<0.0001
FI fattening, kg	229 (20)	238 (20)	<0.05	248 (17)	235 (17)	<0.001	242 (18)	240 (18)	0.60	234 (18)	240 (19)	0.09
FCR fattening, kg /kg gain	2.48 (0.21)	2.62 (0.21)	<0.001	2.68 (0.17)	2.58 (0.17)	<0.01	2.61 (0.19)	2.64 (0.18)	0.55	2.53 (0.18)	2.64 (0.19)	<0.01
ECR fattening, MJ /kg gain	24.08 (2.06)	25.46 (2.06)	<0.001	24.97 (1.66)	25.96 (1.72)	<0.01	24.56 (1.81)	25.84 (1.77)	<0.001	24.59 (1.79)	25.60 (1.89)	<0.01
Fattening duration, days	116.10 (15)	110.49 (12)	<0.05	121.86 (16)	113.64 (11)	<0.01	119.52 (16)	112.96 (11)	<0.05	119.60 (16)	111.64 (11)	<0.01
BW at slaughter, kg	121 (0.4)	121 (0.5)	0.67	121 (0.4)	121 (0.4)	0.88	121 (0.4)	121 (0.4)	0.34	121 (0.4)	121 (0.4)	0.93

PD fattening, g/day	133 (14)	133 (13)	0.97	125 (13)	127 (11)	0.27	128 (14)	128 (11)	0.76	128 (13)	130 (11)	0.25
Carcass weight, kg	95.9 (0.33)	95.9 (0.35)	0.76	95.9 (0.33)	95.9 (0.34)	0.77	96.0 (0.35)	95.9 (0.33)	0.16	95.9 (0.31)	95.9 (0.32)	0.94
Lipid weight at slaughter, kg	23.63 (3.37)	26.99 (2.86)	<0.0001	25.27 (2.87)	28.27 (2.58)	<0.0001	24.74 (3.09)	28.08 (2.65)	<0.0001	24.77 (3.06)	27.71 (2.78)	<0.0001
BFT slaughter, mm	15.82 (1.26)	17.08 (1.07)	<0.0001	16.43 (1.07)	17.56 (0.96)	<0.0001	16.24 (1.15)	17.49 (0.99)	<0.0001	16.25 (1.14)	17.35 (1.04)	<0.0001
Protein weight at slaughter, kg	19.51 (0.48)	19.05 (0.41)	<0.0001	19.29 (0.40)	18.86 (0.37)	<0.0001	19.38 (0.44)	18.89 (0.37)	<0.0001	19.35 (0.44)	18.94 (0.39)	<0.0001
LMP, %	60.7 (2.19)	58.5 (1.86)	<0.0001	59.6 (1.86)	57.7 (1.68)	<0.0001	60.0 (2.01)	57.8 (1.72)	<0.0001	60.0 (1.99)	58.0 (1.81)	<0.0001
BP/BL at slaughter	0.84 (0.14)	0.71 (0.09)	<0.0001	0.77 (0.10)	0.67 (0.07)	<0.0001	0.79 (0.11)	0.67 (0.07)	<0.0001	0.79 (0.11)	0.69 (0.08)	<0.0001

[1]FI: feed intake, FCR: feed conversion ratio, ECR: energy conversion ratio, PD: protein deposition, BFT: back fat thickness, BP/BL: ratio of body protein weight/ body lipid weight at slaughter, BP: body protein content, BL: body lipid content, LMP: lean meat percentage

[2]*P*-values were calculated via a t-test of the line effect

Environmental Assessment of the Lines with the Optimized Diets

When the two lines were simulated with the reference diet and their tailored optimized diets, an individual LCA was performed in SimaPro based on the individual performances simulated with InraPorc to assess the environmental impacts of producing 1 kg of live pig. The resulting average (SD) of the impact categories in the two lines predicted with the different diets are summarized in Table 4. Significant differences between the lines were found in the impact categories of GWP, AP, EP, and LO in all diets ($P < 0.05$). For each optimization objective, the LRFI line, in all impact categories, had systematically smaller environmental burdens HRFI using the four diet scenarios ($P < 0.05$): reference (7.21%), least cost (8.11%), least score (4.91%), and joint optimized (4.29%) diets. The lines impacts predicted with the reference diet showed a maximum difference in AP and a minimum difference in LO ($P < 0.0001$). The lines with the optimized diets were predicted to systematically have lower impacts than the reference diet, except for LO for LRFI fed the least cost diet, and EP for all optimized scenarios. In the HRFI line, among the diets optimized for least cost, least score and joint environment and economic objectives, the maximum and minimum decreases in environmental impacts compared to the reference diet were predicted in LO (-13.21%) and GWP (-5.52%) for the least cost diet. Likewise, in the LRFI line, the maximum and minimum decreases were observed in LO (-17.85%) for least score diet and in GWP (-2.54%) for the least cost diet. To compute a synthetic environmental score at the farm gate similar to the environmental score defined for the diet optimization procedure, an environmental score was set up. It was defined as the sum of the four environmental impacts predicted with the considered diet, divided by the sum of the environmental impacts predicted with the same line least cost diet, to allow comparisons across scenarios. In this way, the global environmental indictors in the LRFI line were observed in almost the same order as the order of the environmental scores of the diets (supplementary material 7).

Individual Profit per Line with the optimized Diets

The individual traits simulated by InraPorc for pigs predicted with their own line diet were imported into the bio-economic model to calculate the line profit for each feeding scenario. The average (SD) of the profits are given in Table 4. The difference in profits between the two lines (P < 0.05) and the reference diet revealed that the profit of the LRFI line was greater than that of the HRFI line. The diets that cost least and had the least score also produced in greater profits in LRFI pigs (P < 0.01), whereas for the joint diet, the difference between the lines was not significant (P > 0.22). The maximum profit in the LRFI line was predicted with the least cost diet (17.75 €/pig), whereas it was obtained with the joint optimized diet in the HRFI line (15.58 €/pig).

Table 4 Average (SD) of four environmental impact categories calculated per kg of pig with BW of 120 kg at the farm gate through individual LCA using the ReCiPe 2016 Midpoint (H) V1.13 method, and mean (SD) of profit per pig (120 kg) at farm gate resulting from the bio-economic model for the low residual feed intake (LRFI) line and the high residual feed intake (HRFI) line predicted with the reference diet and their least cost, least environmental score, and joint cost-environment

		Reference			**Least cost**			**Least score**			**Joint**		
Impact category	Unit	LRFI	HRFI	*P*-value[1]	LRFI	HRFI	*P*-value	LRFI	HRFI	*P*-value	LRFI	HRFI	*P*-value
Global warming potential	kg CO_2 eq	2.07 (0.12)	2.21 (0.12)	<0.0001	2.02 (0.095)	2.09 (0.096)	<0.0001	1.96 (0.098)	2.00 (0.092)	<0.05	1.96 (0.096)	2.02 (0.098)	<0.0001
Acidification	g SO_2 eq	36.8 (2.78)	40.0 (2.79)	<0.0001	33.07 (1.99)	37.1 (2.22)	<0.0001	35.6 (2.37)	36.5 (2.22)	<0.05	34.6 (2.26)	35.3 (2.23)	<0.0001
Eutrophication	g P eq	1.16 (0.077)	1.24 (0.077)	<0.0001	1.39 (0.079)	1.56 (0.092)	<0.0001	1.27 (0.077)	1.39 (0.081)	<0.0001	1.36 (0.083)	1.40 (0.089)	<0.05
Land occupation	m^2a crop eq	4.30 (0.30)	4.58 (0.30)	<0.0001	4.35 (0.25)	3.97 (0.22)	<0.0001	3.53 (0.21)	4.17 (0.24)	<0.0001	3.89 (0.23)	4.22 (0.25)	<0.0001
Profit	€/pig	11.10 (5.83)	8.50 (6.82)	<0.05	17.75 (5.56)	14.47 (7.01)	<0.01	16.28 (5.75)	12.73 (7.32)	<0.01	16.86 (5.68)	15.58 (5.64)	0.22

[1]*P*-values were calculated via a t-test of the line effect

Correlations between Individual Growth Performance Traits and Profit

To illustrate the relationships between growth performance traits and profit, phenotypic correlations were computed between the performances of individual pigs and the individual profit in each line predicted with the different diets. As the correlations were very similar for all diets in a given line, only correlations estimated with the lines outputs predicted with their own joint optimized diet are reported in Table 5. The correlations for the other diets, conventional, least cost, and least score, are reported in Supplementary material 8. Profits with all optimization objectives were highly correlated with FCR (correlation < -0.82) in both lines. With ADG, the correlations were positive and moderate to high, and did not differ from zero with ADFI in either line. For traits related to body and carcass composition (BFT), body protein content (**BP**), body lipid content (**BL**), ratio of body protein weight/ body lipid weight at slaughter (**BP/BL**), and (LMP), correlations with profit were greater in the HRFI line (absolute values > 0.71) than in the LRFI line (absolute values > 0.31), with non-recovering 95% confidence intervals. The profit was highly positively correlated with protein deposition (**PD**) in both lines (> +0.61). In addition, to gain insights into the relationships between the environmental impacts and profits of the lines, phenotypic correlations were computed between the profits and the individual LCA results in each line. No evidence for differences between lines was found for these correlations, which were high and negative (< -0.88).

Table 5 Phenotypic correlations (95% confidence interval) between performance traits, environmental impacts, and profit obtained from the sale of a pig weighing 120 kg at the farm gate, with the simulated performance traits in the LRFI and HRFI lines with their joint cost-environment optimised diets

Trait[1]	**LRFI**	**HRFI**
	Joint	**Joint**
ADG	0.57 (0.37; 0.72)	0.42 (0.18; 0.61)
FCR	-0.90 (-0.94; -0.84)	-0.85 (-0.91; -0.76)
Fattening duration	-0.58 (-0.73; -0.38)	-0.56 (-0.71; -0.35)
ADFI	0.07 (-0.19; 0.32)	-0.20 (-0.44; 0.07)
BP/BL	0.39 (0.15; 0.59)	0.75 (0.61; 0.85)
BFT	-0.47 (-0.65; -0.24)	-0.80 (-0.88; -0.68)
PD	0.73 (0.59; 0.83)	0.63 (0.45; 0.77)
BL	-0.47 (-0.65; -0.24)	-0.80 (-0.88; -0.68)
BP	0.56 (0.35; 0.71)	0.83 (0.73; 0.90)
LMP	0.48 (0.26; 0.66)	0.81 (0.69; 0.88)
GWP	-0.90 (-0.94; -0.84)	-0.92 (-0.95; -0.86)
AP	-0.90 (-0.94; -0.84)	-0.92 (-0.95; -0.87)
EP	-0.90 (-0.94; -0.84)	-0.92 (-0.95; -0.86)
LO	-0.90 (-0.94; -0.84)	-0.92 (-0.95; -0.86)

[1]FCR: feed conversion ratio, BP/BL: ratio of body protein weight/ body lipid weight at slaughter, BFT: back fat thickness, PD: protein deposition, BL: body lipid content, BP: body protein content, LMP: lean meat percentage, GWP: global warming potential, AP: acidification potential, EP: freshwater eutrophication potential, LO: land occupation

Revenue and Production Cost Breakdown

The bio-economic model made it possible to access a non-constant cost breakdown and the revenue for each individual pig in the two lines. The average (SD) of these costs and revenue for each line and each diet are presented in Supplementary material 9, and their costs of diet, energy, water, and labor during fattening and the profit per pig weighing 120 kg at the farm gate predicted with the reference, least cost, least score, and joint optimized diets are presented in Table 6. The cost of the fattening diet within each line was significantly lower with the optimized diets than with the reference diet ($P < 0.0001$), the decreases ranged from 10% (least score diets) to 14% for the joint diet in the LRFI line and for the joint and least cost diets in the HRFI line. Significant line differences in costs, energy, water, and labor during fattening period were observed with the reference, least cost, and least score diets ($P < 0.05$). There was no line difference in the cost of the fattening diet with the joint diets ($P = 0.74$), and the cost of water with the least score diets ($P = 0.63$).

Table 6 Average (SD) and P-values of costs of diet, energy, water, and labor during fattening and the profit per pig weighing 120 kg at the farm gate in the low residual feed intake (LRFI) line and high residual feed intake (HRFI) line predicted with the reference, least cost, least score, and joint optimized diets.

	Reference			**Least Cost**			**Least Score**			**Joint**		
	LRFI	HRFI	*P*-value[1]	LRFI	HRFI	*P*-value	LRFI	HRFI	*P*-value	LRFI	HRFI	*P*-value
Fattening diet, €	53.7 (4.74)	55.9 (4.76)	<0.05	46.4 (3.30)	48.0 (3.56)	<0.05	48.2 (3.72)	50.0 (3.80)	<0.05	47.6 (3.65)	47.8 (3.82)	0.7
Energy, €	3.7 (0.04)	3.6 (0.04)	<0.05	3.7 (0.04)	3.6 (0.04)	<0.01	3.7 (0.04)	3.6 (0.03)	<0.01	3.7 (0.04)	3.6 (0.04)	<0.01
Water, €	2.5 (0.19)	2.5 (0.18)	<0.05	2.6 (0.17)	2.5 (0.16)	<0.001	2.6 (0.17)	2.6 (0.16)	0.6	2.5 (0.17)	2.6 (0.17)	<0.05
Fattening labor, €	4.2 (0.57)	4.0 (0.44)	<0.05	4.4 (0.60)	4.1 (0.42)	<0.01	4.3 (0.59)	4.1 (0.42)	<0.05	4.3 (0.60)	4.0 (0.42)	<0.01
Profit, €/pig	11.1 (5.83)	8.5 (6.82)	<0.05	17.8 (5.56)	14.5 (7.01)	<0.01	16.3 (5.75)	12.7 (7.32)	<0.01	16.9 (5.68)	15.6 (5.64)	0.2

[1]*P*-values were calculated via a t-test of the line effect

Assessment of Profit Sensitivity to Market Price Volatility

Figure 1 shows changes in the costs of the fattening diet and the market price of pigs that would be needed to make zero profit. In the case of an increase in the price of the diet, the HRFI line with the reference diet revealed the minimum possible changes (15.2% increase to reach zero profit), and the LRFI line with least cost diet revealed the maximum possible changes (38.2%) to the increase in the price of this diet. If the price of pig were to go down, the same scenarios show a minimum margin (6.6%) and a maximum margin (13.8%), respectively. With the joint diets, the percentages in the LRFI line were close to those in the least cost diet, while the HRFI line had the highest percentages (32.6% increase in the price of the diet and 12.2% drop in the pig market price).

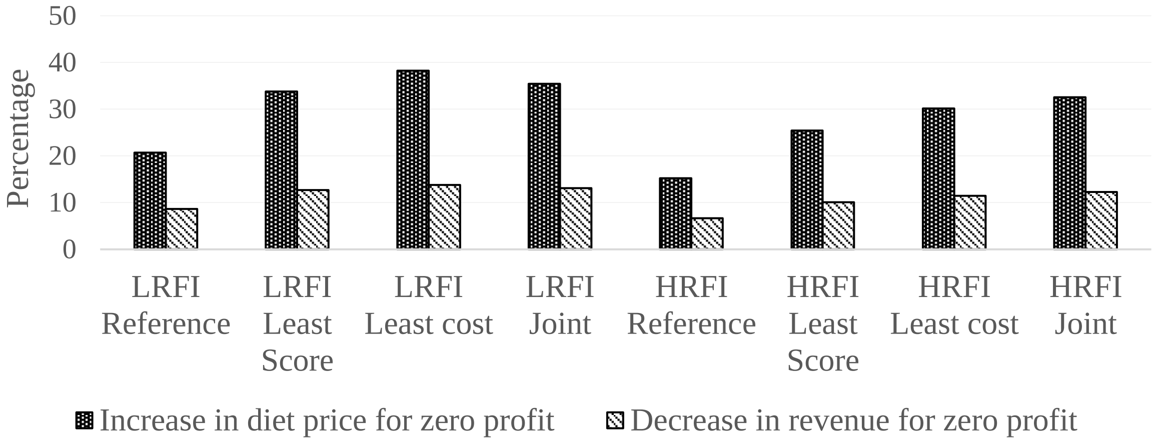

Figure 1. Increase percentage in the price of fattening diet and the percentage reduction in the market price of a pig in each line with the reference, least score, least cost, and joint cost-environmental diets that would result in zero profit for each line.

DISCUSSION

In this study, we used individual trait-based bio-economic and LCA models to investigate possible improvement in pig production sustainability resulting from incorporating economy and environmental impacts in diet optimization to satisfy genetically defined needs and ultimately contribute to overall farm feed efficiency. The bio-economic model was developed specifically for this study whereas the LCA model was previously developed and the procedure, challenges and limitations are reported in Soleimani and Gilbert, (2020a and 2020b).

The Bio-economic Model

Bio-economic models are already available in the literature, e.g. de Vries, (1989) and Ali et al., (2017). The de Vries (1989) model details a sow's life cycle. We decided not to use that model because we wanted to focus on the fattening period, and consequently chose to include the costs of sows and their litters up to weaning in the cost of weaned piglets. In contrast, the fattening period is simulated in detail in our model as we decided to use the InraPorc pig growth simulator as proposed by Ali et al., (2017) to model growth profiles. In addition, using the population version of InraPorc enabled us to simulate the growth performance traits of all individual pigs in response to the specific composition of each diet, rather than the response of the average pig. Ali et al., (2018) incorporated the environmental impact in their bio-economic model by monetizing the impact of greenhouses gases using the shadow price of CO_2. Due to the lack of universal and standardized guidelines on how to monetize the environmental impacts, in our study, we alternated separate economic and environmental assessments of the four main categories affected by pig production (GWP, AP, EP, and LO) using individual models. The results obtained from the individual economic and environmental assessments such as correlations between profits, environmental impacts, and traits maybe applicable for further relative weight assignment of the economic and environmental criteria, or to attribute economic value to environmental impacts with the aim of combining economic and environmental assessment in a single economic assessment. From these results, any choice of relative weight of the economic and environmental criteria, or choice of cost of impacts, can be applied to further combine assessments and compare scenarios. Finally, in a study of feed efficiency, one may wish to assess the economic impact of price volatility at the ingredients level. However, in tailored diet optimization, changes in the price of each ingredient would change the composition of all the diets, including the least cost diet used as the baseline, which would change the composition of all optimized diets. The composition of each new optimized diet should thus be incorporated in InraPorc to simulate the new performance traits in response to new diet composition. Repeating all these procedures when the price of each ingredient changed is not feasible. Performing an economic assessment based on the performance traits of individual pigs, and coupling it with individual LCA enabled us to investigate the correlations between performance traits, environmental impacts, and the final profit obtained with the lines.

Economic and Environmental Evaluation of Combined Genetics and Nutrition Optimization Scenarios

The differences in environmental impacts (Soleimani and Gilbert, 2020a) and profit between the LRFI and HRFI lines using a single reference diet showed that pig selection for feed efficiency based on RFI alone is effective to systematically improve the sustainability of pig production even without combining this selection emphasis with diet optimization. The reference diet provided a baseline to compare the improvements due to combined genetics and nutrition optimization scenarios. If the reference diet was different but also covered all animal requirements, the reduction percentages of impacts and costs would be affected, but not the line comparisons obtained for the optimized diets, as the animal requirements profiles would be very similar. The high profit and low environmental score of the LRFI line with its own joint optimized diet demonstrated that combined genetics and nutrition optimization strategy can increase sustainability with only small compromises with respect to each pillar. The profits of the lines, predicted with the reference diet, differed by 23%, which can be referred to their genetic difference. Therefore, any change in the difference between the old and new diets can mainly be interpreted as the impact of the new diet formulation. Accordingly, the decrease in the difference in profit between the lines from 23% with the reference diet to 8% (not significant) with the joint diets shows that the tailored diet formulation and optimization can alleviate the innate difference in profitability between populations with different genetic potential. Using this approach also reduced the differences in environmental impact in the two lines by half, thereby also alleviating part of the genetically related environmental burden. The joint diets for the lines were obtained with different weighting factors (w_t), reflecting distinct trade-off points between economic and environmental objectives due to differences in the nutritional requirements between the lines. Part of the advantage of having more efficient animals in terms of environmental impacts could then be offset by delivering a more “environment friendly” diet to the less efficient animals. In the HRFI line, the joint optimized diet resulted in maximum profit rather than least cost diet, mainly because of greater revenue due to better market quality of the carcass. Finally, the improved robustness of the lines with the joint diet scenario versus changes in the diet and in the market price of pigs demonstrated that tailored diet formulation combined with genetics is an effective way to achieve economically sustainable pig production. Considering the change of pig price in France from 2007 to 2020 (https://rnm.franceagrimer.fr/prix?PORC), the margins obtained with the worst scenario (HRFI with the reference diet) would lead to 34% of the weeks where the farmer would not cover the production costs by selling the pigs, whereas these situations of negative economic outcome would be reduced to 15 % of the weeks for the best scenario (LRFI with least cost diet). It should be noticed that a different pricing context would lead to different compositions of the optimized diets, and then differences in the predictions for all scenarios, but the main conclusions about the opportunities of the proposed approach would hold. How the approach would respond to different pricing contexts would require further automation of the predictions and assessment models, to run multiple scenarios in a separate study. In developing the bio-economic model, the cost of manure treatment and application from weaning to finishing was assumed to be offset by its revenue. Depending on the geographical context of the farm, manure could be a value or a burden for the farmer (Risse et al., 2006). However, due to low differences of manure quantities between lines as well as market value of manure compared to the market value of pig, the benefit or burden of the manure is expected to have approximately the same low effect on the profit of individual pigs. Further sensitivity studies would be needed to evaluate scenarios with contrasted manure management situations.

To make the results comparable, both bio-economic and LCA models were built using individual performance traits, and all individuals were assessed using the same models. Individual economic and environmental assessments by trait-based models revealed correlations between performance traits, profit, and environmental impacts, and provided more insights into the strategies to develop for a more sustainable pig production. The moderate correlations between ADG and the duration of the fattening period, and low with ADFI, translates into high correlations between profit and FCR. This might be due partly to some of the modelling constraints, and to considering no variation in slaughter weight, which standardizes the outputs but is not realistic, pigs being usually slaughtered in batches. The high correlation between profit and fattening FCR reflects the high contribution of feed costs to the total costs to grow pigs in the fattening period. Moreover, the high correlation between the environmental impacts and fattening FCR (Soleimani and Gilbert, 2020b) underlines the significance of fattening feed efficiency in the sustainability of the pig production systems, as already reported for pigs and other species with different approaches (Ali et al., 2017; Yi et al., 2018; Besson et al., 2020).We also found high correlations between PD and profit and environmental impacts, certainly linked to the carcass pricing system used for the analysis which favors lean carcasses, and the costs of incorporating protein-rich ingredients in the diet. This shows that traits linked to protein deposition are the right ones to incorporate in selection for more sustainable pig production. It should be noted that in the more efficient line, the correlations between leanness and profit were not as high as they were in the less efficient line. We hypothesize that this is due to less variance in these traits in the LRFI line, and hence in less sensitivity of the price of more efficient animals to a payment system based on leanness. High negative correlations between environmental impacts and the profit of the lines for all diets can be interpreted as the close link between feed intake and environmental impacts on the one hand, and profit on the other hand, which again underlines importance of feed efficiency in response to the economic and environmental pillars of sustainability. The optimized diets generally had low environmental scores and their cost was low compared to the reference diet, which shows a marked potential for economic and environmental improvements in diet optimization alone. The marginally greater price of the joint diets per MJ NE relative to the least cost diets (within line) showed that an optimized diet (e.g. the joint diet) can be achieved with a small compromise relative to the price of the least cost diet. The increase in the duration of the fattening period for pigs performance predicted with the optimized diets compared to that of pigs performance with the reference diet may be explained by the fact that a few pigs are not satisfied in the very early growth stages because the line average of the maximum requirements are considered as constraints in diet formulation. A multiphase feeding strategy or establishing the representative requirements to the 75% quantile of the maximum pig requirements per line could compensate for this reduction in growth performance, although certainly at the expense of more spillage and increased costs and impacts. It is notable that despite the increase in the duration of the fattening period, marked economic and environmental advantages were achieved with the combined genetics and nutrition optimization scenarios which would encourage a more overall approach to evaluate production systems, where performance losses could be offset by gains in other dimensions (for instance feeding costs, carcass quality). This would be particularly advantageous for farmers whose feeding system does not allow for much flexibility, e.g. on-farm production systems where breeding highly efficient animals requires greater concentrations of AA and CP per MJ of NE, which might not be the most efficient choice in such systems, as it would require increasing levels of high-protein ingredients imported in the farm, or delivering unbalanced diets to highly efficient pigs, whose nutritional requirements would not be met and which then would fail to achieve their promised performances (Gilbert et al., 2017). Greater improvement in feed efficiency would be expected from individual tailored formulations compared to line tailored formulations. The variability in the input parameters like the price of ingredients, their availability, and the environmental impacts of their production could be dynamically imported into the optimization algorithm and tailored diet formulation and real-time optimization would not lag far behind expectations. In addition, selection indexes could be improved by incorporating traits that are highly correlated with new objectives, such as environment. The results of this study are limited to the simulation tools and choices applied, which are potentially subjected to deviation from predictions under field conditions. Therefore, further field studies will be required to confirm these predictions.

Consistency in the Implementation of Combined Genetics and Nutrition Optimization

In the present study consistency in combined genetics and nutrition optimization processes was obtained by considering NE as the core linkage between genetics, diet formulation, and optimization. Extraction of individual requirements standardized to NE as well as standardized prices and environmental impacts of the dietary ingredients to NE, provides consistency in the whole process of the combined genetic and nutrient optimization. The incorporation of standardized individual requirements to NE among the constraints of diet formulation will make it possible to control the excretion of nutrients that originates from unbalanced dietary nutrients. Mackenzie et al. (2016) included a module to estimate nitrogen excretion at the farm level in their diet formulation process, whereas in our approach, due to the uniformity of the nutrient composition of the diets relative to NE ratios, the same excretion would be expected with all diets without the need for estimation. The incorporation of standardized prices and the impacts of ingredients in the objective functions ranked the ingredients according to their economic and environmental cost per MJ NE, which in turn, optimized their relative rate of incorporation according to their value relative to MJ NE. One important advantage, consistency with NE throughout the process, makes it possible to predict and qualitatively compare the final farm profit and environmental impacts using the standardized price and the environmental score of the diets.

CONCLUSION

Improving feed efficiency in pigs can be achieved by improving animal genetics and the composition of their diet. Genetic selection to improve feed efficiency has systematically improved sustainability of pig production in terms of profitability and environmental impacts. Tailored diet optimization was shown to effectively improve environmental impacts and farm profitability, by minimizing the difference between nutritional requirements and supply while simultaneously orienting dietary improvement toward intended single or multi-objective optimization of the production system. Combining genetic selection for feed efficiency and tailored diet optimization is a promising way to make pig production more sustainable and more efficient. The normalization to NE of animal nutritional requirements, diet prices, environmental impacts, and nutritional characteristics of ingredients provides consistency in the whole optimization procedure, and could be considered in further precision farming developments.

DISCLOSURES

The authors declare that they have no conflict of interest.

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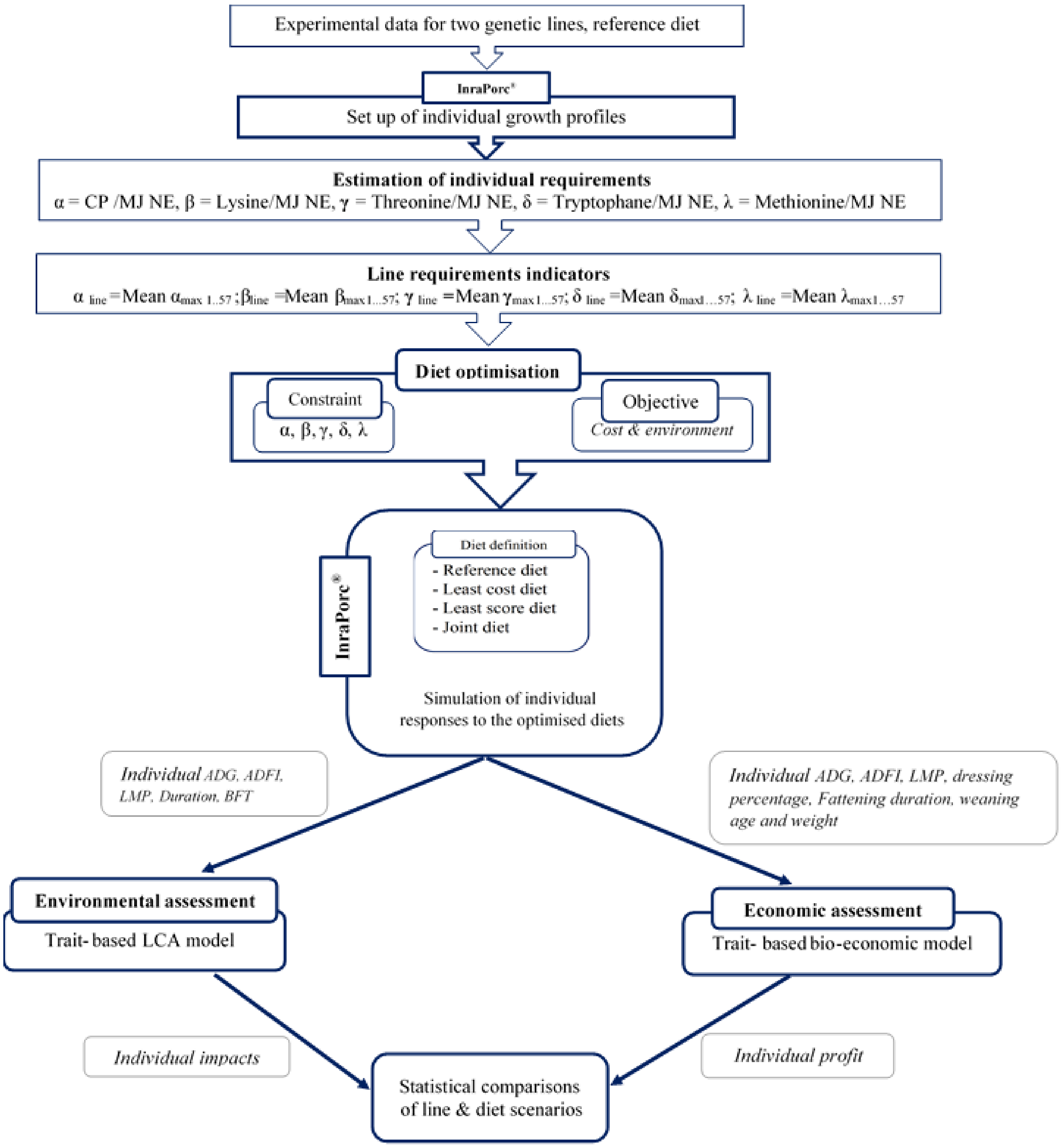
4.3 **Supplementary material of the paper**

Supplementary material 1. Scheme of the procedure implemented for economic and environmental assessment of overall farm feed efficiency strategies.



Supplementary material 2. Market price of items applied in bio-economic model and diet optimisation.

Item	Price (€ per unit)	Reference
Barley (France)	0.167 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
Wheat soft (France)	0.18 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
Soybean meal 48 (South America)	0.348 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
Sunflower oil (France)	0.705 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
Corn (France)	0.178 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
Oat (France)	0.192 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
Pea (France)	0.231 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
Triticale (France)	0.158 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
rapeseed meal (France)	0.252 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
sunflower meal (France)	0.182 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
L-Lysine HCL (France)	1.175 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
L-Threonine (France)	1.1 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
L-Tryptophan (France)	6.5 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
DL-Methionine (France)	1.9 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
Salt (France) (Sodium Chloride)	0.112 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
Calcium carbonate (France)	0.05 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
Dicalcium phosphate (France)	0.51 €/kg	Note de conjoncture Aliment April 2020 (IFIP)
Oligo Vitamin (France)	1€/kg	Note de conjoncture Aliment April 2020 (IFIP)
Post weaning 7kg	35.28 €	https://rnm.franceagrimer.fr/prix?PORCELET#
Water	3.57 €/m^3	https://www.ledauphine.com/france-monde/2017/12/21/eau-quel-est-vraiment-le-juste-prix
Electricity	0.0771 €/kWh	https://www.kelwatt.fr/guide/prix-electricite-france
Labor cost	0.036 €/pig/day	Calculated based on the IFIP information (2.3 workers/200 sows) and SMIC = 10.03 €/hour
100kg carcass & LMP 56%	129.30 €/carcass	https://rnm.franceagrimer.fr/prix?PORC
Buildings and capital costs	0.03 €/pig/day	It is calculated based on total investment per sow: 4937 €/sow/place; Les bâtiments en France; Les coûts pour 3 types d'élevages. IFIP report-2019.
Investment	4937 €/sow/place	Les bâtiments en France ; Les coûts pour 3 types d'élevages. IFIP report- 2019.

Health cost	0.89 €/ pig	Description, evaluation, and validation of the Teagasc Pig Production Model. Calderón 2019
Insurance	1.04 €/ pig	Description, evaluation, and validation of the Teagasc Pig Production Model. Calderón 2019
Maintenance & Repairs	1.04 €/ pig	Description, evaluation, and validation of the Teagasc Pig Production Model. Calderón 2019
Starter (1st age) weaning (2nd age feed)	350€/T 320€/T	https://www.ifip.asso.fr/PagesStatics/resultat/partenaire/tele/criteres%20GTE.pdf page 46.

Supplementary material 3. Correction factor for quantity and quality deviations from the baseline price for a carcass weight of 100kg and lean meat percentage of 56%.

https://www.gis-elevages demain.org/content/download/3429/34955/version/1/file/m%C3%A9moire_ElodieLopez_rectoverso.pdf

PORKS			WEIGHT RANGE												
LMP	Deviation	Total deviation	45 69.9	70 77.9	78 79.9	80 81.9	82 86.9	87 99	99.1 105	105.1 106	106.1 107	107.1 108	108.1 109	109.1 110	110.1 120
			-0.30	-0.18	-0.10	-0.02	0.00	0.02	0.00	-0.04	-0.10	-0.12	-0.14	-0.16	-0.20
>=64	-0.01	0.16	-0.14	-0.02	0.06	0.14	0.16	0.18	0.16	0.12	0.06	0.04	0.02	0.00	-0.04
63	0.00	0.17	-0.13	-0.01	0.07	0.15	0.17	0.19	0.17	0.13	0.07	0.05	0.03	0.01	-0.03
62	0.00	0.17	-0.13	-0.01	0.07	0.15	0.17	0.19	0.17	0.13	0.07	0.05	0.03	0.01	-0.03
61	0.02	0.17	-0.13	-0.01	0.07	0.15	0.17	0.19	0.17	0.13	0.07	0.05	0.03	0.01	-0.03
60	0.03	0.15	-0.15	-0.03	0.05	0.13	0.15	0.17	0.15	0.11	0.05	0.03	0.01	-0.01	-0.05
59	0.04	0.12	-0.18	-0.06	0.02	0.10	0.12	0.14	0.12	0.08	0.02	0.00	-0.02	-0.04	-0.08
58	0.04	0.08	-0.22	-0.10	-0.02	0.06	0.08	0.10	0.08	0.04	-0.02	-0.04	-0.06	-0.08	-0.12
57	0.04	0.04	-0.26	-0.14	-0.06	0.02	0.04	0.06	0.04	0.00	-0.06	-0.08	-0.10	-0.12	-0.16
56	0.00	0.00	-0.30	-0.18	-0.10	-0.02	0.00	0.02	0.00	-0.04	-0.10	-0.12	-0.14	-0.16	-0.20
55	-0.02	-0.02	-0.32	-0.20	-0.12	-0.04	-0.02	0.00	-0.02	-0.06	-0.12	-0.14	-0.16	-0.18	-0.22
54	-0.02	-0.04	-0.34	-0.22	-0.14	-0.06	-0.04	-0.02	-0.04	-0.08	-0.14	-0.16	-0.18	-0.20	-0.24
53	-0.04	-0.08	-0.38	-0.26	-0.18	-0.10	-0.08	-0.06	-0.08	-0.12	-0.18	-0.20	-0.22	-0.24	-0.28
52	-0.04	-0.12	-0.42	-0.30	-0.22	-0.14	-0.12	-0.10	-0.12	-0.16	-0.22	-0.24	-0.26	-0.28	-0.32
51	-0.08	-0.20	-0.50	-0.38	-0.30	-0.22	-0.20	-0.18	-0.20	-0.24	-0.30	-0.32	-0.34	-0.36	-0.40
<=50	-0.20	-0.40	-0.70	-0.58	-0.50	-0.42	-0.40	-0.38	-0.40	-0.44	-0.50	-0.52	-0.54	-0.56	-0.60

Supplementary material 4. The following formulations have been applied to calculate the individual profit.

Cost	Formulation
Fattening_Diet_Cost	ADFI_Fattening * Fattening_Duration* Fattening_Diet_Price
Postweaning_Diet_Cost	Starter_Duration * ADFI_Starter * StarterDiet_Price + Weaning_Diet_Price * (Weaning_Duration_6_19 * ADFI_weaning_6_19 + Weaning_19_InitialFattening_Duration * ADFI_weaning_19_InitialFattening)
Total_Diet_Cost	Fattening_Diet_Cost + Postweaning_Diet_Cost
Energy_Cost	Energy_Consumption * Energy_Price * (BW_End_Fattening - BW_Weaning)
Water_Cost	Water_Price * (Water_To_Feed_Fattening _ratio * ADFI_Fattening * Fattening_Duration + Water_To_Feed_PostWeaning _ ratio * (Starter_Duration * ADFI_Starter + Weaning_Duration_6_19 * ADFI_weaning_6_19 + Weaning_19_InitialFattening_Duration * ADFI_weaning_19_InitialFattening))
Fattening_Labor_Cost	Worker_Cost * Duration_Fattening Worker cost calculation per pig per day: 2.3 workers for farm with 200 sows, 2.3/200 = 0.0115 workers/sow Each sow produces 25 weaned piglets per year on average, 0.0115/25=0.00046 workers/pig Flat-rate remuneration for work: SMIC/hour SMIC = 10.03 €/hour before taxes Worker cost per day = SMIC * 8 hours/day = 80.24 €/day Worker cost per pig per day= 80.24 €/day *0.00046 workers/pig = 0.036 €/pig/day
PostWeaning_Labor_Cost	Worker_Cost * PostWeaning_Duration
Total_Labor_Cost	Fattening_Labor_Cost + PostWeaning_Labor_Cost
Weaning_Cost	Weaned_Piglet_price
Building_and_Capital_Cost	Capital_Cost * (PostWeaning_Duration + Fattening_Duration) Capital costs calculation per pig per day: Total investment per sow: 4937 €/sow/place Interest rate = 6% per year Interest cost = 0.06(6%) * 4937 €/sow = 296.22 €/sow/year Interest cost per pig per day = 296.22/365/25 = 0.03 €/pig/day
Total_Cost	Total_Diet_Cost + Energy_Cost + Water_Cost + Total_Labor_Cost + Weaning_Cost + Building_and_Capital_Cost + Health_Cost + Insurance_Cost

	+ Maintenance_Repair_Cost
Market price (1 pig alive)	Market_price (1 pig alive) = Market price (full carcass) Market price (full carcass) = [Market reference price (100kg carcass & LMP 56%)/100 + Carcass weight price correction + LMP price correction] * Carcass_Weight Carcass_Weight = LiveBW_farm_gate * Dressing percentage/100
Revenue	Market price (1 pig alive)
Profit	Revenue - Total_Cost

Supplementary material 5. The following formulations have been applied to calculate the emissions and excretions using the mass-balance approach.

eBW= 5.969 * BP 0.944 + 0.854 * BL 0.944	(van Milgen et al., 2008)
Lean meat percentage = 72.58 – 43.49 * BL/ eBW	(van Milgen et al., 2008)
N Body = e^(-0.9892 – 0.0145 * Lean%) * eBW^(0.7518 + 0.0044 Lean%) / 6.25	(Dourmad et al., 1992)
N Intake = Feed Intake * N Feed	
N Excreted = N Intake – N Retained	
P_{Body} (g) = 5.39 * eBW	(Rigolot et al., 2010a)
Ca_{Body} (g) = 8.56 * eBW	(Rigolot et al., 2010a)
K_{Body} (g) = -0.0041 * eBW^2 + 2.68 * eBW	(Rigolot et al., 2010a)
Cu_{Body} (mg) = 1.1 * eBW	(Rigolot et al., 2010a)
Zn_{Body} (mg) = 20.6 * eBW	(Rigolot et al., 2010a)
N_20 = 0.002 * N Excreted	(Rigolot et al., 2010b)
N_2 = 5 * N_20	(Rigolot et al., 2010b)
$NH_{3\ Building}$ (kg) = 17 / 14 * 0.24 * N Excreted	(Rigolot et al., 2010b)
ResD = Feed Intake * Residue Feed	(Rigolot et al., 2010b)
$ECH_{4\ growing}$ = ResD * 670	(Rigolot et al., 2010a)
$CH_{4\ Emitted}$ = ECH_4 / 56.65	(Rigolot et al., 2010a)
$CH_{4\ Housing}$ (kg) = VS * B_0 * MCF	(Rigolot et al., 2010b)
OM_{Faeces} = Feed * OM_{feed} * (1 – dCOM)	(Rigolot et al., 2010a)
dCOM = (0.744 + (14.69 DE – 0.50 NDF – 1.54 MM) / DM) / (OM / DM)	(Rigolot et al., 2010a)

eBW = empty body weight ; BP = body protein ; L = body lipid; N Body = nitrogen content of body; N Intake = total uptaken nitrogen; N Feed = nitrogen content of 1kg feed; N Excreted = total excreted nitrogen; NRetained = nitrogen retained in the body; OM = organic matter; MM = mineral mater; DM = dry matter; dCOM = feed organic matter digestibility coefficient; NDF = Neutral detergent fiber; B0 = maximum CH4 producing capacity; MCF = methane conversion factor; ResD = digested fibre ingested.CH4 = methane; N = nitrogen; Ca = calcium; P = phosphorus; K = potassium; Cu = copper; Zn = zinc.

Supplementary material 6. Digestible crude protein (CP) and amino acids, and net energy (NE) of the ingredients retained for diet formulation, and their environmental impacts.

Ingredients	CP (g/ kg_{feed})	Lys. (g/ kg_{feed})	Thr. (g/ kg_{feed})	Trp (g/ kg_{feed})	Met (g/ kg_{feed})	NE (MJ/ kg)	GWP (kg CO_2 eq)	AP (g SO_2 eq)	EP (g P eq)	LO (m^2a crop)
Barley	80.5	2.85	2.62	1.03	1.43	9.56	0.46	5.60	0.16	1.371
Oat	74.2	2.99	2.36	0.94	1.51	8.06	0.50	7.95	0.20	2.079
Triticale	83.4	3.24	2.71	1.06	1.53	10.40	0.48	5.43	0.19	1.837
Corn	69.8	1.92	2.49	0.40	1.55	11.20	0.33	7.11	0.12	1.033
Pea	165.8	12.45	5.93	1.31	1.60	9.75	0.37	3.65	0.57	2.663
Rapeseed meal	254.7	13.5	10.87	3.28	6.00	6.26	0.40	5.36	0.10	1.211
Sunflower meal	273.5	9.68	9.72	3.44	6.99	5.50	0.25	2.94	0.25	1.975
Wheat soft	92.8	2.51	2.66	1.14	1.51	10.54	0.42	7.96	0.129	1.330
Soybean meal	391	25.02	15.4	5.25	5.89	7.86	1.52	5.64	0.385	2.086
Sunflower oil	0	0	0	0	0	29.76	1.17	15.51	1.12	8.701
L-Lysine HCL	954	798	0	0	0	11.88	10.55	76.60	37.85	3.118
L-Threonine	731	0	990	0	0	11.11	10.62	84.23	37.16	3.109
L-Tryptophan	853	0	0	985	0	11.53	21.24	168.47	74.32	6.219
DL-Methionine	584	0	0	0	990	10.61	2.99	8.86	0.270	0.016

CP = crude protein; LO = land occupation; EP= freshwater eutrophication potential; AP = acidification potential; GWP= global warming potential; NE = net energy; P = phosphorous; m^2a crop= area time; NE density and digestible CP and amino acids (lysine, threonine, tryptophan, and methionine) of the ingredients were extracted from the INRA-AFZ database of feed ingredients. The environmental impacts of diet ingredients (GWP, AP, EP, LO) were obtained from the Ecoalim dataset of the AGRIBALYSE® database with the Recipe method 2016.

Supplementary material 7. Diet compositions of the reference, least environmental score, least cost and joint cost-environmental diets of the low residual feed intake (LRFI) and high residual feed intake (HRFI) lines.

Ingredients	Reference	LRFI Least cost	HRFI Least cost	LRFI Least score	HRFI Least score	LRFI Joint	HRFI Joint
Net energy (MJ/kg)	9.70	9.27	10.01	9.38	9.75	9.69	9.66
Oat	0	0	0	0	0	20	0.4
Triticale	0	545	170	53	1	217	158
Corn	0	7	501	319	316	379	170
Pea	0	28	38	0	160	47.2	89
Rapeseed meal	0	34	1	155	82	52	12
Sunflower meal	0	80	24	0	0	60	40
Barley	409.4	264	153	354.4	347.9	121	361.4
Wheat	327	1.2	2.7	74	44	33.7	107
Soybean meal 48	202	0	67	3.9	0	25.6	17
Sunflower oil	23	0	0	0	9	3.4	4.6
L-Lysine HCL	3.5	5.5	7.7	5.6	4.5	5.6	5.1
L-Threonine	1.4	2	1.9	1.7	1.8	1.9	1.9
L-Tryptophan	0.3	0.2	0.5	0.4	0.5	0.5	0.4
DL-Methionine	0.9	0.6	0.7	0.5	0.8	0.6	0.7
Salt	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Calcium carbonate	11	11	11	11	11	11	11
Dicalcium phosphate	12	12	12	12	12	12	12
Vitamins and minerals	5	5	5	5	5	5	5

Supplementary material 8. Global environmental indicator of LRFI and HRFI lines obtained from the sum of the four impact categories with weighing of one, normalised to the corresponding of the least cost diet.

Impact category	Unit	LRFI				HRFI			
		Least cost	Reference	Joint	Least score	Least cost	Reference	Joint	Least score
Global warming potential	kg CO_2 eq	2.024565039	2.07743	1.956578342	1.964893997	2.0940194	2.216420683	2.0289206	2.00876661
Acidification	kg SO_2 eq	0.033078762	0.036778	0.03455181	0.035635412	0.0371808	0.040003775	0.0353864	0.03655861
Eutrophication	kg P eq	0.001390904	0.001168	0.001365895	0.00127469	0.0015651	0.001240719	0.0014021	0.00139793
Land occupation	m^2a crop eq	4.357045629	4.306144	3.897016388	3.537422797	3.9773762	4.583056232	4.2243881	4.17354862
Sum of four impacts		6.416080334	6.42152	5.889512435	5.539226896	6.1101416	6.840721409	6.2900971	6.22027177
Global environmental indicator		1	1.0008	0.9179	0.8633	1	1.1195	1.0294	1.018

$$[\text{GWP (kg)} + \text{AP (kg)} + \text{EP (kg)} + \text{LO } (m^2)]_{\text{diet}} / [\text{GWP (kg)} + \text{AP (kg)} + \text{EP (kg)} + \text{LO } (m^2)]_{\text{Least cost diet}}$$

Supplementary material 9. Phenotypic correlations (95% confidence interval) between profit of a 120kg pig and performance traits and environmental impacts , with the recorded traits in the LRFI and HRFI lines with least cost, least environmental score, joint cost-environment diet optimisations, and the reference diet.

Trait	LRFI Reference	HRFI Reference	LRFI Least Cost	HRFI Least Cost	LRFI Least Score	HRFI Least Score	LRFI Joint	HRFI Joint
ADG	0.67 (0.49 ; 0.79)	0.52 (0.30 ; 0.69)	0.77 (0.64 ; 0.86)	0.41 (0.16 ; 0.60)	0.58 (0.38 ; 0.73)	0.43 (0.19 ; 0.62)	0.57 (0.37 ; 0.72)	0.42 (0.18 ; 0.61)
FCR	-0.89 (-0.93 ; -0.82)	-0.88 (-0.93 ; -0.80)	-0.82 (-0.89 ; -0.71)	-0.89 (-0.93 ; -0.82)	-0.90 (-0.94 ; -0.84)	-0.90 (-0.94 ; -0.83)	-0.90 (-0.94 ; -0.84)	-0.85 (-0.91 ; -0.76)
Fattening duration	-0.67 (-0.79 ; -0.50)	-0.64 (-0.77 ; -0.45)	-0.80 (-0.87 ; -0.68)	-0.56 (-0.72 ; -0.35)	-0.58 (-0.73 ; -0.38)	-0.58 (-0.73 ; -0.37)	-0.58 (-0.73 ; -0.38)	-0.56 (-0.71 ; -0.35)
ADFI	0.08 (-0.18 ; 0.33)	-0.12 (-0.37 ; 0.15)	0.26 (0.01 ; 0.49)	-0.15 (-0.40 ; 0.11)	0.06 (-0.20 ; 0.31)	-0.15 (-0.40 ; 0.11)	0.07 (-0.19 ; 0.32)	-0.20 (-0.44 ; 0.07)
BP/BL	0.40 (0.17 ; 0.60)	0.71 (0.56 ; 0.82)	0.31 (0.06 ; 0.53)	0.73 (0.58 ; 0.83)	0.40 (0.16 ; 0.60)	0.72 (0.57 ; 0.83)	0.39 (0.15 ; 0.59)	0.75 (0.61 ; 0.85)
BFT	-0.47 (-0.65 ; -0.25)	-0.78 (-0.87 ; -0.66)	-0.33 (-0.54 ; -0.08)	-0.79 (-0.87 ; -0.66)	-0.47 (-0.65 ; -0.25)	-0.78 (-0.87 ; -0.66)	-0.47 (-0.65 ; -0.24)	-0.80 (-0.88 ; -0.68)
PD	0.81 (0.70 ; 0.89)	0.70 (0.54 ; 0.81)	0.88 (0.80 ; 0.93)	0.61 (0.42 ; 0.75)	0.74 (0.59 ; 0.84)	0.63 (0.45 ; 0.77)	0.73 (0.59 ; 0.83)	0.63 (0.45 ; 0.77)
BL	-0.47 (-0.65 ; -0.25)	-0.78 (-0.87 ; -0.66)	-0.33 (-0.54 ; -0.08)	-0.79 (-0.87 ; -0.66)	-0.47 (-0.65 ; -0.25)	-0.78 (-0.87 ; -0.66)	-0.47 (-0.65 ; -0.24)	-0.80 (-0.88 ; -0.68)
BP	0.56 (0.35 ; 0.71)	0.83 (0.73 ; 0.90)	0.42 (0.19 ; 0.61)	0.84 (0.74 ; 0.90)	0.58 (0.37 ; 0.72)	0.84 (0.74 ; 0.90)	0.56 (0.35 ; 0.71)	0.83 (0.73 ; 0.90)
LMP	0.49 (0.26 ; 0.66)	0.79 (0.67 ; 0.87)	0.34 (0.10 ; 0.55)	0.80 (0.68 ; 0.88)	0.49 (0.27 ; 0.66)	0.80 (0.68 ; 0.88)	0.48 (0.26 ; 0.66)	0.81 (0.69 ; 0.88)
GWP	-0.92 (-0.95 ; -0.86)	-0.93 (-0.96 ; -0.89)	-0.88 (-0.93 ; -0.81)	-0.95 (-0.97 ; -0.91)	-0.90 (-0.94 ; -0.84)	-0.95 (-0.97 ; -0.91)	-0.90 (-0.94 ; -0.84)	-0.92 (-0.95 ; -0.86)
AP	-0.91 (-0.95 ; -0.86)	-0.94 (-0.96 ; -0.89)	-0.89 (-0.93 ; -0.82)	-0.95 (-0.97 ; -0.92)	-0.91 (-0.94 ; -0.85)	-0.95 (-0.97 ; -0.92)	-0.90 (-0.94 ; -0.84)	-0.92 (-0.95 ; -0.87)
EP	-0.92	-0.93	-0.88	-0.95	-0.90	-0.95	-0.90	-0.92

	(-0.95 ; -0.86)	(-0.96 ; -0.89)	(-0.93 ; -0.81)	(-0.97 ; -0.91)	(-0.94 ; -0.84)	(-0.97 ; -0.91)	(-0.94 ; -0.84)	(-0.95 ; -0.86)
LO	-0.92 (-0.95 ; -0.86)	-0.93 (-0.96 ; -0.89)	-0.88 (-0.93 ; -0.81)	-0.95 (-0.97 ; -0.91)	-0.90 (-0.94 ; -0.84)	-0.95 (-0.97 ; -0.91)	-0.90 (-0.94 ; -0.84)	-0.92 (-0.95 ; -0.86)

LO = land occupation; EP= freshwater eutrophication potential; AP = acidification potential; GWP= global warming potential; BW = body weight; ADG = average daily gain; ADFI = average daily feed intake; FCR = feed conversion ratio; ECR = energy conversion ratio; PD = protein deposition; BFT = back fat thickness; BP/BL = ratio of body protein weight/ body lipid weight at slaughter. BP = body protein content; BL = body lipid content; LMP = lean meat percentage.

Supplementary material 10. Average (SD) of the costs and revenue of the lines fed the reference diet, least cost diet, least score diet and joint diet.

		Fattening diet cost (€)	Energy (€)	Water (€)	Fattening Labor (€)	Total Cost (€)	Revenue
Reference	LRFI	53.67^{a} (4.74)	3.651^{a} (0.040)	2.45^{a} (0.19)	4.18^{a} (0.57)	117.39^{a} (5.61)	128.49 (1.83)
	HRFI	55.88^{b} (4.76)	3.631^{b} (0.043)	2.54^{b} (0.19)	3.97^{b} (0.44)	119.38^{b} (5.35)	127.88 (2.58)
Least cost	LRFI	46.40^{a} (3.30)	3.652^{a} (0.040)	2.63^{a} (0.16)	4.38^{a} (0.60)	110.68 (4.13)	128.44^{a} (2.33)
	HRFI	48.03^{b} (3.56)	3.630^{b} (0.039)	2.51^{b} (0.15)	4.09^{b} (0.42)	111.71 (3.99)	126.18^{b} (3.70)
Least score	LRFI	48.18^{a} (3.72)	3.654^{a} (0.041)	2.57 (0.17)	4.30^{a} (0.58)	112.24 (4.56)	128.53^{a} (2.25)
	HRFI	49.98^{b} (3.80)	3.630^{b} (0.039)	2.56 (0.16)	4.06^{b} (0.42)	113.67 (4.24)	126.40^{b} (3.71)
Joint	LRFI	47.59 (3.65)	3.651^{a} (0.040)	2.50 (0.17)	4.30^{a} (0.59)	111.58 (4.49)	128.45^{a} (2.23)
	HRFI	47.82 (3.82)	3.630^{b} (0.042)	2.56 (0.17)	4.01^{b} (0.42)	111.42 (4.34)	127.00^{b} (2.44)

^{a,b} means significant line difference with the same type of diet (P < 0.05).

4.4 **Main messages from Chapter 4**

An **individual trait-based bio-economic model was developed** along with the previously developed individual LCA model to evaluate the sustainability of incorporating selection for pig feed efficiency, dietary optimisation based on a single or multiple objectives tailored to meet the population's nutritional requirements, as a strategy to achieve an *overall farm feed efficiency* (Figure 13).

An approach was developed for **combining multiple environmental and economic diet optimisation objectives in a single objective** using environmental score and weighting factors while satisfying the lines nutritional requirements as the constraints.

The individual performance traits of pigs from two genetic lines were simulated with InraPorc® in response to diets optimised for least cost, least environmental impacts, or minimum combination of cost and environmental impacts objectives. The **simulated traits were jointly input to the LCA and bio-economic models** for individual pig sustainability assessments in terms of economy and environment.

Significant differences in the environmental impacts (P < 0.0001) and profit (P < 0.05) between lines fed the same reference diet showed that **selection for feed efficiency based on RFI in pigs improves pig production sustainability**.

Implementing **overall farm feed efficiency mitigated the inherent line profit difference from 23.4% with the reference diet to 7.6% with the joint diet**.

The high correlations of FCR with the environmental impacts (> 0.82) and the profit (< -0.88) in both lines confirmed the importance of **feed efficiency as a lever for the sustainability of pig production systems**.

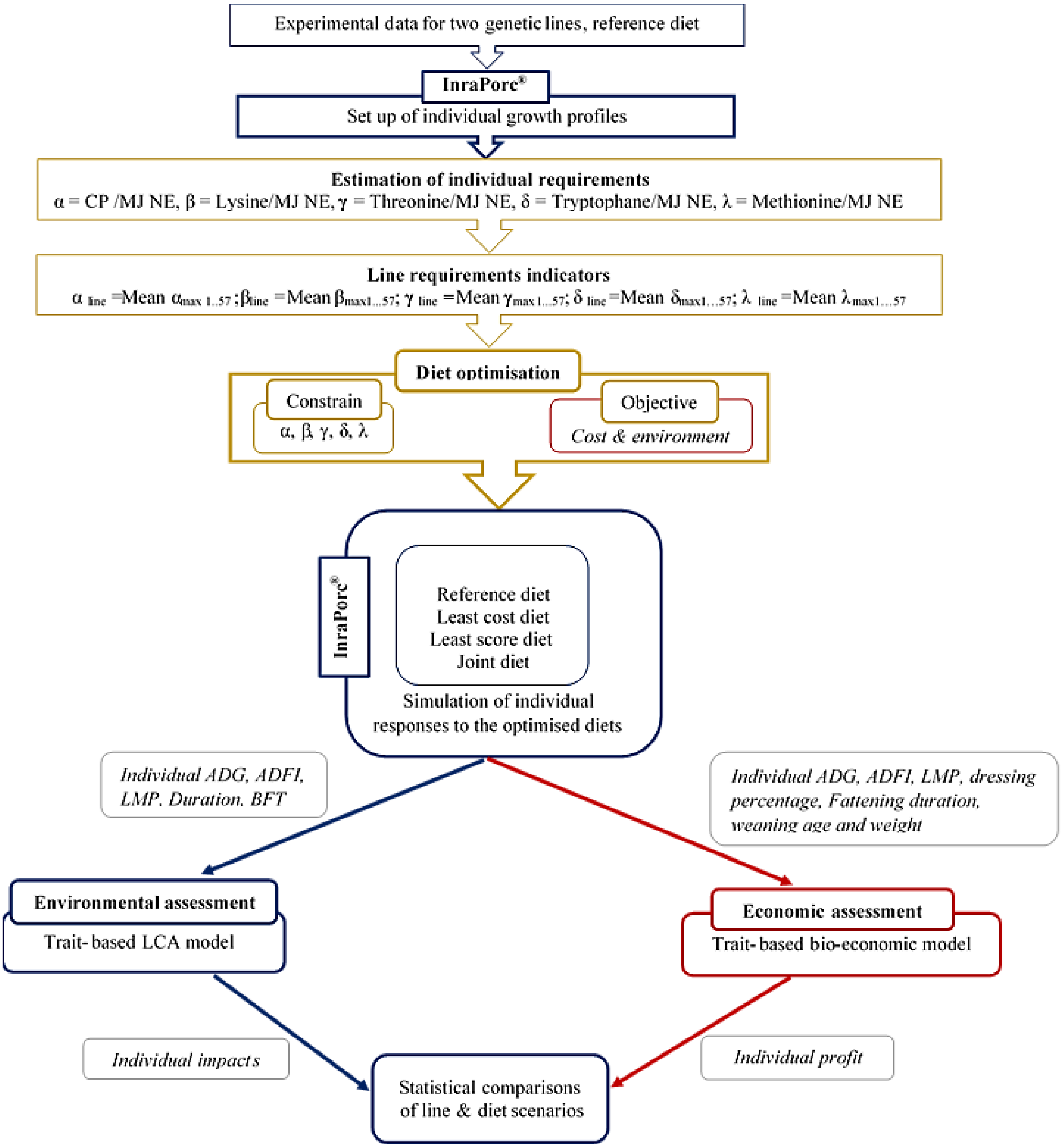


Figure 8. Schematic representation of the base-LCA individual model developments in this second study. The blue parts show the initial model developed in chapter 2, the yellow parts show the additions from chapter 3, and the red parts show the additions to the model in chapter 4.

Chapter 5 General discussion and perspectives

The results of this thesis have already been discussed in each of the chapters of this manuscript. Here we will go beyond these specific points to discuss some of the main achievements, conclusions, limitations and perspectives of the work. First, some of the models choices and properties will be discussed, and then the implications of the results for pig production and selection will be discussed.

To start, I recall here briefly the record of achievements of this thesis:

1. Developing an individual trait-based LCA model.
2. Developing an individual trait-based bio-economic model.
3. Developing an approach to achieve overall farm feed efficiency by combining genetically based nutritional requirements with economic and environmental objectives for diet composition optimisation.
4. Showing that selection for improved feed efficiency in pigs enhances the profitability and mitigates the environmental footprint of pig production.
5. Demonstrating that the overall farm feed efficiency strategy can alleviate the environmental an economic burden of less efficient animals.
6. Establishing the consistency of the strategy via considering NE as the core linkage between line requirements, ingredients dietary composition, price, and environmental impacts.
7. Assessing sustainability at the individual level.
8. Considering individual variations to obtain correlations between the performance traits, environmental impacts and profit.

5.1 **Models to assess sustainability: choices and limits**

5.1.1 ***Models choices***

5.1.1.1 LCA model

The environmental burdens of products and processes can be quantified using modelling techniques such as LCA to identify the hotspots with potential for mitigation. To assess the environmental impacts of pig selection for feed efficiency, alone or integrated with a tailored diet optimisation, a parametric LCA model was developed in the MEANS platform, by incorporating individual performance traits as input variables in the LCA model. The trait based LCA model was flexible enough to perform individual LCA to consider the variations among individual pigs and to unveil the correlations between the growth performance traits and the environmental impacts. As a module, InraPorc® was incorporated in LCA model to simulate the fattening traits of individual pigs, used as inputs for the LCA model. This integration allowed the evaluation of multiple animal x diet combinations. The simulated traits in response to diet compositions were manually imported one by one to the LCA model to run 114 separate individual LCA. The environmental impacts of genetic selection for feed efficiency were assessed through the individual trait based LCA for four impact categories on the lines of pigs divergently selected for feed efficiency on an RFI basis. The four impact categories of GWP, AP, EP, and LO were included in environmental assessment because of their significance in pig farming environmental footprints explained in chapter (4). Due to complexity of considering regional water scarcity index for the areas that ingredients are produced, the water depletion impact was assessed only for environmental assessment of selection for feed efficacy (chapter 2). The choices for the background system of the LCA, including methods, inventories, assumptions, emission factors, and system boundaries make the resulted impacts difficult to compare between the numerous previously existing LCA studies. However, to keep consistency and comparability of the quantified impacts, the standardized recommendations (e.g. IPCC 2006, LEAP and NRC) along with the same LCA method, inventories and system boundary were applied for both lines and all analyses in this thesis.

5.1.1.2 Bioeconomic model

The economics of a pig farm as a biological process (system) can be investigated through simulating the interactions between economic and biological components with a system of equations, which is called bio-economic models (Dekkers et al., 2004). Variety of bio-economic models could be developed with different assumptions including partial or life cycle consideration, and deterministic or stochastic models. In this thesis, a parametric bio-economic model was developed by incorporating individual performance traits as input variables in the profit model. The trait based bio-economic model developed in this study was flexible enough to consider the variations among the individual pigs, to estimate profit for every individual pig directly from its own growth performance traits, and to unveil correlations between the growth performance traits and the profit. As a module, InraPorc® was integrated to the bio-economic model to simulate the fattening traits of individual pigs, allowing the evaluation of multiple animal x diet combinations. Thus, rather than the usual economic assessment for a typical or the average of a group of pigs, an individual profit assessment was targeted in this study, for consistency with the LCA approach. The different stages of the production including sow/litters, post-weaning, and fattening would have different relative importance in terms of cost and final profit. Due to the main contribution of the cost of fattening diet in the total costs, along with the availability of the performance traits, the trait-based bio-economic model was developed considering all the production stages with a focus on the fattening stage.

5.1.1.3 Diet optimisation model

a. NE constraints

The consistency of the overall farm feed efficiency approach was obtained from considering NE as the core linkage between genetic, diet formulation and optimisation. As an advantage over the ME and DE systems, the NE system can better estimate the supplied usable energy to pigs, the feed intake of different diet compositions as well as the resulting growth performance of pigs (Verstegen, 2001; Noblet, 2007; Oresanya et al., 2008; NRC, 2012). On one side, the level of nutrient excretion by pig in the manure depends the density of nutrients in the diet and the feed intake. On the other side, the feed intake is driven by the diet NE since fattening pigs align their feed intake to the NE density of diet (Quiniou and Noblet, 2012; Kil et al., 2013). According to Kebreab et al. (2016) the most effective approach to mitigate environmental impacts is to reduce protein and P intakes. In (2002), Ferket et al, indicated that nutrient efficiency can be improved by adjusting the nutrient supply to more closely match the animal individual requirements. As such, the appropriate approach is to target the right dietary nutrition balance (balanced AAs to NE, balanced essential AAs) for groups of pigs, lines or towards individually precision feeding (Pomar et al., 2014). To make sure that energy is the first limit of the dietary compounds for animal growth, optimum nutrient to energy ratios should be defined as the constraints in diet formulation (Mackenzie et al., 2016). Constrained to the NE content of the resulting diet ensures a consistency with the expected pig intakes, and hence related emissions and excretions at the pig farm level for all the optimised diets. Variability in the requirements for AAs and NE among pigs emerge from the heterogeneity in growth performance, nutrient excretion and slaughter weight (Cadero et al., 2018). In this thesis, as the prerequisite for tailored diet optimisation, the maximum for individual pigs of their nutritional requirements standardised to NE were obtained for all pigs and the average for CP and four AAs were considered as the line representative requirements. Standardisations by NE of costs and environmental impacts of the diet ingredients used in the objective functions, as well as standardised individual requirements to NE, harmonises the whole process of diet optimisation and enables to control later nutrient excretion. In addition, for each line an identical nutritional balance of the optimised diets, in nutrients to NE ratios, was achieved, leading to approximately the same requirement satisfaction for each diet x line combination. Thus, as an advantage, the NE standardisation makes the process independent from an estimation of nutrient excretion during the diet optimisation, as was proposed by Mackenzie et al. (2016), who developed an excretion estimator as a module in diet optimisation procedure. In addition, the incorporation of animal requirements ratio in the constraints of the diet optimisation not only regulates a proper balance between AAs and NE, but also regulates the proper balance between the AAs required as well.

b. Objective functions and normalisation

Various diet optimisation studies have been performed, with approach different objective functions relatively to environmental impacts, reviewed in the previous chapters. In this thesis, the advantages of these approaches were integrated to implement a multi-objective diet optimisation combining environment, cost and line nutritional requirements. Simultaneously minimising the environmental impacts and constraining cost is a multi-objective optimisation problem, with the challenge of having different scales and units for each objective. To overcome this challenge, the least cost diet satisfying the line requirements was retained as a reference for normalisation of the other objectives. Thus, the environmental impacts of the least cost diet were used for normalisation of each environmental impact of the optimised diets, combined with weighting factor of one into an environmental impact score. The single environmental score was then first used as an objective function to obtain the least environmental score diet (Chapter 3). To integrate economy and environment in diet optimisation, this environmental score, weighed by a factor w_t, was combined to the diet cost weighed by a factor $1-w_t$ in a joint economy-environment objective function in chapter (4). The joint diet for each RFI line was obtained with a different optimum weighting factor (w_t), reflecting distinct trade-off points between economic and environment due to genetic requirements differences between the lines. The optimum weighting factor w_t determined the most sustainable diet composition as a line specific trade-off between economy and environment. For different nutritional requirements or market price of ingredients, and changes of impacts of ingredients due to change of origin, the optimum trade-off points would be displaced, resulting in different composition of the optimised diets. How the volatility in the prices and changes of impacts of diet ingredients and line requirements would affect the results was not examined in the thesis project. The lack of connection between the diet optimisation algorithms and the LCA model would make a sensitivity analysis including individual assessments very tedious. Further sensitivity and uncertainty analyses due to these volatilities, as a stochastic approach, would provide insights about the importance of these aspects on the optimum trade-off points.

c. Number of ingredients

Generally the main focus in diet formulation is to reduce the cost of the diet while ensuring the nutritional requirements of the herd, without considering environmental impacts of the incorporated ingredients. In practice increasing the number of ingredients would provide more flexibility toward more environmentally optimised diets. From a nutritional viewpoint, feed ingredients are classified into cereal and cereal co-products (main energy supply), protein rich crops and oil seeds, by-products from industry and additives (Wilfart et al., 2016). To diversify the sources of energy and protein in our diet optimisation, the number of ingredients was increased relatively to the reference diet with the constraint of availability of elaborated nutritional characterisations in the database of InraPorc® and inventory databases of SimaPro, to be able to run the full individual level analyses. Due to dependency of the model on simulations by InraPorc®, we used the INRA-AFZ database, which is an embedded database in InraPorc® with nutritional characterisation of limited ingredients and by-products. In this thesis, the main concern was to demonstrate that the methodology is effective. However, further diversification of ingredients, including local new ingredients and co-products, is expected to improve even more the economic and environmental impacts of pig production. However, besides connecting databases to gather information about a maximum of classic ingredients, a difficulty stands in the availability of appropriate environmental and economic indicators, in particular for novel ingredients that would still be under development. It usually requires some hypotheses related to production upscaling, and cautious uncertainty evaluation to assess the robustness of the results to the hypotheses (Mackenzie et al., 2015; Tallentire et al., 2018).

d. Pig life cycle sustainability assessment

The diets were optimised only for fattening pigs, since selection for feed efficiency in pigs is focused on this phase, as fattening pigs consume the main proportion (70%) of overall pig farm feed, so this phase is responsible for the main economic and environmental impacts. Moreover, the available version of InraPorc® (1.7) was not designed to simulate the performance traits of individual pigs during post-weaning as well as reproductive traits of sows. In case of development of InraPorc® to cover these stages, individual sustainability assessment on sows and post-weaning pigs, in addition to fattening pigs, would provide insights on whole cycle of pigs. Given that the RFI lines were shown to differ during these stages too (Gilbert et al., 2012), in particular with reduced feed intakes and better survival, it would certainly enhance the line differences estimated in this thesis. However, the evaluation at the individual level would not necessary require the sow stage to be implemented, as most fattening pigs would not become breeding animals. A difficulty at the moment resides in the availability of individual data for the earlier stages of the pig life, and dedicated nutritional models, as those recently developed by Gautier et al. (2019), to test different management and feeding strategies impacts.

5.1.2 *Conclusion on models*

The bio-economic and LCA models were developed based on diverse assumptions, fixed and variable parameters, and empirical equations. Therefore, any change in the assumptions, methodological choices and conditions including supply chain of the ingredients (e.g. origin), database inventories, manure management and application, farm operations, pig survival rate, market price of pig, would definitely modify the quantity values of the results. However, due to performing the comparative approach with consistency in all assumptions and conditions, it is expected that these changes would affect the compared scenarios in very similar ways, and the main conclusions would hold. Accordingly, the estimated values may not be robust to variations and uncertainties, but the conclusion about the possibility of improvement of impacts through combination of genetics and diets is probably robust to most of those changes.

5.2 **Automation and connection between models**

Performing individual assessments may face to some challenges when tools, algorithms and databases are not synchronised. In this study, the absence of connectivity between the softwares used for the model developments, like SimaPro, population version of InraPorc®, and R was a bottleneck to multiply individual economic and environmental assessments. Developing the connectivity between these softwares and tools in terms of importation and exportation of data and results would provide the opportunity for dynamic and automatic individual assessment on large populations of pigs. In addition, sensitivity and uncertainty studies on the input parameters of the models, such as volatility of the market price of ingredients, variations in origin of ingredients and line requirements, could be performed more easily for individual assessment analyses if all modules were connected.

5.3 **Individual assessment and correlations**

It is shown that simulating the performance of a group of pigs in response to some feeding plans (scenarios) by using an individual based model instead of an average animal model is more precise, as it considers the nutritional requirements variability among individual pigs (Pomar et al., 2003; Brossard et al., 2014). In previous studies, generally LCA was performed for a typical or the average of a group of pigs, while we produced individual profiles for pigs of each line. Through individual assessment, the covariances between the performance traits as well as their variation between individuals are considered in the simulation, which makes the results more precise and reliable. With this approach, it is possible to statistically test the differences of impacts between populations/systems/feeding scenarios. Such statistical comparisons are rarely presented in LCA studies of pig, and is considered as a flaw of some comparisons. To overcome this, uncertainty analysis is a common complementary part of LCA (Groen et el., 2014), which provides a different type of information. Thus, in case of possibility, individually based LCA would provide highly reliable and valuable data for statistical analyses.

In addition, individual trait-based economic and environmental assessments unveil the correlations between traits, profits, and environmental impacts. The correlations between performance traits and environmental impacts were observed to be robust to feeding the optimised diets as well as to genetics, which reflected the nutritional requirements satisfaction obtained from the diet optimisations. From a genetic perspective, the individual assessment could be a lever towards selection indexes including environmental objectives. Indeed, if the performances of a full pig population could be jointly evaluated under a given feeding program – which clearly depends on the availability of a full connected model as discussed in the previous section – then the proportion of the variance of the environmental impacts transmitted from one generation to the next (heritability) could be estimated, as their genetic correlations with most performances, which is a first step for building selection indexes. An index for selection for sustainability could then be defined using genetic correlations between performance traits and environmental impacts as well as profit.

5.4 **Pig production sustainability and feed efficiency**

5.4.1 ***Identifying levers for pig production sustainability***

The innate genetic difference between efficient and less efficient pigs are reflected into the differences between nutritional requirements, which like a domino, propagates on the downstream diet optimisation procedures, optimised diet compositions, and eventually on the overall costs and environmental impacts of pig farming. In addition, the differences between the nutritional requirements result in distinct least cost diets for different genetics, in terms of types of ingredients and rates of incorporation. The profit differences between lines fed the same diet would be the baseline to quantify the profit differences due to genetics. Consequently, the decrease in the profit difference between lines with the joint diets shows that the tailored diet optimisation can alleviate the innate difference in profitability between populations of different genetic potential. Finally, the higher economic robustness of the lines with the joint diets scenario, tested against the change of diet and pig market prices in chapter 4, illustrated that tailored diet optimisation combined with genetics would be much effective to reach an economically sustainable pig production. It is expected that higher improvement in feed efficiency would be obtained from individual tailored diet optimisation compared to line tailored diet optimisation.

The highest correlations were observed between FCR and both profit and the environmental impacts. This underlines that feed efficiency is a very important factor for the sustainability of the pig production systems, as already reported for various species (Ali et al., 2018; Besson et al., 2020). The medium to high correlation between protein deposition and both profit and environmental impacts for all conventional and optimised diets in both lines made it one promising new trait to improve sustainability in pig production. These correlations certainly stress that some of the reduction of environmental impacts obtained if FCR was changed would come from increases in protein deposition, thanks to their favourable correlations. However, the line differences in all impact categories and moderate to high correlations of RFI with the impacts revealed that it is also possible to improve environmental impacts by improving feed efficiency, with limited changes of other performance traits. Finally, the high negative correlations between environmental impacts and profit of the lines can be interpreted as the tight relation between feed intake and environmental impacts on one hand, and profit on the other hand, but it also highlights the importance of considering feed intake relatively to growth in these assessments, feed intake alone having more moderate correlations with the impacts and profit.

5.4.2 *Towards further management choices*

These results can be used to envisage management choices that would lead to reduced impacts while maintaining the competitiveness of the production. The variations of economic and environmental impacts due to variations in nutritional requirements profiles of individuals in a pig farm could be alleviated through diet optimisation at different levels. In this study, the overall farm feed efficiency was obtained from single phase line tailored diet optimisation, which could be extended to multiphase line tailored diet optimisation, and eventually individual-based tailored diet optimisation. An ultimate feed efficiency would be expected from dynamic individual daily basis tailored diet optimisation (precision feeding, Pomar and Remus 2019), which can be obtained from automatic feeders with the ability to estimate daily requirements of individual pigs.

Overall farm feed efficiency could be customised for each pig farm according to its situation in terms of geographical location, regional resources and pig profiles. Mitigation preference for an impact category in a region could be obtained from adjusting the weighting factor of that category in the environmental score in the objective function of diet optimisation. Higher uniformity in the nutritional requirements profiles within a farm, diversification between farms based on pig profiles, diet optimisation to meet the requirements using available local by-products and novel ingredients, could move from feed efficiency at the farm level towards overall efficiency at the pig industry level.

5.4.3 *Towards further genetics and selection choices*

Generally, selection choices has been derived from economic breeding goals without accounting for environmental impacts of pig production systems. Due to the increased importance of sustainability, efforts has been performed to incorporate environmental impacts in breeding goals. Identification of relationships between traits and environmental impact categories as well as profit is a prerequisite to develop a selection index for sustainability. Considering a sustainable breeding goal, rather than an economically driven breeding goal, may alter the structure of the selection index, while offering an alternative selection direction in favour of traits correlated to sustainable pig production. A selection index for more sustainable production should be developed based on the traits with the highest (genetic) correlations to profit and environmental impacts. One study recently investigated the variations in environmental impacts due to the genetic variations of traits through conducting a local one-at-a-time sensitivity analysis and global sensitivity analysis, which considered the correlations between the traits. Ottosen et al. (2020) applied this approach to estimate the changes of environmental impacts from genetic change in pig production systems. In their study, for global sensitivity analysis, similar traits were clustered based on their correlations to evaluate the changes in environmental impacts due to changes in each cluster independently from the other clusters. In another approach, some tried to integrate environmental impacts in a bio-economic model through monetising the impacts. In this way, the economic weights of the traits would be altered due to the costs of environmental impacts, which could be used to improve a selection index towards the sustainability of pig production systems. Ali et al. (2018) applied this to incorporate GHGs (CO_2, CH_4 and N_2O) as a cost in breeding goal through monetising of GHGs based on the shadow price of CO_2 emission. However, this approach, although very effective to define a selection index, has shortcomings due to the lack of universal agreement and standard guidelines for monetising environmental impacts. As an alternative to incorporate environmental impacts in breading goal, the obtained correlations between the traits and impacts as well as profit could be used to develop a prospective approach for desired sustainability response, which, combined with the economic weights of the heritable traits of interest, could lead to the definition of a selection index for sustainability.

5.5 General conclusion

The economic and environmental assessments showed that selection for improved feed efficiency in pigs increases the profitability and mitigates the environmental footprint of the pig production. Selection for feed efficiency combined with diet optimisation to meet the individual nutritional requirements even enhanced these economic and environmental improvements through restoring part of the advantages of selection that cannot emerge when feeding animals the same diet. Nevertheless, feeding low efficient pigs an optimised diet strongly reduces the genetic differences and alleviates most of their innate economic and environmental burdens. Thus, for increased pig sustainability, a selection for feed efficiency should be combined to diet optimisation. Furthermore, the assessment at the individual level gives access to the covariances between the performance traits and the environmental impacts and profit. The high correlations of FCR with environmental impacts and profit in both lines confirmed the importance of feed efficiency as a lever for the sustainability of pig production. Also the moderate correlations with RFI pointed this trait as a potential lever to improve environmental impacts with limited correlated effects on other production traits. From the results of this thesis, it seems possible to move from an economic point of view for genetic and management improvement of pig feed efficiency to a more holistic and sustainable point of view, to achieve more balanced breeding goals including combinations of the most influential traits in terms of economy and environment.

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Chapter 6 **Scientific communications**

6.1 **Poster**

Soleimani Tara, Gilbert Hélène. 2019. Evaluating environmental impacts of selection for residual feed intake in pigs. In 70th Annual Meeting of the European Federation of Animal Science (EAAP), Ghent, Belgium.

6.2 **Oral communications**

Soleimani T, Hermesch S, Gilbert H. 2020. Evaluation economic and environmental impacts for residual feed intake and tailored diet formulation in pigs. UNE postgraduate conference 2020, New England Award (NEA), Armidale, Australia.

Soleimani Tara, Gilbert Hélène. 2020. Environmental optimisation of diets for genetically selected pigs. In 71th Annual Meeting of the European Federation of Animal Science- virtual EAAP. Session 04, P.115.

Soleimani Tara, Gilbert Hélène. 2021. Combiner génétique et nutrition pour une optimisation économique et environnementale en production porcine. *53èmes Journées de la Recherche Porcine.* Paris.

6.3 **Journal papers (published version)**

Soleimani Tara, Gilbert Hélène. 2020. Evaluating environmental impacts of selection for residual feed intake in pigs.animal.10.1017/S175173112000138X.

Soleimani Tara, Gilbert Hélène. 2021. An approach to achieve overall farm feed efficiency in pig production: environmental evaluation through individual life cycle assessment. International Journal of Life Cycle Assessment.10.1007/s11367-020-01860-3.

Soleimani Tara, Hermesch Susanne, Gilbert Hélène. 2021. Combined economic and environmental assessments of pig production systems to improve pork production sustainability. Journal of Animal Science.10.1093/jas/skab051.

Evaluating environmental impacts of selection for residual feed intake in pigs

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INTRODUCTION

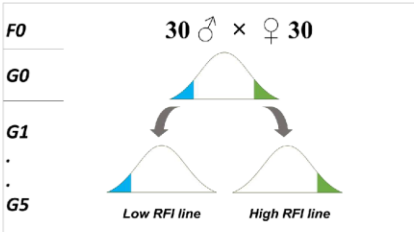
Beyond being an economic bottleneck, feed greatly contributes to the environmental impacts of pig farming. Consequently, improvement of feed efficiency is a major goal for pig production sustainability, by reducing environmental fluxes associated with feed production and the amount of effluent per pig.

The aim of the present study was to develop a model adapted for evaluation of pig selection strategies for feed efficiency and use it to estimate the environmental impacts of pig selection for residual feed intake (RFI), through comparative life cycle assessment (LCA) of two lines of pigs divergently selected for RFI.

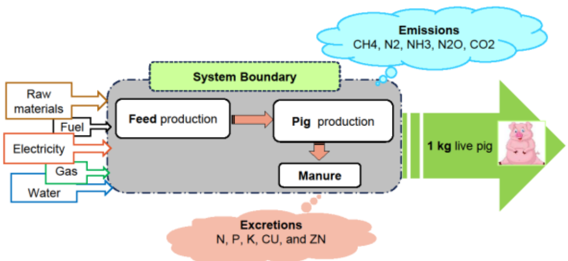
MATERIAL & METHODS

Data

The data were extracted from the fifth generation of two pig lines divergently selected for residual feed intake (low line, more efficient pigs, LRFI; high line, less efficient pigs HRFI).

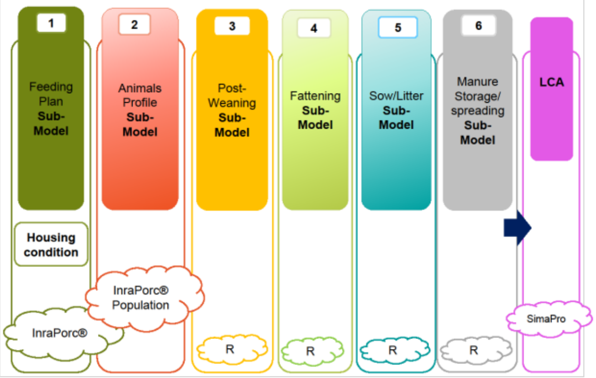


The 'cradle-to-farm-gate' system boundary for life cycle assessment of 1 kg live pig as the functional unit.



Model Structure

The model consists of six modules.



Acknowledgements

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RESULTS

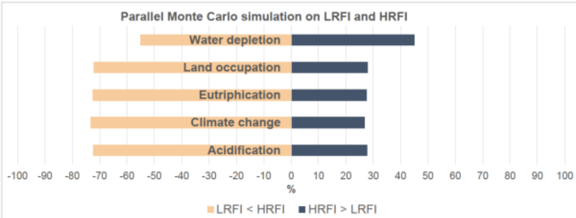
Selection for Low RFI improved the protein to lipid ratio (P/L) mainly through a decrease in lipid deposition (LD).

	Mean HRFI	Mean LRFI	SD LRFI	SD HRFI	P-value	Mean Differences %
Protein/lipid	0.73	0.85	0.13	0.13	<0.0001	15.18
Protein content	18.6	18.4	1.31	1.34	0.32	1.08
Lipid content	25.7	22.4	3.28	4.11	<0.0001	13.72

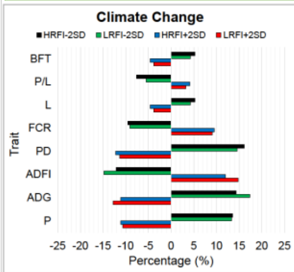
The comparative LCA showed that LRFI had on average 6% lower environmental impacts than HRFI on the environmental impact categories.

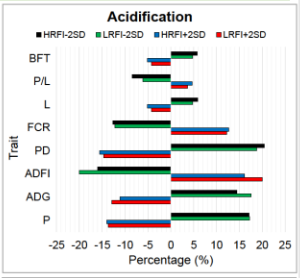
Impacts results from LCA based on mean trait values for each line				
Impact category	**Unit**	**HRFI**	**LRFI**	**Difference %**
Climate change	kg CO2 eq	2.76	2.61	5.76
Acidification	g SO2 eq	48.0	44.8	6.89
Eutrophication	g P eq	3.6	3.3	7.15
Land occupation	m2a	4.44	4.20	5.36
Water depletion	m3	0.047	0.045	4.34

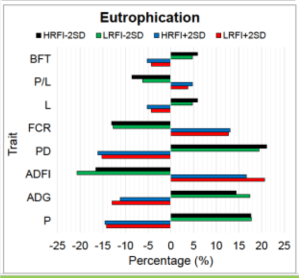
Uncertainty analysis through parallel Monte Carlo simulations revealed that differences between lines are not systematic.

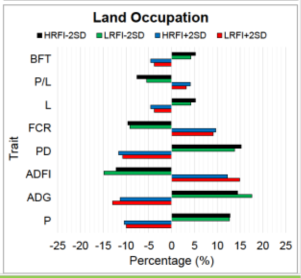


One-at-a-time sensitivity analysis (mean trait value ±2SD) revealed that all the environmental impact categories were higly sensitive (>5%) to average daily feed intake (ADFI), protein deposition (PD), feed convertion ratio (FCR), protein at slaughter (P), average daily gain (ADG) and less sensitive to back fat thickness (BFT) and lipid at slaughter (L) for both LRFI and HRFI lines.









CONCLUSION

An integrated parametric model was developed to account for animal performance traits in life cycle assessment method to quantify the responses to selection. The model was applied to compare the environmental burdens of the lines selected for RFI. Selection for Low RFI improves the environmental impacts, however it could not directly control the protein deposition and excreted nitrogen as one of the main sources of environmental concerns. Therefore, RFI may not be the optimum measure for selection, from an environmental point of view.

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ALIMENTATION AGRICULTURE ENVIRONNEMENT

Evaluating Economic and Environmental Impacts of Selection for Residual Feed Intake and Tailored Diet Formulation in Pigs

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Doctorate
Animal Genetics and Breeding Unit
Oral Presentation

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To identify proper strategies for future feed efficient pig farming animal selection scenarios should be evaluated. Selection based on residual feed intake (RFI) has been proposed to improve feed efficiency. The aim of this project is to develop a model to account for individual animal performance in life cycle assessment methods to quantify the economic and environmental impacts of the selection. Experimental data from 118 pigs were collected from lines divergently selected for residual feed intake (low line, more efficient pigs, LRFI; high line, less efficient pigs HRFI). A parametric model was developed for life cycle assessment (LCA) based on the net energy fluxes in a pig system. A nutritional pig growth tool, InraPorc®, was included as a module in the model to embed flexibility for changes in feed, traits and housing conditions, and to simulate individual pig performance. The comparative LCA showed that LRFI pigs had lower environmental impacts than HRFI pigs, on climate change, acidification potential, fresh water eutrophication potential and land occupation. A sensitivity analysis based on pig performance traits revealed that these environmental impacts were least sensitive to carcass lipid contents and back fat thickness, and most sensitive to protein content, growth rate, feed intake and feed conversion ratio. Further modelling showed line differences in requirements for energy, protein and amino acids, which was used to formulate separate diets adjusted to the line requirements. The environmental assessment of the simulated line responses to these diets revealed that tailored diet formulation, according to the innate requirements of the pigs, is a promising strategy for achieving more sustainable pig production. An additional economic optimisation is currently being developed to propose an integrated framework to pig production stakeholders.

Keywords: Feed Efficiency, Life Cycle Assessment, Environment, Economic, Pigs
Research Method: Mixed Method, Life Cycle Assessment (LCA)

Environmental optimization of diets for genetically selected pigs

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Abstract

The environmental impact of pig production is largely dependent on the diet composition, via impacts of the feed production stage and of the pig consumption efficiency stage. Considering these stages jointly for diet formulation seems suitable to improve the environmental impacts of pig production systems. In this study, tailoring the diet formulation precisely to satisfy energy and nutrient requirements was combined with an environmental optimization of the diet composition. Normalized digestible crude protein (CP) and amino acids (AAs) based on the net energy (NE) were retained to capture the animal growth requirements. An approach was developed to use these indicators to determine for two pig lines selected for different levels of feed efficiency (residual feed intake, RFI) a list of possible tailored candidate diets, to quantify their respective environmental impacts using a life cycle assessment (LCA) approach, and to extract the best environmentally optimized diet. Data from the two pig lines were used to calibrate the nutritional requirements related to high efficient (LRFI) and low efficient (HRFI) animals. The responses of the lines to their corresponding tailored optimized diets were assessed through an LCA method. The environmentally optimized diets tailored for the pig requirements reduced the environmental impacts on average by 8.8 % for LRFI and 11.4 % for HRFI pigs relative to the conventional diet. Using the optimized diet for HRFI pigs led to even lower impacts than the LRFI pigs fed a conventional diet. In conclusion, the combination of diet formulation tailored to the nutritional requirements of a genetic group of pigs with its environmental optimization can highly reduce the overall environmental impacts of pig production.

Keywords: life cycle assessment, residual feed intake, diet environmental optimization, pig, selection

Introduction

The main environmental impacts of the pig production come from the feed production (Garcia *et al.*, 2018) and from the emissions and excretions related to the wastage of feed during pig farming (Dourmad and Jondreville, 2007). Consequently, to limit environmental impacts, both aspects should be considered simultaneously in diet formulation. Pigs adjust their ad-libitum feed intake to the net energy density (NE) of the diet (Quinion and Noblet, 2012). Due to this, the diet nutrients would be up taken proportionally to the NE of the diet. In addition, balancing energy and amino acids (AAs) is important for diet formulation, since oversupply of energy would be converted to fat, and insufficient energy would prohibit the maximum protein deposition, contributing to AAs excretion and further nitrogen emissions. Therefore, any deviation from the balance between AAs and NE in the diet, compared to the animal requirements, would be a deviation from an environmentally optimized diet. Thus, an environmental optimization of the diet composition can only be expected among diets, which fit the requirements of pigs. The aim of this study was to develop an approach to optimize from an environmental perspective the choice of diets tailored for pig requirements, and to assess the environmental impacts of feeding efficient and less efficient pigs with optimized diets to their requirements through a life cycle assessment (LCA) method.

Methodology

Input data and parameters. Experimental data (body weights, feed intakes, body composition) collected from 10 weeks of age until slaughter weight under ad libitum feeding for two lines of pigs selected for feed efficiency based on residual feed intake (RFI) were imported to InraPorc®. These data were used to calibrate a growth performance profile for each individual pig (57 pigs per line). The calibration of the profiles was performed according to the daily ad-libitum uptaken net energy (NE) during the whole fattening period. Since pigs adapt their ad-libitum feed intake to the diet NE, the calibrated profiles can play a predictive role to estimate the feed intake of pigs when they are offered different net energy diets. In addition, from these profiles the individual protein and amino acids (AAs) requirement profiles of the pigs under the test conventional diet could be inferred (reference diet). Because this test diet was formulated to cover the dietary requirements of all pigs so they could express their ad libitum potential, excesses of protein and amino acids (AAs) were pointed out for the main part of their fattening duration. These excesses contribute to downstream excretions and emissions during housing, manure storage and spreading.

Tailored diet formulation. The first step was to adjust the diet to the normalized requirements of the pig lines, to obtain a "tailored diet". The daily animal requirements were extracted from InraPorc® for all individuals in five categories of digestible crude protein (CP), digestible lysine, threonine, tryptophan and methionine, as standardized requirements to the diet NE (g/MJ), later called normalized requirements. From these five daily data, the pig maximum daily normalized requirement for each component was extracted, and the mean per line was computed (Table 1). On average, the low RFI (LRFI) line had +4.8 % requirements in g/MJ NE compared to the high RFI (HRFI) line.

Table 1. Average maximum individual normalized requirements (g/MJ NE) for the LRFI and HRFI lines (standard deviation)

	LRFI	HRFI
α: Crud protein requirements per MJ NE	11.75 (2.46)	11.04 (2.33)
β: Lysine requirements per MJ NE	0.91 (0.20)	0.86 (0.18)
γ: Threonine requirements per MJ NE	0.58 (0.12)	0.55 (0.11)
λ: Methionine requirements per MJ NE	0.27 (0.03)	0.26 (0.05)
δ: Tryptophan requirements per MJ NE	0.16 (0.06)	0.15 (0.03)

Then, the diet composition was adjusted to the animal requirements: the conventional diet (reference) included barely (quantity b), wheat (w), soybean (s), sunflower oil (f), L_lysine (LLY), L_threonine (LTH), L_tryptophan (LTR), DL_methionine (DLM). Ingredients like salt, carbonate calcium and vitamins, which do not have any digestible energy, CP or AAs, were excluded from the diet formulation.

To consider the animal requirements in the reformulation, the following linear system of equations should be satisfied for each line requirements. Since the diet would be reformulated for the unit of one kg, the first equation controls that the reformulated diet plus the additives do not exceed from one kg and the rest of equations assure that the diet nutrients correspond to the animal requirements. The digestible CP and AAs of the ingredients were extracted from the INRA-AFZ database of feed ingredients (Sauvant et al., 2004) to link the ingredients quantities to their nutritional contents.

- b + w + s + f + LLY + LTH + LTR + DLM = 1 kg – additives (kg)
- CP_diet/NE_diet= α
- LLY_diet/NE_diet= β
- LTH _diet/NE_diet= γ
- LTR _diet/NE_diet= δ
- DLM _diet/NE_diet= λ

A list of all the tailored candidate diets satisfying the dietary maximum average requirements was then obtained for each pig line, solving the system of equations using the lsqnonneq function of Pracma package (library) in R.

Least environmental impact diet choice. Second, for each line the diet with least environmental impact was identified. The environmental impacts of all candidate diets were calculated through LCA in Simapro V8.5.4.0 (PRé Consultants, Amersfoort, The Netherlands) on the MEANS (MulticritEria AssessmeNt of Sustainability) platform by the method of ReCiPe Midpoint 2016 (H) V1.13 for the categories of climate change, acidification potential, eutrophication potential, and land occupation (LO). For each line, the tailored diet with lower environmental impacts was retained for further complete evaluation of the related pig performances and environmental impact of the production of 1 kg of pig at the farm gate as the functional unit of LCA.

Performance and environmental evaluations of environmentally optimized tailored diets. The growth performance with the conventional diet and the environmentally optimized tailored diets were simulated with InraPorc® for each pig. The averages of the fattening traits for LRFI and HRFI lines were then used as input parameters in the LCA model previously developed (Soleimani and Gilbert, 2019) to assess the global environmental impacts of each combination of line and diet.

Results and discussion

Diet composition and impacts. The three tested diet compositions are provided in Table 2. From the LRFI to the HRFI optimized diets, the main difference was in the relative incorporation of barley compared to soybean meal, to respond the line difference for AA requirements, which was reported before (Gilbert et al, 2017). The environmental impacts of each diet were calculated from the ingredient impacts (Table 3). The two optimized diets showed large reductions of environmental impacts (from -13.9% for acidification to -21.7% for climate change in the HRFI optimized diet except eutrophication) compared to the conventional diet. In all categories the HRFI, optimized diet had lower impacts than the LRFI diet.

Table 2. Composition (g/kg feed) of the tested diets.

Ingredients	Conventional	LRFI optimized	HRFI optimized
Barley	409	884	904
Wheat soft	327	0	0
Soybean meal 48	202	75	55
Sunflower oil	21	0	0
L-Lysine HCL	3.5	5	4.9
L-Threonine	1.4	1.91	1.85
L-Tryptophan	0.3	0.19	0.18

DL-Methionine	0.9	0.84	0.77
Salt (Sodium Chloride)	4.5	4.5	4.5
Calcium carbonate	11	11	11
Dicalcium phosphate	12	12	12
Vitamins and minerals	5	5	5

Table 3. Environmental impact of the conventional, optimized LRFI and HRFI diets.

Environmental Impacts	Conventional diet	LRFI optimized diet	HRFI optimized diet
Climate change, kg CO2-eq	0.722	0.603	0.580
Acidification, g SO2-eq	6.8	5.9	5.9
Eutrophication, g P-eq	0.41	0.44	0.43
Land occupation, m²a	1.63	1.39	1.37

Performance assessment. The responses of all individual pigs to the diets were simulated via InraPorc® (Table 4).

Table 4. Mean performance traits of the LRFI and HRFI lines (standard deviation), in response to the conventional and optimized diets, simulated with InraPorc®. N=57 pigs per line.

Traits	**LRFI**		**HRFI**	
	conventional	**optimized**	**conventional**	**optimized**
Daily feed intake, kg	1.97 (0.21)	2.06 (0.22)	2.15 (0.19)	2.24 (0.21)
Average daily gain, g/d	800 (80)	780 (82)	830 (71)	810 (60)
Feed conversion ratio, kg /kg gain	2.45 (0.16)	2.62 (0.15)	2.58 (0.18)	2.77 (0.14)
Body weight at slaughter, kg	116.3 (7.0)	114.3 (6.4)	117.5 (8.3)	115.0 (8.4)
Backfat thickness at slaughter, mm	15.3 (1.2)	15.5 (1.2)	16.5 (1.5)	16.8 (1.4)

The performance traits showed a decrease in growth rate for both lines with the optimized diets, despite a slight increase of feed intake. This lower growth rates were due to the nonsatisfaction of the dietary requirements of some animals in the early stages of growth. Diet formulation from the 75% quantile of the maximum pig requirements per line, rather than the average maximum, could limit this undesired impact.

Environmental assessment of the global optimization strategy. To assess the environmental impacts for producing 1 kg of pig with the line optimized diets, we applied an LCA with SimaPro. The results of four impact categories for the lines fed optimized diets can be compared with the impacts resulting from the conventional diet (Table 5).

Table 5. Environmental impacts of 1 kg of pig from the LRFI and HRFI lines fed the conventional or the optimized diets.

Impact category	LRFI conventional	LRFI optimized	HRFI conventional	HRFI optimized
Climate change, kg CO2 eq	2.61	2.49	2.76	2.56
Acidification, g SO2 eq	44.8	38.8	48.0	40.0
Eutrophication, g P eq	3.37	3.06	3.62	3.18
Land occupation, m^2a	4.20	3.93	4.44	4.13

With the conventional non-optimized diet, the LRFI line had an average environmental advantage of 6% compared to the HRFI line, as shown earlier by Soleimani and Gilbert (2019). For the two lines, all environmental impacts decreased relative to the conventional diet, with lower decreases affecting climate change and land occupation (from 4.7% to 7.5% reductions) and larger decreases for eutrophication (from 9.6 to 12.9 %) and acidification (14.3 to 18.2%). Thanks to the optimization of diets towards each line needs, the larger overall decreases were obtained for the HRFI line fed the optimized diet. When fed the optimized diet the HRFI (less efficient) line reached lower environmental impacts than the LRFI line (more efficient) fed the conventional diet.

Conclusion

Diet formulation based on the dietary requirements of pigs may not be environmentally optimized. Precision diet formulation tailored to satisfy the specific requirements of a genetic group of pigs accompanied by environmental optimization can improve the overall environmental impacts of the pig production, especially by limiting the environmental impacts of groups of less efficient animals, while maintaining the appropriate delivery of nutrients to more efficient animals. This study sets the basis for formulating diets accounting for environmental impacts of the ingredients. Better optimization could be obtained by enlarging the list of possible ingredients, and sensitivity analyses will be needed to further understand the observed impacts. This approach should ultimately be combined with a least cost formulation approach and global economic evaluation to assess all the sustainability pillars of the strategy.

Acknowledgements

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Combiner génétique et nutrition pour une optimisation économique et environnementale en production porcine

Une modélisation à partir de données individuelles pour améliorer la durabilité de la production

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Combiner génétique et nutrition pour une optimisation économique et environnementale en production porcine

Les impacts environnementaux (IE) et les résultats économiques des systèmes de production peuvent être évalués par des analyses de cycle de vie couplées à des modèles bioéconomiques. De tels modèles ont été développés à partir des performances individuelles de porcs, pour quantifier les IE (potentiel de changement climatique - CC, d'acidification des sols - AP, d'eutrophisation des eaux - EP, occupation des sols - OS), et le résultat économique de scénarios combinant des génétiques différentes pour l'efficacité alimentaire - levier majeur de réduction des coûts et de la production d'effluents, et des formulations multi-objectifs des aliments. Après définition des besoins nutritionnels spécifiques de chaque génétique, des aliments dédiés ont été formulés à moindre coût (MC), à moindre impact environnemental (ME, poids équilibrés pour les 4 catégories), ou combinant ces deux critères (MEC). Les données génétiques (2x57 porcs de lignées divergentes pour l'efficacité alimentaire, performances individuelles obtenues avec un aliment conventionnel) ont permis d'estimer les besoins nutritionnels par lignée, puis de simuler des performances individuelles en réponse aux aliments optimisés. Avec le régime conventionnel initial, la lignée plus efficace avait -7 % d'IE et un meilleur profit (P < 0,001). Avec les aliments ME et MEC, l'avantage environnemental des animaux efficaces était réduit (4,91 % et 4,29 %), et l'aliment MEC permettait d'atteindre des profits similaires pour les deux lignées. Cette approche permet donc dans une certaine mesure de compenser, par l'ajustement sous contraintes des rations alimentaires, les désavantages génétiques des animaux les moins efficaces sur les plans économiques et environnementaux. Il est alors envisageable d'orienter des choix stratégiques de sélection et de conduite pour proposer une production porcine durable.

Combining genetics and nutrition in economic and environmental optimization of pig production systems

Life cycle assessment, combined with bioeconomic models, can be used to assess environmental impacts (EI) and profits of production systems. Such models were developed on an individual performance trait basis to quantify the main EI (global warming potential - GWP, terrestrial acidification potential - AP, freshwater eutrophication potential - EP, and land occupation - LO) and the profit for scenarios that combined different genetic levels for feed efficiency, as a principal mechanism to reduce costs and excretion, and multiobjective formulation diets. First, nutritional requirements were obtained for each genetic line separately. Then, diets were optimised for the nutritional objectives and a least-cost (LC), least-EI (LE) or combined LC and LE (joint) objective. Performance records for 57 pigs per line fed a unique conventional diet were used to calibrate the individual pig nutritional profiles and estimate line nutritional requirements. Next, individual performances in response to the optimized diets were simulated. With the experimental conventional diet, the more efficient line had 7% lower EI and better profit (P <0.001) than the less efficient line. With the LE and joint diets, the EI advantage of the more efficient animals was reduced (by 4.91% and 4.29%, respectively), and the two lines had similar profit (P > 0.05) with their joint diets. The approach that was developed mitigated, due to the constraints applied to the diet formulation, the innate genetic disadvantages of the less efficient pigs at the economic and environmental levels. These approaches can be used to orientate strategic choices at the selection and management levels for more sustainable pig production.

INTRODUCTION

L'amélioration de l'efficacité alimentaire du porc en croissance peut être obtenue par la combinaison de leviers génétiques (sélection pour une meilleure efficacité), nutritionnels (adéquation de la ration aux besoins de l'animal) et de conduite des porcs (conditions optimales d'utilisation de l'énergie et des nutriments pour la croissance). Cette étude visait à évaluer comment, en actionnant les deux premiers leviers, les piliers économiques et environnementaux de la durabilité des systèmes de production porcins pouvaient être améliorés. Pour ce faire, un modèle d'analyse de cycle de vie (ACV), reconnu pour l'évaluation environnementale des systèmes de production porcins (Monteiro *et al.*, 2020 ; Espagnol *et al.*, 2020), a été développé et associé à un modèle bioéconomique. Pour permettre la prise en compte de différents profils génétiques soumis à des stratégies nutritionnelles adaptées, des outils d'évaluation dédiés, intégrant la prise en compte de la variabilité individuelle des besoins et des performances des porcs, ont été développés. Ces modèles ont été appliqués à des profils de porcs de lignées expérimentales divergentes pour l'efficacité alimentaire, soumis à des régimes alimentaires optimisés, selon le cas, sur les plans nutritionnel et économique, nutritionnel et environnemental, ou nutritionnel, économique et environnemental.

1. MATERIEL ET METHODES

1.1. Données expérimentales

Les moyennes des données expérimentales des truies reproductrices et de leurs porcelets Large White de chacune de deux lignées divergentes pour l'efficacité alimentaire ont été collectées à l'unité expérimentale INRAE GenESI (Surgères, France) (GenESI, INRAE, 2018. Unité expérimentale Elevages porcins innovants, doi : 10.15454/1.5572415481185847E12) comme décrit par Gilbert *et al.* (2012). Les enregistrements individuels, de 10 semaines d'âge à l'abattage (110 kg de poids vif), ont été collectés sur les porcs de ces lignées après 5 générations de sélection. Des porcs mâles de chaque lignée (n=57 par lignée) ont eu un accès libre à un aliment conventionnel (aliment de référence) couvrant leurs besoins nutritionnels de 10 semaines d'âge à l'abattage. Pendant cette période, les consommations individuelles journalières ont été enregistrées grâce à des automates d'alimentation (ACEMO, Pontivy, France), tandis que par ailleurs les poids individuels en début et fin de croissance et des mesures d'épaisseur de lard dorsal aux ultrasons (ALOKA SSD-500, Cergy Pontoise, France) en fin de croissance étaient disponibles. La consommation moyenne journalière (CMJ), le gain moyen quotidien (GMQ) et l'épaisseur de lard dorsal moyenne (ELD) ont été calculés, ainsi que deux critères d'efficacité alimentaire, l'indice de consommation (IC) et la consommation moyenne journalière résiduelle (CMJR) (Gilbert *et al.*, 2017).

1.2. Profils individuels de croissance et simulations

Les données individuelles pendant la croissance ont été importées dans le logiciel InraPorc® (Brossard *et al.*, 2014) pour déterminer le profil individuel des besoins nutritionnels de chaque porc sur la période. Les profils ont été calibrés d'après l'ingéré volontaire d'énergie nette (EN) à partir d'une fonction Gamma. Ces profils ont ensuite permis de simuler les performances individuelles des porcs soumis à différents régimes optimisés, jusqu'à un poids d'abattage de 120 kg. Ces performances individuelles simulées ont finalement servi de paramètres d'entrée pour les modèles bioéconomiques et d'analyse de cycle de vie décrits dans les sections suivantes.

1.3. Modèle bioéconomique

Le modèle retenu suit une modélisation linéaire classique du résultat économique, qui est obtenu comme la différence entre le revenu et les coûts de production pour un porc au poids d'abattage. Le cycle de vie d'un porc a été décomposé en trois phases : de la naissance au sevrage (28 jours d'âge), du sevrage au début d'engraissement (10 semaines d'âge), enfin la période d'engraissement jusqu'au poids d'abattage. Le coût de production d'un porcelet sevré intégrait tous les coûts précédant le sevrage, dont la mise à la reproduction et le renouvellement du troupeau de truies, la santé, l'énergie, l'aliment, l'entretien des bâtiments, le travail, la gestion des effluents et l'amortissement des immobilisations. Les coûts de production pendant la période de post-sevrage ont été estimés d'après des simulations de profils moyens de croissance et d'ingestion des lignées expérimentales à partir de poids individuels et des niveaux d'ingestion par loge et par lignée. Les coûts pendant la période d'engraissement ont été calculés à l'échelle individuelle d'après les performances simulées (section 1.2), et agrégés en quatre catégories : aliment et eau, bâtiment et capital, énergie, travail. Les autres coûts (assurances, frais vétérinaires et de santé, entretien des bâtiments) ont été considérés comme fixes pour chaque porc (Calderón Díaz *et al.*, 2019). Les prix des ingrédients des aliments pour les différentes phases (IFIP, 2020), les coûts énergétiques par porc et la consommation d'eau relativement à l'ingéré ont été extraits des rapports et bases de données de l'IFIP (2014).

Le produit associé à chaque porc était considéré comme uniquement lié à la vente de la carcasse et calculé selon la grille en cours en France (https://rnm.franceagrimer.fr/prix?PORC), c'est-à-dire un prix de base pour 100 kg de carcasse à 56 % de taux de maigre des pièces (TMP) (129,30 €/carcasse, juillet 2020), corrigé selon un barème spécifique pour le poids et le TMP réels de la carcasse.

1.4. Modèle d'analyse de cycle de vie

Les impacts environnementaux retenus pour cette étude sont les impacts majeurs de la production porcine identifiés dans la littérature : le potentiel de changement climatique (CC, kg CO_2-eq), le potentiel d'acidification des sols (AP, kg SO_2 eq), le potentiel d'eutrophisation des eaux (EP, kg P eq) et l'occupation des sols (OS, m^2an). Le modèle d'ACV a été construit autour des performances des porcs soit, avant 10 semaines, les performances moyennes des lignées, et pour la période d'engraissement, les performances individuelles. Le modèle se compose de six modules : profils de performance, plan d'alimentation, émissions, excrétion, consommation d'eau, et consommation d'énergie (Soleimani et Gilbert, 2020a). Les jeux de données ReCiPe Midpoint 2016 (H) V1.02 et ECOALIM (Wilfart *et al.*, 2016) des bases AGRIBALYSE® and Ecoinvent du logiciel SimaPro V8.5.4.0 disponible sur la plateforme MEANS (https://www6.inrae.fr/means) ont été utilisés pour, d'abord, déterminer les impacts environnementaux des aliments (de référence et optimisés), puis estimer les impacts de la production d'un kg de porc vivant à l'abattage (unité fonctionnelle du modèle).

1.5. Formulation d'aliments multi objectifs

Les huit ingrédients de l'aliment expérimental de référence (blé, orge, tourteau de soja, huile de tournesol, et acides aminés (AA) de synthèse (L_lysine, L_thréonine, L_tryptophane, DL_méthionine), auxquels se sont ajoutés le maïs, l'avoine, le pois, le triticale et des tourteaux de colza et de tournesol, ont été retenus pour formuler de nouveaux aliments. Les compositions en protéine digestible (CP), AA et EN de ces ingrédients ont été extraites de la base de données INRA-AFZ (Sauvant *et al.*, 2004).

Les formulations optimisées d'aliments ont été effectuées pour couvrir les besoins nutritionnels de chaque lignée séparément, avec les objectifs suivants : (i) le moindre coût (MC, utilisée comme référence pour les autres formulations), (ii) le moindre impact environnemental (ME) dans une limite de + 10 % du coût par rapport à l'aliment MC, (iii) la minimisation conjointe du coût et de l'impact environnemental (MEC). Six aliments (trois par lignée) plus l'aliment expérimental de référence ont donc été évalués.

1.5.1. *Détermination des besoins nutritionnels des lignées*

Le maximum pendant la croissance des besoins nutritionnels individuels, exprimés en g par MJ EN, obtenus pour les profils InraPorc®, ont été considérés pour cinq indicateurs : protéine digestible (α), lysine digestible (β), thréonine digestible (γ), méthionine digestible (λ) et tryptophane digestible (δ) (Soleimani et Gilbert, 2020b). Pour chaque lignée, la moyenne de ces besoins individuels a été calculée, et retenue comme objectif de formulation d'un aliment unique pour chaque lignée.

1.5.2. *Calcul des coûts des aliments*

Le coût d'un aliment par unité d'EN a été calculé comme la somme des prix de chaque ingrédient multiplié par la quantité incorporée. L'aliment MC a été formulé pour chaque lignée en minimisant cette fonction tout en respectant les besoins nutritionnels des lignées.

1.5.3. *Calcul du score environnemental*

Pour chaque aliment, l'impact environnemental de chaque catégorie (CC, AP, EP, OS) a été calculé comme la somme des impacts environnementaux de cette catégorie pour chaque ingrédient, pondérés de la quantité incorporée. Comme proposé par Garcia-Launay *et al.* (2018), chacune de ces composantes a d'abord été normalisée relativement à l'impact environnemental de l'aliment MC de la lignée correspondante, avant de sommer l'ensemble dans un score environnemental global. Un poids identique a été affecté aux quatre impacts retenus. Les aliments ME ont été obtenus en minimisant ce score environnemental tout en couvrant les besoins nutritionnels de chaque lignée.

1.5.4. *Optimisations*

L'objectif à minimiser pour les aliments MEC a été établi comme la somme du coût de l'aliment, exprimé relativement au coût de l'aliment MC, pondéré d'un facteur $1\text{-}w_t$, et de son score environnemental décrit à la section précédente, pondéré d'un facteur w_t. Les formules pour des aliments satisfaisant chacun des trois objectifs ont été obtenues pour chaque lignée avec le package R *mco*, grâce à l'algorithme NSGA-II (paramètres de taille de population de 340 et 3500 générations).

1.6. Statistiques

Pour l'ensemble des paramètres étudiés, les différences entre lignées pour chaque type d'aliment ont été appréciées par des tests de Student et déclarées significatives pour $P < 0,05$.

Les estimations individuelles pour les performances simulées, les impacts environnementaux et les résultats économiques ont finalement permis d'estimer les corrélations entre ces trois résultats.

2. RESULTATS ET DISCUSSION

2.1.1. *Coûts et impacts des aliments optimisés*

Les besoins nutritionnels (en g/MJ EN) de la lignée CMJR- étaient systématiquement plus élevés ($P < 0,05$ pour un test de Student des différences entre lignées) que ceux de la lignée CMJR+: 11,75 ± 2,46 (moyenne ± écart-type) vs 11,04 ± 2,33 pour α, 0,91 ± 0,20 vs 0,86 ± 0,18 pour β, 0,58 ± 0,12 vs 0,55 ± 0,11 pour γ, 0,27 ± 0,03 vs 0,26 ± 0,05 pour λ, et 0,16 ± 0,06 vs 0,15 ± 0,03 pour δ. Les impacts environnementaux et les prix des aliments MC, ME et MEC optimisés pour couvrir les besoins nutritionnels des lignées, ainsi que ceux de l'aliment expérimental de référence, sont présentés dans le Tableau 1.

Tableau 1 – Impacts environnementaux[1], score environnemental et prix par unité d'énergie nette (EN) des aliments expérimentaux de référence (Ref.), formulés à moindre coût (MC), à moindre impact environnemental (ME) ou en minimisant les deux conjointement (MEC), pour les lignées à faible (CMJR-) ou forte (CMJR+) consommation moyenne journalière résiduelle

	CC g CO_2 eq	AP g SO_2 eq	EP g P eq	OS m^2 an eq	Score env.	Coûts 10^{-2} €	EN MJ
Ref.	509	0,69	0,042	0,19	0,420	2,41	9,7
CMJR-							
MC	541	0,61	0,053	0,18	0,430	2,01	9,3
ME	486	0,71	0,046	0,13	0,392	2,12	9,4
MEC	486	0,66	0,051	0,15	0,394	2,10	9,7
CMJR+							
MC	483	0,68	0,060	0,14	0,399	2,03	10,0
ME	442	0,65	0,059	0,15	0,393	2,13	9,8
MEC	490	0,64	0,050	0,16	0,395	2,06	9,7

[1]CC = potentiel de changement climatique ; AP = potentiel d'acidification ; EP = potentiel d'eutrophisation ; OS = occupation des sols ; Score env. = score environnemental

Tous les aliments optimisés avaient un coût et un score environnemental réduits par rapport à l'aliment de référence, à l'exception du score de l'aliment MC pour la lignée CMJR-. Cela souligne le potentiel d'amélioration par ces formulations optimisées sur les besoins nutritionnels du troupeau, quel que soit le pilier considéré pour l'optimisation : économique, environnemental, ou les deux. Par ailleurs, dans nos conditions, l'accroissement de prix entre les aliments MC et MEC (< +5 %), et du score environnemental entre les aliments ME et MEC (+0,5 %) indique que les pertes liées à l'optimisation conjointe des deux piliers étaient relativement faibles.

L'aliment MEC était obtenu pour w_t = 0,24 pour la lignée CMJR- et w_t = 0,44 pour la lignée CMJR+. Le poids plus élevé pour le score environnemental de l'aliment MEC de la lignée moins efficace est certainement à mettre en relation avec les besoins nutritionnels plus faibles par unité d'EN, qui permettent l'incorporation d'ingrédients moins riches en AA, ayant, pour certains, de plus faibles impacts environnementaux. En dépit de cette différence de pondération, le score environnemental des aliments MEC était similaire pour les deux lignées et le coût légèrement inférieur pour l'aliment CMJR+.

Ces résultats dépendent fortement de la composition de l'objectif à optimiser. Dans notre étude, tous les objectifs des aliments optimisés ont été normalisés relativement aux prix et impacts environnementaux des aliments MC, considérés comme référence. Par ailleurs, en raison des différences d'unités entre les différents objectifs considérés, les 4 dimensions environnementales ont été pondérées avec des poids égaux de façon arbitraire, et les volets économiques et environnementaux ont été minimisés selon une stratégie d'optimisation multi-objectif. La monétarisation des impacts environnementaux ou des choix stratégiques déterminés permettraient de lever l'arbitraire de ce choix.

Tableau 2 – Moyenne (écart-type) des performances de croissance, d'ingestion et de composition corporelle à 120 kg de poids vif simulées avec InraPorc® pour les lignées à faible (CMJR-) ou forte (CMJR+) consommation moyenne journalière résiduelle nourries avec l'aliment expérimental de référence ou avec les aliments formulés par lignée à moindre coût (MC), moindre impact environnemental (ME) ou en minimisant les deux impacts (MEC) (n = 57 porcs/lignée)

		Reference	*P*[1]	MC	*P*	ME	*P*	MEC	*P*
Gain moyen quotidien, kg/d	CMJR-	0,80 (0,091)	ns	0,77 (0,089)	*	0,78 (0,089)	t	0,78 (0,090)	*
	CMJR+	0,83 (0,080)		0,80 (0,071)		0,81 (0,072)		0,82 (0,074)	
Consommation moyenne journalière, kg/d	CMJR-	1,99 (0,20)	***	2,06 (0,21)	ns	2,04 (0,21)	*	1,98 (0,20)	***
	CMJR+	2,17 (0,16)		2,08 (0,15)		2,13 (0,16)		2,16 (0,16)	
Indice de consommation, kg /kg gain	CMJR-	2,48 (0,21)	***	2,68 (0,17)	**	2,61 (0,19)	ns	2,53 (0,18)	**
	CMJR+	2,62 (0,21)		2,58 (0,17)		2,64 (0,18)		2,64 (0,19)	
Indice de conversion énergétique, MJ /kg gain	CMJR-	24,08 (2,06)	***	24,97 (1,66)	**	24,56 (1,81)	***	24,59 (1,79)	**
	CMJR+	25,46 (2,06)		25,96 (1,72)		25,84 (1,77)		25,60 (1,89)	
Taux de maigre des pièces, %	CMJR-	60,69 (2,19)	***	59,63 (1,86)	***	59,98 (2,01)	***	59,95 (1,99)	***
	CMJR+	58,52 (1,86)		57,68 (1,68)		57,80 (1,72)		58,04 (1,81)	
Poids de protéines, kg	CMJR-	19,51 (0,48)	***	19,29 (0,40)	***	19,38 (0,44)	***	19,35 (0,44)	***
	CMJR+	19,05 (0,41)		18,86 (0,37)		18,89 (0,37)		18,94 (0,39)	
Poids de lipides, kg	CMJR-	23,63 (3,37)	***	25,27 (2,87)	***	24,74 (3,09)	***	24,77 (3,06)	***
	CMJR+	26,99 (2,86)		28,27 (2,58)		28,08 (2,65)		27,71 (2,78)	
Epaisseur de lard dorsal, mm	CMJR-	15,82 (1,26)	***	16,43 (1,07)	***	16,24 (1,15)	***	16,25 (1,14)	***
	CMJR+	17,08 (1,07)		17,56 (0,96)		17,49 (0,99)		17,35 (1,04)	

*[1]P-valeur de l'effet lignée dans un test de Student appliqué pour chaque type d'aliment : *** P < 0,001 ; ** P < 0,01 ; * P < 0,05 ; t = P < 0,10 ; ns = non significatif*

2.1.2. *Performances individuelles en réponse aux aliments optimisés*

Les moyennes et écarts-types des performances simulées par InraPorc® pour les lignées alimentées avec les aliments optimisés par lignée ou l'aliment de référence jusqu'à un poids vif de 120 kg sont présentés dans le Tableau 2. Avec l'aliment de référence, tous les indicateurs différaient entre lignées (*P* < 0,01) sauf le GMQ. Comme rapporté dans des études précédentes (voir revue de Gilbert *et al.,* 2017), les animaux CMJR- ingèrent moins, sont plus efficaces et plus maigres. Les différences d'IC ne se retrouvaient pas systématiquement avec les aliments optimisés, mais elles étaient significatives avec un indice de conversion énergétique, exprimé en MJ d'EN ingéré. L'écart entre lignées pour le GMQ (~35g/j de moins en CMJR-), qui n'était pas significatif avec l'aliment de référence, est conservé numériquement et significatif avec les aliments optimisés, en lien peut être avec des écarts-types légèrement réduits. Les autres différences de performances entre lignées sont maintenues avec les aliments optimisés. Ces éléments indiquent que l'optimisation des formules alimentaires a bien respecté les contraintes nutritionnelles, n'affectant pas de façon importante les performances obtenues en dépit du choix de la moyenne des maxima individuels comme référence pour chaque lignée, qui aurait pu entraîner une restriction alimentaire pour certains individus en début de période d'engraissement.

Tableau 3 – Moyenne (écart-type) des impacts environnementaux (par kg de porc vif) et des résultats économiques par porc de 120 kg de lignées à faible (CMJR-) ou forte (CMJR+) consommation moyenne journalière résiduelle nourris avec un aliment de référence ou formulé par lignée à moindre coût (MC), moindre impact environnemental (ME) ou en minimisant les deux impacts (MEC)

		Référence	*P*[1]	MC	*P*	ME	*P*	MEC	*P*
Potentiel de changement climatique, kg CO_2 eq	CMJR-	2,07 (0,124)	***	2,02 (0,095)	***	1,96 (0,098)	*	1,96 (0,096)	***
	CMJR+	2,21 (0,125)		2,09 (0,096)		2,00 (0,092)		2,02 (0,098)	
Potentiel d'acidification, g SO_2 eq	CMJR-	36,8 (2,78)	***	33,1 (1,99)	***	35,6 (2,37)	*	34,6 (2,26)	***
	CMJR+	40,0 (2,79)		37,1 (2,22)		36,5 (2,22)		35,3 (2,23)	
Potentiel d'eutrophisation, g P eq	CMJR-	1,16 (0,077)	***	1,39 (0,079)	***	1,27 (0,077)	***	1,36 (0,083)	*
	CMJR+	1,24 (0,077)		1,56 (0,092)		1,39 (0,081)		1,40 (0,089)	
Occupation des sols, m^2an	CMJR-	4,30 (0,30)	***	4,35 (0,25)	***	3,53 (0,21)	***	3,89 (0,23)	***
	CMJR+	4,58 (0,30)		3,97 (0,22)		4,17 (0,24)		4,22 (0,25)	
Produit, €	CMJR-	11,10 (5,83)	*	17,75 (5,56)	**	16,28 (5,75)	**	16,86 (5,68)	ns
	CMJR+	8,50 (6,82)		14,47 (7,01)		12,73 (7,32)		15,58 (5,64)	

*[1]P-valeur de l'effet lignée dans un test de Student appliqué pour chaque type d'aliment : *** P < 0,001 ; ** P < 0,01 ; * P < 0,05 ; ns = non significatif*

2.1.3. *Evaluations environnementale et économique globales*

Les performances des animaux de chaque lignée, nourris avec les différents aliments optimisés, ont été utilisées pour évaluer les impacts environnementaux et économiques pour l'obtention d'un kg de porc vivant avant abattage (Tableau 3). Pour chaque type d'aliment, tous les impacts environnementaux différaient entre les lignées (*P* < 0,05). Seul l'OS était plus faible pour la lignée CMJR+ avec l'aliment MC, conduisant à des impacts environnementaux réduits pour la lignée CMJR- en moyenne, respectivement, de 7,21 %, 8,11 %, 4,91 % et 4,29 % pour les aliments de référence, MC, ME, et MEC par rapport à la lignée CMJR+. Par conséquent, cette différence entre lignées a été réduite par l'optimisation environnementale de la composition des aliments, permettant même, pour les aliments ME, d'obtenir des différences de CC et EP entre lignées réduites à 2 % de ces impacts. Au contraire, la différence d'occupation des sols est augmentée pour les scénarios avec ME et MEC, en lien avec l'incorporation accrue de pois, d'huile de tournesol et de thréonine de synthèse, à plus faible OS, dans ces aliments pour la lignée CMJR+. Sauf pour EP, les scénarios où les animaux sont nourris avec un aliment optimisé permettent pour les deux lignées de réduire l'impact environnemental par rapport aux scénarios avec l'aliment de référence.

Le résultat économique par porc était augmenté de 46 % à 83 % pour les scénarios avec des aliments optimisés par rapport aux scénarios avec l'aliment de référence, soulignant le potentiel de ces optimisations de formulation pour consolider le revenu de l'éleveur. De plus, pour tous les scénarios sauf avec MEC, le résultat économique par porc était supérieur de plus de 20 % pour la lignée CMJR- par rapport à la lignée CMJR+ ($P < 0,05$). Dans la lignée CMJR-, le résultat maximum était obtenu avec l'aliment MC (17,75 €/porc), alors que pour la lignée CMJR+ il est obtenu avec l'aliment MEC (15,58 €/porc), en raison certainement de qualités de carcasse légèrement meilleures avec cet aliment. Finalement, les résultats économiques moyens avec les aliments optimisés selon les deux piliers de la durabilité étaient statistiquement similaires pour les deux lignées, suggérant que ces stratégies d'optimisation raisonnées permettent de trouver des marges économiques substantielles même avec des animaux génétiquement moins performants, de type CMJR+. Si l'on considère de plus que les formulations d'aliments tenant compte des besoins nutritionnels des troupeaux et de l'impact environnemental des ressources alimentaires permettent de compenser partiellement les moins bons impacts environnementaux de ces animaux moins efficaces, des stratégies intégrant génétique et nutrition peuvent être dégagées pour améliorer conjointement deux des piliers de la durabilité des systèmes de production porcins. Il est à noter que les animaux les plus efficaces restent néanmoins dans tous les scénarios ceux qui ont les résultats les plus favorables sur les deux piliers, à condition de bénéficier de régimes alimentaires adaptés à leurs besoins. Des travaux précédents ont montré une forte dégradation de la vitesse de croissance et de la composition corporelle de ces individus s'ils sont alimentés avec un aliment correspondant aux besoins nutritionnels des CMJR+, ce qui aurait vraisemblablement des impacts économiques et environnementaux défavorables (Brossard *et al.*, 2012).

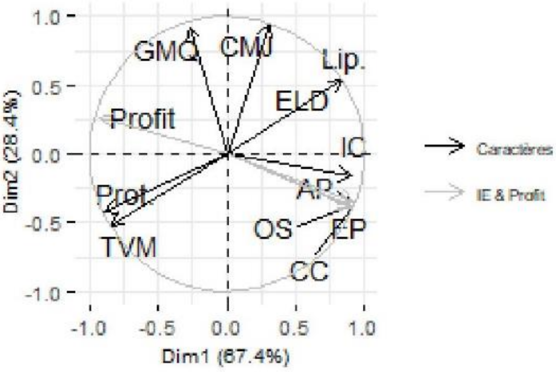

Figure 1 – Projection des performances, impacts environnementaux (IE) et résultat économique (profit) selon les deux premiers axes d'une analyse en composantes principales après ajustement pour l'effet lignée (n = 114 porcs)

CMJ = consommation moyenne journalière ; GMQ = gain moyen quotidien ; Prot. = quantité de protéines à l'abattage ; Lip. = quantité de lipides à l'abattage ; TMP = taux de muscle des pièces ; ELD = épaisseur de lard dorsal ; IC = indice de consommation ; CC = potentiel de changement climatique ; AP = potentiel d'acidification ; EP = potentiel d'eutrophisation ; OS = occupation des sols

2.1.4. *Corrélations entre performances, impacts environnementaux et résultat économique*

Les évaluations individuelles obtenues grâce à ces modèles ACV et bioéconomique permettent d'estimer les corrélations entre les différents résultats des modèles (Figure 1). Les corrélations les plus élevées avec les impacts environnementaux et les résultats économiques étaient obtenues pour l'IC (> 0,82) quelle que soit la combinaison de lignée et d'aliment considérée. Ces estimations consolident les conclusions du paragraphe précédent, et sont conformes aux résultats de la littérature pour les porcs (Monteiro *et al.*, 2020) ou dans certains systèmes de production piscicoles (Besson *et al.*, 2020). Les caractères marqueurs de la quantité de dépôt protéique pendant la croissance avaient aussi des corrélations élevées avec les impacts environnementaux et le résultat économique (> 0,61), en lien avec les contraintes de formulation et les règles de paiement des carcasses.

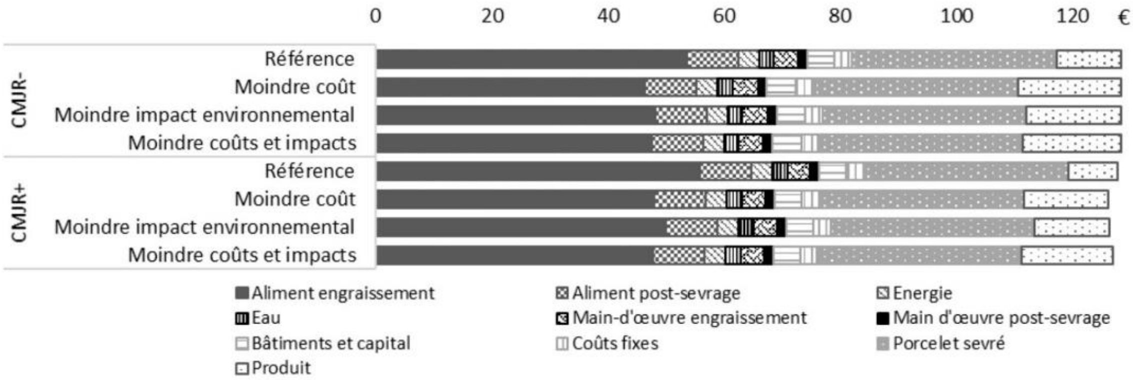

Figure 2 – Coûts élémentaires et résultat économique pour un porc de 120 kg au départ à l'abattoir

2.1.5. *Structure des coûts*

La structure des coûts de production des porcs pour chaque scénario est présentée sur la Figure 2. Pour les deux lignées, l'utilisation d'un aliment optimisé réduisait d'au moins 10 % les coûts alimentaires pendant l'engraissement ($P < 0,001$). Pour un type d'aliment donné, ces coûts alimentaires étaient plus faibles ($P < 0,05$) pour la lignée CMJR- que pour la lignée CMJR+, sauf avec les aliments MEC (coûts équivalents dans les deux lignées). Les autres postes de coûts ne différaient pas entre lignées ou aliments pour les scénarios retenus, soulignant l'importance stratégique du coût alimentaire dans l'optimisation des systèmes de production porcins, et la marge dégagée par l'éleveur. Avec ces aliments optimisés, les marges accrues permettent par ailleurs à l'éleveur de faire face à de plus grandes variations du prix payé par animal : dans le scénario le plus pessimiste (porcs CMJR+ avec l'aliment de référence), la marge est nulle si le prix du porc est réduit de 6,6 %, alors que dans le scénario le plus favorable (porcs CMJR- et aliment MC), la marge est nulle pour un changement de 13,8 % du prix du porc. Si on se fie à l'évolution du prix du porc depuis 2007 (https://rnm.franceagrimer.fr/prix?PORC), toutes choses étant égales par ailleurs, cela revient à diviser par 2,3 le nombre de semaines où le prix moyen du porc ne permet pas à l'éleveur de dégager une marge positive (15 % contre 34 % des semaines pour ces deux scénarios).

3. CONCLUSION

L'efficacité alimentaire a le potentiel d'améliorer plusieurs piliers de la durabilité des élevages et ce, d'autant plus efficacement que les leviers génétiques et nutritionnels sont combinés. Les modèles proposés ici permettent d'envisager la prise en compte de plusieurs piliers de la durabilité dans les objectifs de sélection, grâce à des évaluations individuelles qui permettent l'estimation des corrélations entre critères de sélection actuels, définis d'après des critères économiques, et de nouveaux indicateurs, environnementaux. La combinaison d'objectifs formulés dans des unités différentes selon la dimension considérée reste cependant une difficulté pour le choix de pondérations relatives. En particulier, notre étude suggère que cette stratégie permet une meilleure valorisation économique des animaux moins efficaces grâce au recrutement de matières premières différentes. L'optimisation des systèmes de production pour satisfaire les différents piliers de la durabilité pourrait donc s'appuyer sur l'utilisation d'algorithmes multi-objectifs pour répondre plus efficacement aux différents niveaux de contraintes. Pour aller plus loin, ces optimisations combinant les objectifs économiques et environnementaux pourraient être réalisées en fonction de la dynamique de croissance des animaux, tendant ainsi vers des stratégies individualisées proches de l'alimentation de précision. L'intégration des différents piliers de ces optimisations permettrait alors d'atteindre une efficacité globale des systèmes de production.

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Evaluating environmental impacts of selection for residual feed intake in pigs

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*To identify a proper strategy for future feed-efficient pig farming, it is required to evaluate the ongoing selection scenarios. Tools are lacking for the evaluation of pig selection scenarios in terms of environmental impacts to provide selection guidelines for a more sustainable pig production. Selection on residual feed intake (**RFI**) has been proposed to improve feed efficiency and potentially reduce the associated environmental impacts. The aim of this study was thus to develop a model to account for individual animal performance in life cycle assessment (**LCA**) methods to quantify the responses to selection. Experimental data were collected from the fifth generation of pig lines divergently selected for RFI (low line, more efficient pigs, **LRFI**; high line, less efficient pigs, **HRFI**). The average feed conversion ratio (**FCR**) and daily feed intake of LRFI pigs were 7% lower than the average of HRFI pigs ($P < 0.0001$). A parametric model was developed for LCA based on the dietary net energy fluxes in a pig system. A nutritional pig growth tool, InraPorc®, was included as a module in the model to embed flexibility for changes in feed composition, animal performance traits and housing conditions and to simulate individual pig performance. The comparative individual-based LCA showed that LRFI had an average of 7% lower environmental impacts per kilogram live pig at farm gate compared to HRFI ($P < 0.0001$) on climate change, acidification potential, freshwater eutrophication potential, land occupation and water depletion. High correlations between FCR and all environmental impact categories (>0.95) confirmed the importance of improvement in feed efficiency to reduce environmental impacts. Significant line differences in all impact categories and moderate correlations with impacts (>0.51) revealed that RFI is an effective measure to select for improved environmental impacts, despite lower correlations compared to FCR. Altogether more optimal criteria for efficient environment-friendly selection can then be expected through restructuring the selection indexes from an environmental point of view.*

Keywords: feed efficiency, life cycle assessment, growth performance traits, selection by genetics, net energy flux

Implications

Selection on feed efficiency results in large correlated reductions in the environmental impacts of pig production; with gross feed efficiency having more impact than net feed efficiency. Our pig-based evaluation model will allow definition of selection criteria that result in even larger reductions in environmental impact.

Introduction

Beyond being an economic bottleneck, feed greatly contributes to the environmental impacts of pig farming (McAuliffe *et al.*, 2016). Improvement in feed efficiency is a major goal for pig production sustainability, because it reduces environmental fluxes associated with feed production (Nguyen *et al.*, 2011) and reduces the amount of effluent per pig as a result of mass balance (Ali *et al.*, 2018). Feed efficiency, which is usually inversely expressed as feed conversion ratio (**FCR**), stands for the BW gain per unit of feed consumed. Selection for FCR, directly or via increased growth rate or reduced fatness, has been very effective to improve feed efficiency in the past. However, as a ratio, FCR is closely correlated with production traits, and selection on this trait has uncontrolled effects on the components of the ratio (Saintilan *et al.*, 2013). In 1963, Koch *et al.* introduced a more targeted indicator for net feed efficiency, residual feed intake (**RFI**). The RFI, which is a linear combination of traits, is moderately heritable in pigs (Saintilan *et al.*, 2013) and is defined as the difference between observed feed intake and the feed intake expected from individual maintenance and production requirements. Among the range of approaches for measuring feed efficiency, RFI is increasingly becoming the measure of choice in some species (Kenny *et al.*, 2018). Improving animal

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feed efficiency is possible at two stages. The first stage, which arises from the interaction between feed and animal in the digestive tract, is to improve conversion of the feed gross energy into metabolisable energy (ME). The second stage is to improve the partitioning of uptaken energy between maintenance and tissue accretion through protein (**PD**) and lipid deposition (**LD**) (Nguyen *et al.*, 2005). Improving feed efficiency through selection based on RFI essentially corresponds to the latter (Gilbert *et al.* 2017). Separate selection for RFI has been investigated and impacts on production performance (Gilbert *et al.*, 2007; Cai *et al.*, 2008) as well as on sow reproduction and piglet traits were reported (Gilbert *et al.*, 2012; Young *et al.*, 2016). However, to date, its impacts have not been thoroughly assessed from an environmental viewpoint due to the lack of an appropriate model. To quantify environmental impacts, several studies using life cycle assessment (**LCA**) examined the environmental burdens of different pig production options (Garcia-Launay *et al.*, 2014; Mackenzie *et al.*, 2015; McAuliffe *et al.*, 2017). The aim of the present study was to develop a model adapted to the evaluation of pig selection strategies and use it to estimate the environmental impacts of selection for RFI, through comparative LCA of two lines of pigs divergently selected for RFI.

Material and methods

Experimental data

The experimental data were obtained from the fifth generation of Large White pigs divergently selected for RFI. The selection process and results concerning low RFI (LRFI, more efficient pigs) and high RFI (HRFI, less efficient pigs) lines are reviewed in Gilbert *et al.* (2017). The present data set includes 60 male pigs in the LRFI line and 58 male pigs in the HRFI line. Growing pigs had *ad libitum* access to a one-phase conventional diet (Table 1). The experimental data were collected from birth to slaughter. Body weight was recorded at birth; at weaning (average 28 days of age); at the beginning of the fattening period (10 weeks of age); at 11, 15, 19, and 23 weeks of age; and at the end of the test (target BW 115 kg). During the fattening period, data on individual daily feed intake (**DFI**) recorded on ACEMA 64 automatic feeders (ACEMO, Pontivy, France) were available, and back fat thickness (**BFT**) was measured by ultrasound on live animals at 23 weeks of age, using an ALOKA SSD-500 echograph (Aloka, Cergy Pontoise, France). From these records, FCR and RFI were computed as described in Gilbert *et al.* (2007). For LRFI and HRFI sows/litters, the mean values of age at farrowing and weaning, sow BW and BFT before farrowing and at weaning, lactation DFI, number of total born, stillborn, weaned piglets, piglet BW at birth and at weaning and weaning age were taken from the experimental data presented in Gilbert *et al.* (2012).

Goal, scope and framework of the environmental assessment

A 'cradle-to-farm-gate' system boundary was chosen, including feed production, manure management and the entire pig production system comprising reproducing sows and their piglets, post-weaning and fattening pigs. One kilogram of live weight (**LW**) of pig at the farm gate was used as the functional unit with the goal of comparing the environmental impacts between the HRFI and LRFI lines. To implement LCA, all the materials and energy consumed in the production of one functional unit of the system have to be included in the life cycle inventory (**LCI**), in addition to all excretions and emissions to the environment. The LCI needs to consider all the processes that take place inside the system boundary. To obtain a flexible and predictive model for daily feed intake, it was required to switch from the mass context of the data recording to the energy context for modelling. Due to the pigs' ability to adapt their feed intake to the net energy (**NE**) concentration of different diets (Quiniou and Noblet, 2012), the model was developed based on the daily NE supply during fattening to allow prediction for different diet compositions and guaranty generality. Our model was consequently developed based on NE for the fattening period and ME for reproducing sows, to estimate the flux of dietary

Table 1 *Ingredients, chemical composition and nutritional value of the experimental diet of pig lines*

Item	Quantity
Ingredient (g/kg)	
Barley	409
Soft wheat	327
Soybean meal (48% CP)	202
Sunflower oil	23
L-Lysine HCL	3.5
L-Threonine	1.4
L-Tryptophane	0.3
DL-Methionine	0.9
Salt	4.5
Calcium carbonate	11
Dicalcium phosphate	12
Oligo vitamins	5
Chemical composition (g/kg)	
Ash	58.5
Dry matter	877.7
Organic matter	819.2
CP	172.3
Starch	411.9
Gross energy (MJ/kg)	16.22
NDF	141.7
ADF	47.4
Crude fibre	38.1
Residue	163
Calcium	9.97
Phosphorus	6.21
Nutritional value	
NE[1] (MJ/kg)	9.70
ME[1] (MJ/kg)	13.09
Std.dig. Lysine[2] (g/kg)	9.83

NE = net energy; ME = metabolisable energy.
[1]Calculated according to the method of Sauvant *et al.* (2004).
[2]Standardised ileal digestible lysine.

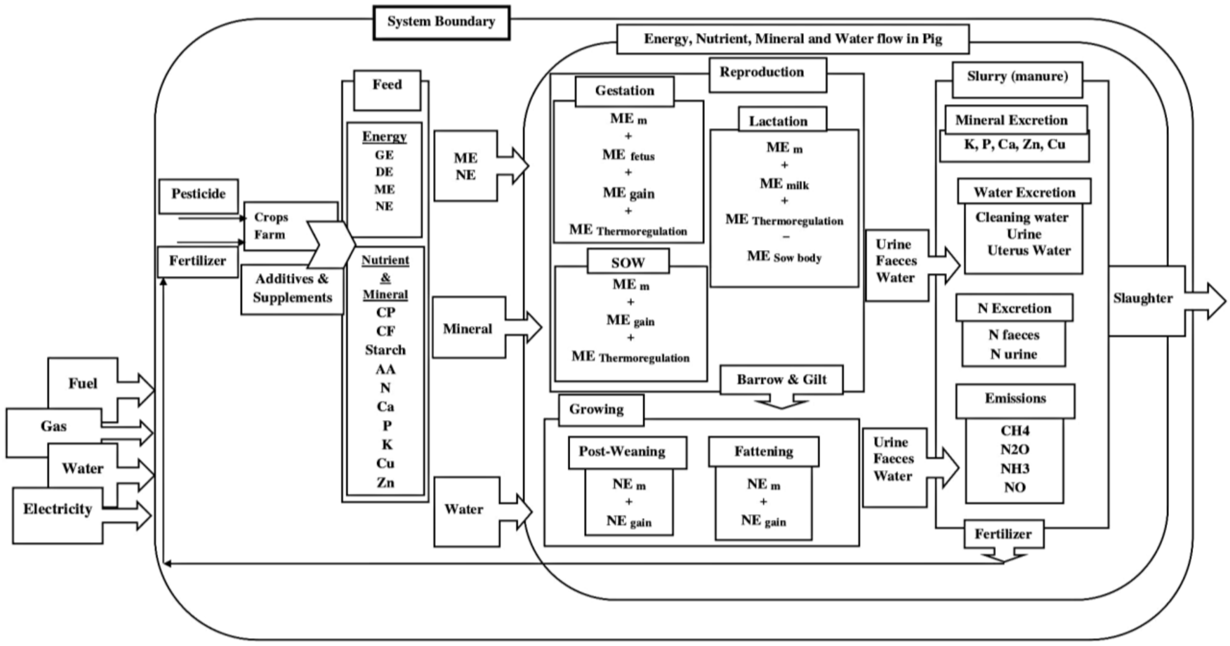

Figure 1 Scheme of the system boundary, which includes the entire pig farm, feed production processes and manure management. GE = gross energy; DE = digestible energy; ME = metabolisable energy; NE = net energy; ME_m = metabolisable energy required for maintenance; NE_m = net energy required for maintenance; NE_{gain} = net energy required for gain; CF = crude fibre; AA = amino acid; N = nitrogen; Ca = calcium; P = phosphorus; K = potassium; Cu = copper; Zn = zinc.

energy which propagates through all individual pigs within the system boundary (Figure 1).

Model structure

The model consists of six modules with distinct functions.

Feeding plan module. InraPorc®, which is a model and software designed to simulate the performance response of pigs to different nutritional strategies (Dourmad *et al.*, 2008; van Milgen *et al.*, 2008), was incorporated in the LCA model to benefit from its features. It contains the licensed INRA-AFZ database of characterised feed ingredients (Sauvant *et al.*, 2004) as an embedded library. This library distinguishes different nutritional values depending on the animal physiological status (sows and growing pigs). In the feeding sub-module, the composition of the diet and the feeding plan (rationing and sequencing plan) during the different periods of the animal's lifetime were defined based on experimental data. The outcome of this sub-module is the chemical compositions and nutritional values of the diets, based on the INRA-AFZ database.

Animal profile module. Each animal profile is the compilation of the feeding plan, housing conditions, experimental data, NE system and a final calibration in InraPorc®. The Gamma function was used to express *ad libitum* feed intake because of its flexibility which enables it to adjust to changes in feed intake and BW (van Milgen *et al.*, 2008). The daily *ad libitum* feed intake and NE of the feed characterised the animal daily NE requirements. InraPorc® was used to establish the individual profiles for each pig separately in the lines during the fattening period (day 68 to day 179), based on the animal's individual data, which were recorded daily, as previously proposed by Saintilan *et al.*, 2015. The average profiles for groups of sows and their piglets were defined separately in InraPorc® based on the experimental data on the average HRFI and LRFI sows/litters performance summarised by Gilbert *et al.* (2012). The outcome of this module is the predicted growth performance (average daily gain (**ADG**) and average daily feed intake (**ADFI**)), PD and LD during fattening, respectively, the ratio of body protein to and body lipid (**BP/BL** ratio) and mineral excretions of the pigs. As InraPorc® was not designed to model the performance of animals post-weaning, a calculation module was developed in R to estimate the excretions and emissions during the post-weaning period (28 days to 10 weeks of age), according to Rigolot *et al.* (2010a and 2010b).

Emission and excretion module. To calculate the emissions and excretions, and the slurry composition, three sub-modules were developed in R for the sow-litter, post-weaning and fattening stages. The average performance data were used for the sow-litter stage and the individual performance data were used for the post-weaning and fattening stages. The components of the excreta (DM, organic matter (**OM**), nitrogen (**N**), phosphorus (**P**), potassium (**K**), copper (**Cu**) and zinc (Zn) were calculated using the mass-balance approach, as the difference between nutrients taken up from the feed and the nutrients retained in the body. Emissions of enteric methane (**CH_4**), nitrogen monoxide (**NO**), nitrous oxide (**N_2O**), ammonia (**NH_3**) and carbon dioxide (**CO_2**) during housing were calculated according to Rigolot *et al.* (2010a and 2010b). Subtraction of N excretion and gaseous N lost in housing determined the quantity of N at the beginning of manure storage (Garcia-Launay *et al.*, 2014).

A sub-module was developed to estimate emissions, leaching and runoff during manure storage and application in the field. The NH_3 emissions during outside storage were calculated according to the emission factors recommended by Rigolot *et al.* (2010b). The NO_x emissions were calculated according to Nemecek *et al.* (2004). Methane emissions from manure during storage were calculated using guidelines by the Intergovernmental Panel on Climate Change (IPCC, 2006). Direct and indirect emissions of N_2O and NH_3 during the spreading of slurry were calculated according to IPCC (2006). The value of the manure as a replacement for synthetic fertiliser was considered according to the mineral fertiliser equivalency of 75% for N (Nguyen *et al.*, 2010) and 100% for P and K (Nguyen *et al.*, 2011).

Water, energy expenditure and transport modules. The model linked drinking water to feed intake according to the Institut de la Filière porcine (**IFIP**) report on typical French farms (IFIP, 2014), with water to feed ratios of 4.5, 4.0, 2.5 and 2.7 for lactating, gestating, post-weaning and fattening pigs, respectively. Cleaning water was estimated at 2300 l per sow and 30 l per fattening pig according to IFIP (2014) and Rigolot *et al.* (2010a). In addition, the energy expenditure link to the functional unit was 0.42 kWh/kg LW and was broken down into electricity, oil and gas components, according to IFIP (2014). Transport of feed was calculated as a coefficient of feed intake. Linking water and transport to feed intake made the model sensitive to feed efficiency for further sensitivity and uncertainty analyses.

Life cycle impact assessment

An individual LCA was conducted for each pig in the LRFI and HRFI lines through incorporating its own experimental recorded traits and the traits obtained from InraPorc® in the LCA model. The outputs of the LCA model were the impact categories of climate change (**CC**), terrestrial acidification potential (**AP**), freshwater eutrophication potential (**EP**), land occupation (**LO**) and water depletion (**WD**). For impact analyses, the ReCiPe Midpoint 2016 (H) V1.13 (Huijbregts *et al.*, 2016), one of the most recently updated life cycle impact assessment methods, with the Ecoalim (Wilfart *et al.*, 2016) and Ecoinvent (Wernet *et al.*, 2016) inventory databases, were used. The equivalency factors for the impact categories were assigned according to the factors recommended in the ReCiPe method. All environmental impact assessments were implemented in the SimaPro V8.5.4.0 on the MEANS (MulticritEria AssessmeNt of Sustainability) platform (http://www.inra.fr/means).

The line impact differences were tested with a *t* test, and impacts were declared significantly different for $P < 0.05$. In addition, correlations between performances and environmental impacts were calculated within lines, for a better understanding of the relationships between the components.

Uncertainty analysis

Monte Carlo simulations is an approach, available in SimaPro V8.5.4.0, to quantify the effects of the uncertainties in the model parameters on the estimated environmental impacts: by resampling the parameter values based on assumptions about their uncertainties, a confidence interval for each impact can be obtained. In addition, the Ecoinvent LCA databases, which are embedded in SimaPro V8.5.4.0, provide quantitative uncertainties for parameters in most of its processes, mainly with log normal distributions (Ivanov *et al.*, 2019). To incorporate the intended traits in the LCA, a trait-based model was developed based on the growth performance equations presented by van Milgen *et al.* (2008) (also applied in InraPorc®) and linked to the emissions and excretions according to Rigolot *et al.* (2010a and 2010b). The quantities of all feed ingredients were linked to the related traits, such as ADFI and fattening duration, by considering their incorporation rate in the diet. This integrated and connected model made it possible to perform uncertainty and sensitivity analyses in SimaPro. To evaluate the impact of the LCA model parameter uncertainty on the results, the line mean values of the performance traits (ADFI, FCR, ADG, BP/BL ratio, PD, fattening duration, BP and BL at slaughter and BFT) were extracted from the experimental data and InraPorc® outputs and used as inputs for the uncertainty analysis. Then the parallel Monte Carlo simulations were run on the two lines jointly to evaluate the sensitivity of the impact categories to the model parameter uncertainties.

Sensitivity analysis

Sensitivity analysis is the study of the relative importance of the different input parameters in the model outputs. To perform a sensitivity analysis, it is necessary to have a parametric model in which all the parameters are mathematically interlinked (Supplementary material S1). To perform the sensitivity analysis on animal performance traits, related traits had to be incorporated in the model as direct input parameters accompanied by their distributions. In this way, any change in animal traits propagates through the model and affects the appropriate material, process, emission and excretion sub-inventories in the LCI.

An one-at-a-time (**OAT**) sensitivity analysis, an appropriate approach for limited parameter and linear LCA models, was conducted based on the upper and lower bounds of the 95% confidence interval (CI) (±2 SD) of the main production trait distributions. The LCA model was considered sensitive to a trait if a change in any impact value was greater than 5% after a change to the upper and lower bounds of the intended trait compared to the initial impact value (Mackenzie *et al.*, 2015). The OAT sensitivity analysis of the traits made it possible to identify the best candidate traits for improvement in the corresponding environmental impact categories.

Results

Traits comparison between lines

Prior to LCA, a statistical review of the experimental data provided a general overview on the variation in the growth performance traits between the two lines. The mean growth performance traits in the two lines were compared with a Student's *t* test (Table 2) as well as the trait predictions from InraPorc®. The FCR differed significantly between the lines (−130 g/kg gain for LRFI compared to HRFI pigs; $P < 0.001$), as did the ADFI ($P < 0.0001$) and RFI ($P < 0.01$). The lines also differed in their ADG ($P < 0.05$), age at slaughter ($P < 0.05$), fattening duration ($P < 0.05$), but not in BW at slaughter ($P = 0.43$). The two lines had similar protein content at slaughter ($P = 0.32$), but not lipid content, back fat thickness and LMP ($P < 0.0001$), leading to a difference in the BP/BL ratio ($P < 0.0001$).

Individual life cycle assessment on the low and high residual feed intake lines

The five impact categories were calculated for 116 pigs through individual LCA. The outcomes of individual LCA on the LRFI and HRFI lines in the five impact categories are summarised in Table 3. The values in all impact categories were lower in the LRFI line than in the HRFI pigs ($P < 0.0001$): CC (2.60 *v.* 2.77 kg CO_2-eq), AP (44.5 *v.* 48.1 gr SO_2-eq), EP (3.35 *v.* 3.63 g P-eq), LO (4.19 *v.* 4.45 m^2a) and WD (0.044 *v.* 0.047 m^3). The minimum and the maximum differences between HRFI and LRFI were in LO (6.01%) and EP (8.02%), respectively, and the average difference for the five

Table 2 *Growth performance traits and InraPorc® estimations of body composition of pigs in low residual feed intake (LRFI) and high residual feed intake (HRFI) lines*

	Mean LRFI	Mean HRFI	Mean differences (%)	SD LRFI	SD HRFI	P^1
Traits records						
BW birth (kg)	1.50	1.53	1.98	0.20	0.33	0.63
BW weaning (kg)	8.51	9.12	6.92	1.18	1.22	0.007
BW initial fattening (kg)	28.7	29.9	4.09	4.06	4.70	0.14
ADG fattening (kg/day)	0.80	0.83	3.68	0.080	0.071	0.047
ADFI fattening (kg/day)	1.97	2.15	8.73	0.21	0.19	<0.0001
FI fattening (kg)	214.3	225.5	5.09	18.3	28.1	0.011
FCR fattening (kg/kg gain)	2.45	2.58	5.16	0.16	0.18	<0.0001
RFI (g/day)	−36.1	35.1	197.1	130.8	104.8	<0.01
ECR fattening (MJ/kg gain)	23.78	25.03	5.45	1.63	1.77	<0.0001
Fattening duration (days)	109.6	104.9	4.38	12.00	9.34	0.02
Age at slaughter (days)	181.1	177.0	2.28	10.00	7.44	0.011
BW slaughter (kg)	116.3	117.4	0.94	7.04	8.30	0.43
InraPorc® estimations						
PD fattening (g/day)	133.0	136.9	2.88	13.9	15.4	0.38
Carcass weight (kg)	91.9	92.7	0.86	5.56	6.55	0.43
Lipid weight at slaughter (kg)	22.4	25.7	13.72	3.28	4.11	<0.0001
BFT slaughter (mm)	15.3	16.5	7.54	1.20	1.49	<0.0001
Protein weight at slaughter (kg)	18.6	18.4	1.08	1.31	1.34	0.32
LMP (%)	60.9	58.8	3.50	2.00	2.01	<0.0001
LMC (kg)	55.9	54.5	2.53	3.93	3.72	0.042
BP/BL at slaughter	0.85	0.73	15.18	0.13	0.13	<0.0001

BW = body weight; ADG = average daily gain; ADFI = average daily feed intake; FI = total feed intake; FCR = feed conversion ratio; RFI = residual feed intake; ECR = energy conversion ratio; PD = protein deposition; BFT = back fat thickness; LMP = lean meat percentage; LMC = Lean meat content; BP/BL = ratio of body protein weight/ Body lipid weight at slaughter.
[1] *P* were calculated via a *t* test on the line effect.

Table 3 *Five impact categories calculated per kg pig weight at farm gate by the life cycle assessment (LCA) model based on ReCiPe 2016 Midpoint (H) V1.13 method for low residual feed intake (LRFI) and high residual feed intake (HRFI) lines*

Impact category	Unit	Mean HRFI	Mean LRFI	Difference (%)	SD LRFI	SD HRFI	P^1
Climate change	kg CO_2 eq	2.77	2.60	6.33	0.12	0.11	<0.0001
Acidification	g SO_2 eq	48.1	44.5	7.77	2.91	2.61	<0.0001
Eutrophication	g P eq	3.63	3.35	8.02	0.22	0.20	<0.0001
Land occupation	m^2a	4.45	4.19	6.01	0.19	0.18	<0.0001
Water depletion	m^3	0.047	0.044	6.59	0.0018	0.0017	<0.0001

P = phosphorous; m^2a = area time; m^3 = cubic meter;
[1] *P* were calculated via a *t* test on the line effect.

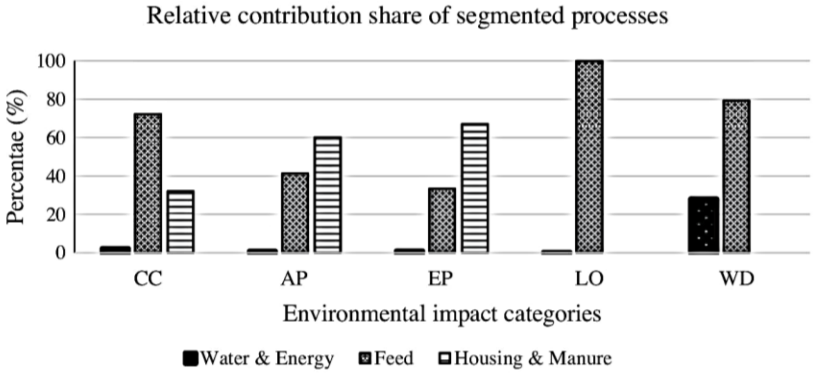

Figure 2 Relative contribution of the segmented pig farming processes within the system boundary of life cycle assessment (LCA), in the five impact categories. Feed ingredients are clustered as 1. feed; 2. emissions and excretion during housing, manure storage and spreading are clustered as housing and manure; 3. On-farm consumption of water and energy are clustered as on-farm water and energy. CC = climate change; AP = acidification potential; EP = freshwater eutrophication potential; LO = land occupation; WD = water depletion.

impact categories was 7%. To test the relative contributions of the different processes involved in the LCA, the impact categories were segmented into feed, housing and manure and on-farm water and energy (electricity, gas, etc.) use. Their percentage contribution to each segment is shown in Figure 2 for the two lines combined, as there were limited line differences. Feed had the maximum share in the impact categories of CC (72%), LO (100%) and WD (79%), whereas housing and manure had the biggest share in EP (66%) and AP (60%). On-farm water and energy had relevant impacts only in WD (28%).

The correlations between impact categories and performance traits, obtained from experimental data (ADG, FCR, ADFI and RFI) and traits simulated by InraPorc® (BP/BL ratio, BFT, PD, BL, and BP), are reported in Table 4. Based on the 95% CI of the correlation estimations, no line differences were evident, except for BP with EP and AP, with a higher negative correlation in LRFI line. All impact categories were highly correlated to FCR, with values higher than 0.96 for both lines. All impact categories had moderate to high correlations with RFI (from 0.51 in HRFI pigs to 0.74 in LRFI pigs) and BP/BL ratio (values between −0.68 and −0.85). All impact categories are highly correlated to BFT, BP, BL and PD, with the absolute values higher than 0.48 for both lines except BP for HRFI line whose correlations had lower magnitude with AP and EP.

Uncertainty analysis

A parallel Monte Carlo simulation study based on the mean values of the traits was run on both lines. The results are graphically represented in Figure 3 in five impact categories. In 100% of the simulations for CC, AP, EP and LO and 61% for WD, the LRFI line had less impacts than the HRFI line, indicating that the line differences are not sensitive to the uncertainty of the model parameters imbedded in SimaPro, except for WD.

Sensitivity analysis

To perform the OAT sensitivity analysis, all incorporated production traits were kept constant, but the value of one trait was changed by ± 2 SD based on the distributions listed in Table 2. The focus traits BP, ADG, ADFI, PD, BL, FCR and BP/BL were changed OAT.

The percentage change in the environmental impact categories compared to the initial impact values due to the changes in any trait are presented in Figure 4. For all categories, the environmental impacts were sensitive to ADFI, ADG, FCR, BP and PD, which corresponded to more than 5% changes in the impacts compared to the initial values. The maximum and the minimum sensitivity for ADFI (+20.6% and −10.7%) were related to EP and WD, for ADG (+17.6% and −10.5%) to LO and WD, for FCR (+13% and −8%) to EP and WD, for BP (+17.7% and −9%) to EP and WD and for PD (+21% and −16%) both maximum and the minimum sensitivity were related to EP.

Discussion

The aim of this study was to develop a model to evaluate the environmental impacts of selection for feed efficiency using comparative LCA and to apply the model to individual records of two divergent pig lines after five generations of selection for RFI. The FCR is correlated with RFI, and selection for reduced RFI has been shown to also reduce the FCR in these lines (Gilbert *et al.*, 2017). Lower FCR is generally due to lower feed intake, higher BW gain or both. Major differences in ADFI in the two lines and minor differences in ADG indicated that lower FCR in LRFI was mostly due to lower ADFI, which matches the objectives of selecting for RFI and agrees with earlier results in the same lines at that stage of the selection experiment (Gilbert *et al.*, 2007).

Studies have reported a negative (favourable) correlation between RFI and body leanness (e.g. Cai *et al.*, 2008). On the other hand, energy partitioning between PD and fat deposition can be modified by improving the feed efficiency (Noblet and van Milgen, 2004). If the general weight gain was little affected by selection, the InraPorc® model showed that the protein to lipid ratio differed significantly between the lines, mainly due to the significant differences in lipid content at

Table 4 *Phenotypic correlations (95% CI) of five environmental impact categories with the recorded traits in the low residual feed intake (LRFI) and high residual feed intake (HRFI) pig lines*

Trait	CC	AP	EP	LO	WD
LRFI line					
ADG fattening	−0.32 (−0.53; −0.07)	−0.35 (−0.56; −0.1)	−0.35 (−0.56; −0.11)	−0.31 (−0.52; −0.06)	−0.30 (−0.52; −0.05)
FCR fattening	0.97 (0.95; 0.98)	0.96 (0.94; 0.98)	0.96 (0.93; 0.98)	0.98 (0.96; 0.99)	0.97 (0.95; 0.98)
RFI (g/day)	0.73 (0.58; 0.83)	0.74 (0.6; 0.84)	0.75 (0.61; 0.84)	0.71 (0.56; 0.82)	0.71 (0.55; 0.82)
ADFI fattening	0.29 (0.03; 0.51)	0.26 (0.00; 0.48)	0.25 (0.00; 0.48)	0.30 (0.05; 0.52)	0.31 (0.06; 0.52)
BP/BL ratio	−0.68 (−0.80; −0.51)	−0.68 (−0.80; −0.51)	−0.68 (−0.79; −0.51)	−0.68 (−0.80; −0.51)	−0.68 (−0.80; −0.51)
BFT	0.58 (0.39; 0.73)	0.59 (0.39; 0.73)	0.58 (0.38; 0.73)	0.61 (0.42; 0.75)	0.60 (0.41; 0.74)
PD	−0.58 (−0.73; −0.38)	−0.61 (−0.75; −0.42)	−0.62 (−0.75; −0.43)	−0.57 (−0.72; −0.36)	−0.56 (−0.71; −0.35)
BL	0.58 (0.39; 0.73)	0.59 (0.39; 0.73)	0.58 (0.38; 0.73)	0.61 (0.42; 0.75)	0.60 (0.41; 0.74)
BP	−0.56 (−0.71; −0.36)	−0.55 (−0.7; −0.34)	−0.55 (−0.71; −0.34)	−0.51 (−0.68; −0.29)	−0.52 (−0.69; −0.31)
HRFI line					
ADG fattening	−0.47 (−0.65; −0.23)	−0.37 (−0.57; −0.12)	−0.36 (−0.57; −0.11)	−0.41 (−0.61; −0.17)	−0.44 (−0.63; −0.21)
FCR fattening	0.98 (0.97; 0.99)	0.99 (0.98; 0.99)	0.98 (0.97; 0.99)	0.99 (0.99;1.00)	0.98 (0.97; 0.99)
RFI (g/day)	0.51 (0.29; 0.68)	0.55 (0.34; 0.71)	0.55 (0.34; 0.71)	0.53 (0.31; 0.69)	0.51 (0.29; 0.68)
ADFI fattening	0.21 (−0.06; 0.44)	0.31 (0.06; 0.53)	0.32 (0.06; 0.53)	0.27 (0.01; 0.49)	0.23 (−0.03; 0.46)
BP/BL ratio	−0.74 (−0.84; −0.59)	−0.83 (−0.90; −0.72)	−0.83 (−0.9; −0.73)	−0.77 (−0.86; −0.64)	−0.74 (−0.84; −0.59)
BFT	0.48 (0.26; 0.66)	0.62 (0.42; 0.75)	0.62 (0.43; 0.76)	0.55 (0.34; 0.71)	0.51 (0.28; 0.68)
PD	−0.66 (−0.79; −0.48)	−0.59 (−0.73; −0.38)	−0.58 (−0.73; −0.38)	−0.61 (−0.75; −0.42)	−0.63 (−0.77; −0.45)
BL	0.48 (0.26; 0.66)	0.62 (0.42; 0.75)	0.62 (0.43; 0.76)	0.55 (0.34; 0.71)	0.51 (0.28; 0.68)
BP	−0.16 (−0.40; 0.11)	−0.03 (−0.29; 0.23)	−0.03 (−0.28; 0.24)	−0.07 (−0.32; 0.20)	−0.11 (−0.36; 0.15)

ADG = average daily gain; ADFI = average daily feed intake; FCR = feed conversion ratio; RFI = residual feed intake; Outcomes from InraPorc®: PD = protein deposition; BFT = back fat thickness; BP/BL = ratio of body protein weight/ Body lipid weight; Outcomes from life cycle assessment: CC = climate change; AP = acidification potential; EP = fresh water eutrophication potential; LO = land occupation; WD = water depletion.

slaughter, meaning that selection for LRFI improved the protein to lipid ratio mainly through reduced LD and back fat thickness, in agreement with the hypothesis stated by Dekkers and Gilbert (2010) concerning the switch of more efficient pigs to a more oxidative metabolism.

Inferring from the differences between LRFI and HRFI feed intake, we hypothesised that the lines would have different environmental impacts. Indeed, the LRFI impacts were on average 7% lower than HRFI impacts in all categories, in agreement with the positive genetic correlation between FCR and RFI with excretion traits (N and P) reported by Saintilan *et al.* (2013) and Shirali *et al.* (2012) who used models at the level of the animal only to predict individual excretion of pigs.

Differences in the level of environmental impact categories between different LCA studies may be due to the differences in the methods, inventories, assumptions, emission factors and system boundaries. To guarantee consistency in the calculation model, LCA method, inventories and system boundary, when comparing the lines, we applied the same model to both. By changing the method to the CML-IA baseline V3.04 (Center of Environmental Science of Leiden University, http://cml.leiden.edu/software/data-cmlia.html) with the same inventories, the impact values decreased to 2.56 kg CO_2-eq for LRFI and to 2.70 kg CO_2-eq for HRFI, confirming the importance of the model for comparing impacts. Thus, although it may not be reasonable to compare the results of two different studies, one can

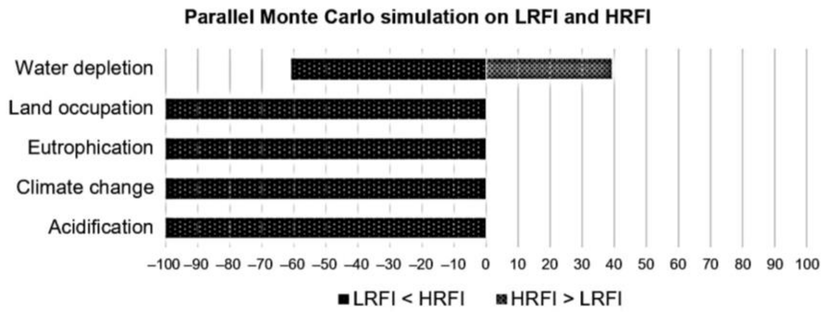

Figure 3 Life cycle assessment (LCA) applied to parallel Monte Carlo simulations for the high residual feed intake (HRFI) and low residual feed intake (LRFI) lines. The figure shows the percentage of scenarios from 1000 Monte Carlo simulations in which each line outperformed the other. Parallel Monte Carlo simulations use identical values from shared uncertainties to calculate environmental impacts. Therefore, the percentage difference in the results can be referred to as the difference between the lines. Positive values are associated with simulations in which the HRFI line has more favourable impacts than LRFI pigs, and negative values, the reverse.

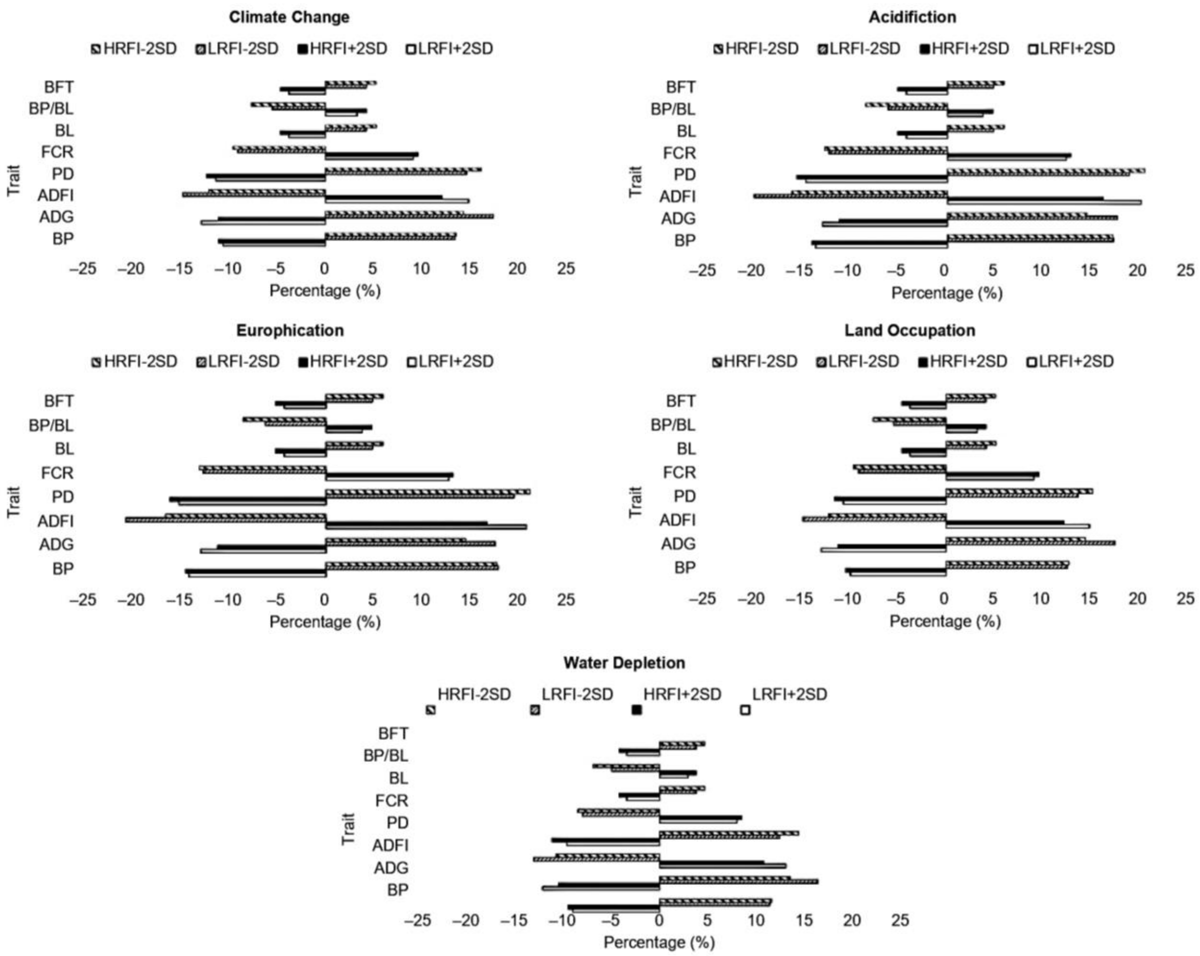

Figure 4 One-at-a-time sensitivity analysis based on the performance traits for the low residual feed intake (LRFI) and high residual feed intake (HRFI) pig lines. Percentage of changes in environmental impacts compared to the mean values due to changes in ± 2 SD in each trait. ADFI = average daily feed intake; ADG = average daily gain; BP = body protein at slaughter; BP/BL = ratio of body protein and body lipid at slaughter; PD = average daily protein deposition; BFT= back fat thickness; FCR = feed conversion ratio; BL = body lipid content at slaughter.

reasonably compare their orders of magnitude and range. The values of the CC impact for LRFI and HRFI were in the same ranges as the values reported by Dourmad *et al.* (2014) (2.3 to 3.5 kg CO_2-eq/kg LW) and de Vries and de Boer (2010) (2.3 to 5.0 kg CO_2-eq/kg LW) for typical European production farms. The impacts of LRFI and HRFI on AP were also in the range of values reported by de Vries and de Boer (2010) (8 to 120 g SO_2-eq/kg LW). The impact on EP for LRFI and HRFI differed from the impacts reported in the literature. These variations were due to the use of ReCiPe midpoint 2016, which accounts for the impact of freshwater EP based on P-eq rather than PO_4-eq. When EP was calculated based on PO_4-eq (according to the CML-IA baseline method) the values changed to 25 g PO_4-eq for LRFI and 27 g PO_4-eq for HRFI, which is in the same range of values reported by de Vries and de Boer (2010) (12 to 38 g PO_4-eq/kg LW). The LO values were also in the range reported by de Vries and de Boer (2010) (4.2 to 6.9 m^2/kg LW).

Clustering the different processes involved in the system boundary provided further insights into the relative contributions of each segment to the impact categories, with limited differences between lines. The relative importance of feed and manure were in accordance with the results published by Garcia-Launay *et al.* (2014). The higher feed contribution to three impact categories of CC, LO and WD is certainly the main driver of the higher environmental impacts of HRFI compared to LRFI. Moreover, as HRFI pigs consume more feed with limited difference in digestibility (Barea *et al.*, 2010; Montagne *et al.*, 2014), they excrete more nutrients and produce more manure because of the mass balance. Considering manure as organic fertiliser partly compensated for the higher environmental impacts of HRFI associated with higher excretion and emission rates. Relative contribution of the segmented process confirmed that improving feed efficiency and manure management presents the main opportunities for improvement in pig farming.

According to the average values of the traits, the RFI lines only marginally differ in BP and PD ($P = 0.32$). The PD plays a role in affecting the environmental impacts in two ways. On the one hand, BW is strongly dependent on protein accretion and LD (Noblet and Etienne, 1987), which could affect FCR. On the other hand, changes in protein content influence N retention and subsequent excretion. Excreted N is at the origin of the emissions of N gas as N_2O and NH_3 during animal housing, outdoor storage of manure and application of manure in the field. A change in body protein, on the one hand, alters FCR through a change in BW, and on the other hand, may – due to a domino effect – influence all downstream N-associated excretions and emissions. While all impact categories are moderately correlated to PD (−0.58), the marginal difference in the lines in BP suggests that selection for RFI would have only limited effects on PD and thus N excretion, which is one of the main sources of environmental impacts. However, the RFI correlations with impacts were of similar magnitude as PD, which could indicate that these two criteria would reduce the environment impacts partly via different levers. Thus, it could be inferred that selection for RFI could be combined with other criteria to target PD. In that respect, the close genetic correlation between FCR and lean meat growth rate (Clutter *et al.*, 2011) makes this trait a more promising criterion for environmental improvement, which from a practical perspective is interesting, as it has been for decades the main criterion used on pig farms to improve feed efficiency. The very high correlation between FCR and all impact categories confirmed FCR as a key trait to reduce the environmental burdens of pig production. However, selecting for FCR has major impacts on decreasing leanness, which might not be any more desirable for some commercial lines in the future. Our study shows that RFI would be a valid alternative to select for feed efficiency with positive environmental impacts.

The statistical analysis of the results of individual LCA, performed on all pigs, revealed that the lines are significantly different for the five categories of environmental impacts. The results of parallel Monte Carlo simulations confirmed these differences and showed that the line difference is not sensitive to the model parameter uncertainties. The OAT sensitivity analysis showed that the impact categories are highly sensitive to ADFI, PD, ADG and FCR and less sensitive to BFT, BL and BP/BL. On the other hand, the correlations between the impacts and the traits show that the impacts are highly correlated to FCR, BP/BL, BFT and BL. This discrepancy between the OAT results and the correlations obtained from individual LCA could be due to not considering the correlations between the traits in the OAT sensitivity analysis, as proposed by Ottosen *et al.* (2019). Consequently, further global sensitivity analyses accounting for trait dependencies should enable a more global understanding of the influence of genetic trait changes on the environmental impacts. Ultimately, this could be used to propose new selection indexes optimising the economic and environmental components jointly, as explored recently by Besson *et al.* (2020).

Conclusion

The feed-efficiency concept arose from an economic incentive as the ratio of gain (pig weight gain) to cost (feed). To date, emissions associated with pig farming have not been accounted for in selection strategies, neither as a cost nor as an income. In the environmental context, P and N excretions, associated emissions and other fluxes emerge as main sources of the environmental burden of pig farming. Ignoring that economic drivers influence the main sources of environmental costs was pointed out, and we suggest that including environmentally optimised criteria could alleviate the environmental burden of pig production, while still satisfying economic requirements. Consequently, our study shows that more optimal selection criteria could emerge through restructuring the trait weights from an environmental point of view.

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Declaration of interest

None.

Ethics statement

None.

Software and data repository resources

The model was not deposited in an official repository.

Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1017/S175173112000138X

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LCA FOR AGRICULTURE

An approach to achieve overall farm feed efficiency in pig production: environmental evaluation through individual life cycle assessment

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Abstract
Purpose Use a holistic individual life cycle assessment (LCA) to investigate possible mitigation of environmental impacts through optimisation of overall farm feed efficiency by combining animal selection for feed efficiency and formulation of diets with minimum environmental impacts tailored to pig nutritional requirements.
Methods A linear multi-objective optimisation method was used to combine diet optimisation tailored to meet the representative nutritional requirements of genetic lines with environmental optimisation of the environmental impacts of the diet. Environmental optimisation was obtained by weighting the environmental impacts of the diet in a single environmental impact score. An individual trait-based LCA model with a cradle-to-farm-gate system boundary and functional unit of 1 kg live pig at the farm gate was applied to genetic lines selected for high (LRFI, high feed efficient line) and low (HRFI, low feed efficient line) feed efficiency data. The production traits of each individual animal in response to the optimised diets were simulated with InraPorc® and imported into the individual LCA model to assess global warming potential (GWP), terrestrial acidification potential (AP), freshwater eutrophication potential (EP), and land occupation (LO) of the overall farm feed efficiency approach.
Results and discussion Integrating selection for feed efficiency, nutritional requirements of genetic lines (HRFI and LRFI) and environmental diet optimisation resulted in overall mitigation of environmental impacts. Compared to the conventional diet, the environmental score of the optimised tailored diets was reduced by 5.8% and 5.2% for LRFI and HRFI lines, respectively. At the general production system level, the environmental impacts decreased by an average of 4.2% for LRFI and 3.8% for HRFI lines compared to environmental impacts of the lines fed the conventional diet ($P < 0.05$). The HRFI line with its optimised tailored diet had fewer impacts than the LRFI line with the conventional diet, except for EP. Individual LCA revealed high correlations between environmental impacts and feed efficiency and protein deposition traits.
Conclusions Implementation of overall farm feed efficiency would effectively mitigate environmental impacts. A holistic economic evaluation of the resulting trade-off between diet costs and pig performances is now needed to design a comprehensive tool to orientate selection and formulation decisions for sustainable pig production systems.

Keyword Environmental impact · Life cycle assessment · Residual feed intake · Feed efficiency · Nutrient tailored diet · Diet environmental optimisation · Pig

1 Introduction

Improving feed efficiency is a major objective to enhance pig production sustainability in terms of economy and environment. The main environmental impacts of pig production originate from feed production (Opio et al. 2013) and from manure excretion and emissions during pig farming (Dourmad and Jondreville 2007; Mackenzie el al. 2016). The improvement in the main environmental burden sources can be obtained through reduction in feed intakes, and supply of nutrients tailored to the animal requirements, to achieve better use of lower quantities of feed by the animals. Feed efficiency, which is usually expressed as its inverse, feed conversion ratio (FCR), stands for the body weight gain per unit of feed consumed. Selecting pigs based on feed conversion ratio (FCR) or residual feed intake (RFI) has been shown to be effective to improve feed efficiency in growing pigs (Gilbert

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et al. 2007 and 2017; Cai et al. 2008; Rothschild and Ruvinsky 2011). Unbalanced dietary nutrients and energy in the feed ration can result in unnecessary high excretion rate. Thus, a diet tailored to nutritional requirements is an important aspect for the environmental optimisation of pig production (Hauschild et al. 2012; Pomar and Remus 2019). Improving feed efficiency by adjusting the composition of the diet to the nutritional requirements of a group or an individual animal (precision feeding) has also been investigated (Pomar et al. 2009; Remus et al. 2019; Monteiro et al. 2017), and some related methods, decision support tools, and systems are under development (Brossard et al. 2017 and 2019). Other methods are available for environmental diet optimisation either by accounting for the choice of ingredients to be incorporated (Garcia-Launay et al. 2018; Tallentire et al. 2017) or combining diet optimisation with minimum nutrient excretion impacts (Mackenzie et al. 2016). Life cycle assessment (LCA) has already been used for environmental assessment of various aspects of pig production systems (Lammers. 2011; Garcia-Launay et al. 2014; Mackenzie et al. 2015; McAuliffe et al. 2016 and 2017; Ottosen et al. 2019). We assessed the environmental impacts of pig selection for feed efficiency in a previous study by using individual LCA (Soleimani and Gilbert 2020), which made it possible to link individual genetic profiles to individual environmental impacts. Here, we propose an overall environmental optimisation approach for pig production which combines ‘pig selection for feed efficiency’, ‘formulation of a nutritionally tailored diet’ and ‘environmental optimisation of the diet’ as a strategy to achieve an overall farm feed efficiency. To achieve overall farm feed efficiency, diets were formulated according to the nutritional requirements of lines selected for different feed efficiency levels. Given these constraints, diets with minimum environmental impacts were determined, and the resulting environmental impacts of a system combining selected lines fed their optimised tailored diet were quantified to assess overall farm feed efficiency. The aim of this study was to establish the optimisation model and assess the total environmental impacts of improvements in overall farm feed efficiency on pig production, by performing individual LCA. The performance traits correlated with the environmental impacts could then use for further pig selection choices for environmental objectives.

2 Materials and methods

2.1 LCA

Environmental impacts were evaluated using life cycle assessment (LCA), which is most frequently used to assess the environmental impacts of products and services (Itskos et al. 2016). The marked contribution of emissions during animal farming, manure storage and application, quantified as global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP) (de Vries and de Boer 2010), have massive implications on human health and ecosystems. Thus, these three impact categories are the most common in LCA studies of pig production (McAuliffe et al. 2016). In addition, since vast land areas are required for producing ingredients for feed, relatively to those for vegetable protein and oil (Basset-Mens et al. 2005), some being located in sensitive ecosystems exposed to high land conversion rate, the land occupation impact category is important for an environmental impact assessment of pig production. Consequently, the impact categories GWP (kg CO_2-eq), AP (kg SO_2 eq), EP (kg P eq), and LO (m^2a crop eq) were used to assess the environmental impacts in our study. ReCiPe Midpoint 2016 (H) V1.02 (Huijbregts et al., 2017), was used together with Ecoalim (Wilfart et al. 2016) and Ecoinvent (Wernet et al. 2016) inventory databases for the impact assessment. Individual environmental assessments for each pig were implemented in SimaPro V8.5.4.0 on the MEANS (MulticritEria AssessmeNt of Sustainability) platform (http://www.inra.fr/means), following the approach we proposed in a previous study (Soleimani and Gilbert 2020).

2.1.1 Goal and scope

The goal of the present study was to develop an approach to achieve overall farm efficiency in pig farms, and to investigate the resulting environmental impacts using a trait-based individual LCA model (Soleimani and Gilbert 2020). A ‘cradle-to-farm-gate’ system boundary including feed production, sow-litter, post-weaning, fattening pigs and manure management, was taken from conventional French pig farming systems. A simplified process flow diagram of the system is shown in Fig. 1. One kilogram of pig live weight (LW) at the farm gate was chosen as the functional unit, and used as a reference to compare the environmental impacts of the different scenarios.

2.1.2 The LCA model

The LCA model was developed in six separate modules: feeding plan, animal profile, emissions, excretion, water expenditure and energy expenditure (Soleimani and Gilbert 2020). Briefly, the model was developed based on pig net energy (NE) requirements, with a focus on the fattening period to allow prediction of the different performance profiles resulting from the composition of the tested diet. InraPorc® software, designed to simulate the performance pigs’ response to different nutritional strategies (van Milgen et al. 2008; Dourmad et al. 2008), was incorporated in the LCA model to obtain sow-litter profiles (identical in all

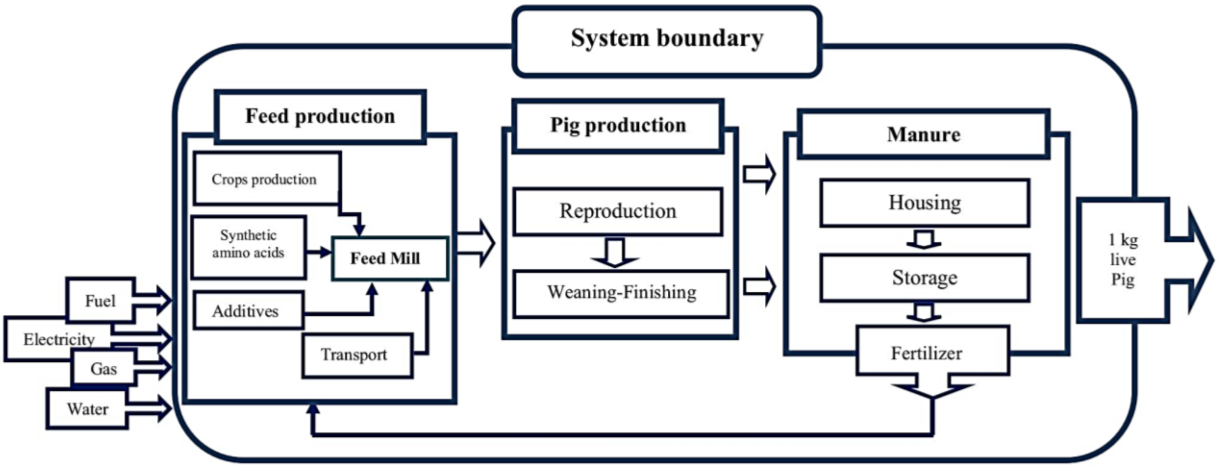

Fig. 1 Scheme of the system boundary, which includes the entire pig farm, feed production processes and manure management

scenarios), feeding plans and corresponding simulated growth performance during fattening. Water and energy expenditures were calculated based on the IFIP report on typical French farms (IFIP—Institut de la Filière porcine 2014). The individual fattening performance traits were used as input parameters in the life cycle inventory (LCI) in SimaPro to perform individual LCAs. The components of excreta (dry matter (DM), organic matter (OM), nitrogen (N), phosphorus (P) and potassium (K)) were calculated using the mass-balance approach, as the difference between nutrient intake in the feed and the nutrients retained in the body (Supplementary Material S1). A typical French slatted floor type of housing and slurry storage was adopted, along with system expansion approach considering that the manure produced replaced a certain percentage of mineral fertilisers (Garcia-Launay et al. 2014). Average performance data were used for the sow-litter stage, and individual performance data were used for the postweaning and fattening stages. Emissions of enteric methane (CH_4), nitrous oxide (N_2O), nitrogen (N_2) and ammonia (NH_3) in the building and during outside storage were calculated according to the IPCC guidelines (Tier I and Tier II) using model and emission factors developed by Rigolot et al. (2010a and 2010b) for French pig systems. Methane emissions from manure during storage, emissions of N_2O, were calculated using the guidelines provided by the intergovernmental panel on climate change IPCC (2006, Tier 2) and the potential leaching rate of PO4 and NO3 during spreading of slurry were adopted from Nguyen et al. (2012). NO_x emissions were calculated according to Nemecek et al. (2004). The fertiliser equivalence value of the manure as a replacement for synthetic fertiliser was considered to be 100% for P and K (Nguyen et al. 2011) and 75% for N (Nguyen et al. 2010). To ensure the results were comparable, the inventories, methods and calculations were kept the same in all the LCA runs. The environmental impacts of the diet ingredients were obtained from the Ecoalim dataset (Wilfart et al. 2016) of the AGRIBALYSE® database using the Recipe method 2016, applying the attributional approach. Values of 500 km for cereals and 100 km for meals were used for the transport of ingredients from the farm to the feed factory (Garcia-Launay et al. 2018), and a value of 30 km (Cadéro et al. 2018) was used for the distance from the feed factory to the pig farm, taken from the attributional life cycle inventories of the ecoinvent version 3.1 database.

2.2 Experimental data

Experimental data (body weights, feed intakes, body composition) were available from birth to slaughter weight for two lines of Large White pigs divergently selected for RFI under ad libitum feeding with the conventional diet. The composition of the conventional diet is reported in the Supplementary Material S2. The selection process concerning low RFI (LRFI, more efficient pigs) and high RFI (HRFI, less efficient pigs) lines are reviewed in Gilbert et al. (2017). The dataset used in the present study included data from 57 male pigs of the fifth generation of each line fed a conventional diet formulated to cover pig requirements. Growing pigs had ad libitum access to a one-phase conventional diet from 10 weeks of age to slaughter (at about 115 kg body weight). The data on individual daily feed intake (DFI) for the whole fattening period were recorded on automatic feeders (ACEMO, Pontivy, France), and back fat thickness (BFT) was measured via ultrasounds on live animals at 23 weeks of age, using an echograph (ALOKA SSD-500, Cergy Pontoise, France). Average daily gain (ADG), feed conversion ratio (FCR), and RFI were then computed as reported in Gilbert et al. (2007). The experimental data for reproductive sows and litters of the same lines (LRFI and HRFI) including the mean sow and piglet BW at weaning and farrowing, sow BFT before farrowing, sow lactation DFI, number of total born, still born and weaned piglets, piglet BW at birth and at weaning, and farrowing and weaning age, were adopted from Gilbert et al. (2012).

2.3 Line diet optimisation

In this study, the diet formulation was optimised to obtain diets with minimum environmental impacts but covering the specific nutritional requirements of the different genetic lines. To diversify the sources of energy and protein available for the diet formulation, six ingredients, oats, triticale, corn, peas, rapeseed meal, and sunflower meal were added to the eight ingredients of the conventional diet (barley, wheat, soybean meal, sunflower oil, and synthetic AA L_lysine (LLY), L_threonine (LTH), L_tryptophan (LTR), DL_methionine (DLM)), to formulate new diets. The new ingredients were selected based on their availability at the market and on the accessibility of their characterization data in the embedded database of InraPorc®. The net energy (NE) density and digestible CP and AAs of the ingredients were extracted from the INRA-AFZ database (Sauvant et al. 2004) of feed ingredients (Table 1). Ingredients like salt, carbonate calcium and vitamins, which do not have digestible energy, CP or AAs, were considered as additives and excluded from the formulation step, so in total $Q = 14$ ingredients were retained for formulation. Some common industrial rules and recommendations for commercial diet formulation, such as storage availability, are beyond the scope of this study and are not accounted for.

2.3.1 Choice of nutritional requirements for diet formulation

To formulate a diet tailored to animal dietary requirements, the nutritional constraints which should be satisfied by the diet have to be identified. Pigs adjust their ad libitum feed intake to the net energy density (NE) of the diet (Quiniou and Noblet 2012). Consequently, dietary nutrients are up taken proportionally to the NE of the diet. In cereal-based diets, essential amino acids (AA) lysine, threonine, tryptophan, and methionine are the most limiting AA (D'Mello. 1993), which turned out to be mostly added as synthetic AA to cereals to achieve balanced nutritional composition, as in the conventional diet used to obtain the pig performances in our previous study (see Table 1, Soleimani and Gilbert 2020, for details). Thus, to avoid AA deficiency, these four amino acids were set as target constraints in the formulation. In addition, to satisfy the dietary requirements of all amino acids, crude protein (CP) was also set as a target constraint to ensure coverage of the remaining essential and non-essential amino acids. Finally, digestible CP and AA requirements were standardised to the NE content of the diet, to account for the feed intake regulation by NE density. Therefore digestible crude protein (CP), digestible lysine, digestible threonine, digestible tryptophan, and digestible methionine, expressed as standardised requirements to the diet NE (g/MJ NE), were retained as the target constraints to be satisfied by the diets tailored to the pig requirements.

2.3.2 Determination of the representative nutritional requirements of the lines

The experimental data were imported into InraPorc® to calibrate a growth performance profile for each individual pig. The profiles were calibrated using the recorded daily ad libitum feed intake during the fattening period with the conventional diet, expressed relative to the NE of the diet. The individual digestible CP and AA requirement profiles of the pigs were then obtained as InraPorc® outputs. Pigs are usually fed in groups with a single diet adjusted to the nutrient requirements of a representative pig in the group (Remus et al. 2019). Accordingly, the five targeted daily requirements for the whole fattening period were extracted from InraPorc® for each individual to identify the representative pig for each line in our dataset. For all individuals, the maximum requirements for these five indicators were observed in the early stages of the growing period. From these individual maxima, the mean maximum requirement for each line was computed for each indicator as the representative requirement of each line. In the following, *Alpha* is the digestible crude protein requirement (g per MJ NE), *Beta* is the digestible lysine requirement (g per MJ NE), *Gamma* is the digestible threonine requirement (g per MJ NE), *Lambda* is the digestible methionine requirement (g per MJ NE), and *Delta* is the digestible tryptophan requirement (g per MJ NE).

2.3.3 Diet formulation tailored to each line

To consider the representative requirement of each line in the tailored diet formulation, linear Eqs. (1–6) were retained as constraints for each line l ($l = 2$ in our study) and Q possible ingredients ($Q = 14$ in our study). Since the diet would be formulated for 1 kg of feed, the first equation ensures the prospective diet plus the additives does not exceed one kg, and the rest of the equations ensure the dietary nutrients correspond to the representative requirements of each line.

$$1\text{kg} - \text{additives (kg)} = \sum_{i=1}^{Q} q_{i_l} \quad (1)$$

Table 1 Digestible crude protein (CP) and amino acids, and net energy (NE) of the ingredients retained for diet formulation, and their environmental impacts

Ingredients	Quantity notation	CP (g/kg_{feed})	Lysine (g/kg_{feed})	Threonine (g/kg_{feed})	Tryptophan (g/kg_{feed})	Methionine (g/kg_{feed})	NE (MJ/kg)	GWP (kg) CO_2 eq	AP (gr) SO_2 eq	EP (gr) P eq	LO (m^2a crop)
Barley	b	80.5	2.85	2.62	1.03	1.43	9.56	0.46	5.60	0.16	1.371
Oat	o	74.2	2.99	2.36	0.94	1.51	8.06	0.50	7.95	0.20	2.079
Triticale	T	83.4	3.24	2.71	1.06	1.53	10.40	0.48	5.43	0.19	1.837
Corn	c	69.8	1.92	2.49	0.40	1.55	11.20	0.33	7.11	0.12	1.033
Pea	p	165.8	12.45	5.93	1.31	1.60	9.75	0.37	3.65	0.57	2.663
Rapeseed meal	r	254.7	13.5	10.87	3.28	6.00	6.26	0.40	5.36	0.10	1.211
Sunflower meal	sm	273.5	9.68	9.72	3.44	6.99	5.50	0.25	2.94	0.25	1.975
Wheat soft	w	92.8	2.51	2.66	1.14	1.51	10.54	0.42	7.96	0.129	1.330
Soybean meal	s	391	25.02	15.4	5.25	5.89	7.86	1.52	5.64	0.385	2.086
Sunflower oil	f	0	0	0	0	0	29.76	1.17	15.51	1.12	8.701
L-Lysine HCL	LLY	954	798	0	0	0	11.88	10.55	76.60	37.85	3.118
L-Threonine	LTH	731	0	990	0	0	11.11	10.62	84.23	37.16	3.109
L-Tryptophan	LTR	853	0	0	985	0	11.53	21.24	168.47	74.32	6.219
DL-Methionine	DLM	584	0	0	0	990	10.61	2.99	8.86	0.270	0.016

NE density and digestible CP and amino acids (lysine, threonine, tryptophan, and methionine) of the ingredients were extracted from the INRA-AFZ database of feed ingredients. The environmental impacts of diet ingredients (GWP, AP, EP, LO) were obtained from the Ecoalim dataset of the AGRIBALYSE® database with the Recipe method 2016

$$Alpha_l = \sum_{i=1}^{Q} q_{i_l} CP_i \Big/ \sum_{i=1}^{Q} q_{i_l} NE_i \tag{2}$$

$$Beta_l = \sum_{i=1}^{Q} q_i LLY_i \Big/ \sum_{i=1}^{Q} q_{i_l} NE_i \tag{3}$$

$$Gamma_l = \sum_{i=1}^{Q} q_{i_l} LTH_i \Big/ \sum_{i=1}^{Q} q_{i_l} NE_i \tag{4}$$

$$Delta_l = \sum_{i=1}^{Q} q_{i_l} LTR_i \Big/ \sum_{i=1}^{Q} q_{i_l} NE_i \tag{5}$$

$$Lambda_l = \sum_{i=1}^{Q} q_{i_l} DLM_i \Big/ \sum_{i=1}^{Q} q_{i_l} NE_i \tag{6}$$

2.3.4 Formulating tailored diets with minimum environmental impacts for each line

The least environmental impact formulation approach implemented in this study involves two steps: (1) formulating a least cost (LC) diet as the baseline reference for environmental impacts and cost, and (2) formulating a diet with the lowest environmental impact score in an acceptable cost interval compared to the least cost diet. In step 1, the objective function of the optimisation is the cost, which should be minimised conditionally to the nutritional constraints in Eqs. (1)–(2). For the nutritional constraints, the cost constraint was normalized to the ingredient NE to compute the diet cost to minimise:

$$min\ cost = \sum_{i=1}^{Q} q_{i_l} p_i / NE_i \tag{7}$$

where q_{i_l}, p_i and NE_i are the rate of incorporation of the ith ingredient in line l, the price and net energy of ith ingredient, respectively, with $i = 1,\ldots, Q$. The least cost diet for each line was obtained through an evolutionary optimisation algorithm of NSGA-II from Eqs. (1)–(2) with library of mco in R version 3.6.3 (population size of 340 and 3500 generations). This algorithm identifies the non-dominated solutions on the Pareto-optimal front curve that best satisfy the nutritional and cost constraints. The price of each ingredient was obtained from the monthly average of the market price of ingredients in France reported by IFIP (IFIP, Mensuel d'information aliment, May 2020). The environmental impacts of the least cost diet (GWP_{LC}, AP_{LC}, EP_{LC}, LO_{LC}) for each line l were calculated by summing the environmental impacts of each ingredient (Table 1) in proportion to its rate of corporation in the diet:

$$impact_{LC_l} = \sum_{i=1}^{Q} q_{i_l} impact_i \tag{8}$$

where $impact_i$ is the environmental impact of ingredient i, and $impact$ is GWP, AP, EP, or LO.

For step 2, the first task was to define an environmental impact score to minimise. The environmental impacts of the least cost diet were used for each line as normalization factors for each impact, as proposed by Garcia-Launay et al. (2018). Then, weights were applied to obtain an environmental impact score (EI score) to minimise as a new objective function:

$$EI_{score\_l} = \sum_{impact=1}^{4} w_{impact} \left(\left(\sum_{i=l}^{Q} q'_{i_l} impact_i / NE_i \right) \Big/ \left(impact_{LC_l} \right) \right) \tag{9}$$

where q'_{i_l} is the quantity of ith ingredient in the diet with the lowest environmental impact score for line l. In our study, an equal weighting of one was first used for w_{GWP}, w_{EP}, w_{AP}, and w_{LO} to avoid unbalanced impacts of the environmentally optimised tailored diet. Finally, the costs of the least environmental score diets were limited to avoid exceeding the cost of the least cost diet by more than 10%. The NSGA-II algorithm was applied to obtain the diets with the lowest environmental impact score under the dietary requirement constraints for each line, from Eqs. (1)–(2) and (3) with cost < 110% least cost.

2.3.5 Sensitivity analysis of the environmental impacts of the diets to the representative requirements of the lines and environmental score weights

To define an approach to assess the sensitivity of the environmental impacts of the diets to changes in the representative requirements of the lines, first the correlations between the individual maximum requirements of the pigs in each line were computed. All the representative requirements were highly correlated (> 0.99). To consider these high correlations in a sensitivity analysis, an all-at-once sensitivity analysis was conducted based on changes in all the requirements combined, first for + 1 standard deviation (SD), and then for − 1SD, separately for the two lines. Then, the full diet optimisation process described above was applied again, and the differences in the environmental impacts of the new optimised tailored diet relative to the initial optimised tailored diet were used for within-line sensitivity analysis. An impact category was considered to be sensitive to changes in the representative requirements of the line if the change in that impact category was greater than 5% (Mackenzie et al. 2016) due to changing by + 1SD or − 1SD all the representative requirements of the lines at once. In addition, in the environmental score used for optimisation, the environmental impact weights (w_{GWP}, w_{EP}, w_{AP} and w_{LO}) were equal to 1. To assess the sensitivity of optimised tailored diet environmental impacts to the choice of weight, a one-at-a-time sensitivity analysis was performed based on successive changes of + 0.5 and − 0.5 for each weight in each diet optimisation run, separately for the two lines.

2.4 Environmental evaluations of overall farm feed efficiency

The growth performance traits, including average daily feed intake, average daily gain, back fat thickness, body protein and body lipid at slaughter (120 kg) and length of the fattening period, were simulated with InraPorc® for each pig in response to its line optimised tailored diet. These performances were then used as input parameters for the individual trait-based LCA mode (Soleimani and Gilbert 2020) to assess the environmental impacts of the overall farm feed efficiency approach. Statistical analyses were applied to the outputs of the different steps of this evaluation, based on calculation of the line means and SDs of growth performance traits and their environmental impacts. *t* Tests were used to test the line differences, and environmental impacts were declared significantly different between scenarios when $P < 0.05$. Correlations between traits and environmental impacts were performed to identify the traits with maximum environmental impact. In addition, a principal component analysis was also performed for a better understanding of the relationships between the components (using fviz function from library of factoextera in R).

3 Results

3.1 Representative requirements of the lines based on individual requirements

Table 2 lists the means and standard deviations of the five representative requirements of the two genetic lines (digestive CP, lysine, threonine, methionine and tryptophan). On average, the LRFI line had + 5% requirements in g/MJ NE compared to the HRFI line ($P < 0.05$), with the crude protein requirements showing the largest difference (6.4%) between lines.

3.2 Environmentally optimised diets tailored to the nutritional requirements of each line

The least environmental impact score diet which satisfies the representative requirements of each line at a cost less than 110% of that of the least cost diet was retained as the optimised tailored diet for the corresponding line. The LRFI optimised tailored diet had 9.38 MJ NE/kg, and the HRFI optimised tailored diet had 9.75 MJ NE/kg, with triticale, in which the proportions of sunflower meal and soybean meal were highest in the LRFI optimised tailored diet, whereas pea and sunflower oil were incorporated only in the HRFI optimised tailored diet (Supplementary Material S3). In addition, smaller quantities of synthetic AA were incorporated in the LRFI optimised tailored diet (L-tryptophan and DL-methionine), whereas L-lysine was higher in this diet. Compared to their respective least cost diets with the 9.27 MJ NE/kg for LRFI and 10.01 MJ NE/kg for HRFI, the main differences in composition were in triticale, wheat, sunflower meal and corn along with less incorporation of L-Lysine in HRFI optimised tailored diet. Table 3 lists the environmental impacts and cost of the line optimised tailored diets and least cost diets, together with the conventional diet. The environmental impact score of the optimised tailored diets decreased of − 5.2% for HRFI and − 5.8% for LRFI compared to the score of conventional diet, as the feed cost per MJ NE (− 11.5% and − 12.0%). When considering the detailed E environmental impacts, the optimised tailored diets showed reductions per MJ NE of feed for GWP (− 12.8% and − 4.5% for the HRFI optimised tailored diet and LRFI optimised tailored diet, respectively), LO (− 18.6% and − 27.4%), AP (− 5.2% for HRFI), and increased in EP (+ 3.1% for LRFI) and EP (+ 40.7% and + 8.4%). The price of optimised tailored diets (0.199 €/kg for LRFI and 0.208 €/kg HRFI) was lower than the price of the conventional diet (0.234 €/kg) per kg of feed and per MJ of NE. These feed prices were less than 110% of the least cost diets prices of each line.

Table 2 Mean maximum individual standardised requirements for the low residual feed intake (LRFI) line and the high residual feed intake (HRFI) line and their standard deviations ($N = 57$ pigs per line)

	LRFI	HRFI	*P*
Alpha: digestible crude protein requirement (g/MJ NE)	11.75 (2.46)	11.04 (2.33)	< 0.05
Beta: digestible lysine requirement (g/MJ NE)	0.91 (0.20)	0.86 (0.18)	< 0.05
Gamma: digestible threonine requirement (g/MJ NE)	0.58 (0.12)	0.55 (0.11)	< 0.05
Lambda: digestible methionine requirement (g/MJ NE)	0.27 (0.03)	0.26 (0.05)	< 0.05
Delta: digestible tryptophan requirement (g/MJ NE)	0.16 (0.06)	0.15 (0.03)	< 0.05

Table 3 Environmental impacts of 1 kg of the conventional, optimised tailored diet (OTD) and least cost diets for the low residual feed intake (LRFI) line and the high RFI (HRFI) line

	GWP (kg CO_2 eq)	AP (g SO_2 eq)	EP (g P eq)	LO (m^2a crop eq)	EI_{score}	Price (€)	NE (MJ)
/kg feed							
LRFI OTD	0.456	6.64	0.43	1.27	3.68	0.199	9.38
LRFI least cost diet	0.504	5.71	0.49	1.69	4.00	0.187	9.30
HRFI OTD	0.433	6.34	0.58	1.48	3.85	0.208	9.78
HRFI least cost diet	0.484	6.84	0.60	1.42	4.00	0.204	10.01
Conventional diet	0.494	6.66	0.41	1.81	4.04	0.234	9.70
/MJ NE							
LRFI OTD	0.0486	0.707	0.0458	0.135	0.392	0.0212	
LRFI least cost diet	0.0541	0.613	0.0526	0.181	0.430	0.0201	
HRFI OTD	0.0442	0.648	0.0593	0.151	0.393	0.0213	
HRFI least cost diet	0.0483	0.683	0.0599	0.141	0.399	0.0203	
Conventional diet	0.0509	0.686	0.0422	0.186	0.416	0.0241	

The difference in percentage between the low residual feed intake line (LRFI) and the high RFI (HRFI) line optimised tailored diets (OTDs) with conventional diet standardised to their net energy (NE)

P phosphorous, *m^2a crop eq* area time, *EI_{score}* environmental impact score obtained from normalized impacts to the least cost diet combined additively with a weigh of one

3.3 Sensitivity analysis of the environmental impacts of the diets to the representative requirements of the lines and weighting factors

To evaluate the sensitivity of the optimised tailored diet environmental impacts to the changes in representative requirements of the lines, a sensitivity analysis was performed by changing all the requirements by + 1 or − 1 SD at once. The percentage changes in the environmental impacts and the environmental score of the new optimised tailored diets (details on composition are provided in Supplementary Material S3) are shown in Fig. 2. All environmental impacts increased after increasing the representative requirements of the lines by + 1SD in the two lines, except AP for LRFI line and EP for HRFI. Changes in the HRFI line were more than 5% for all environmental impacts with the exception of AP (+ 4%), whereas sensitivity was much higher for the LRFI optimised tailored diet, with marked increases in LO and EP (> + 35%). On the other hand, decreasing all the representative requirements of the lines by 1SD led to moderate changes in the

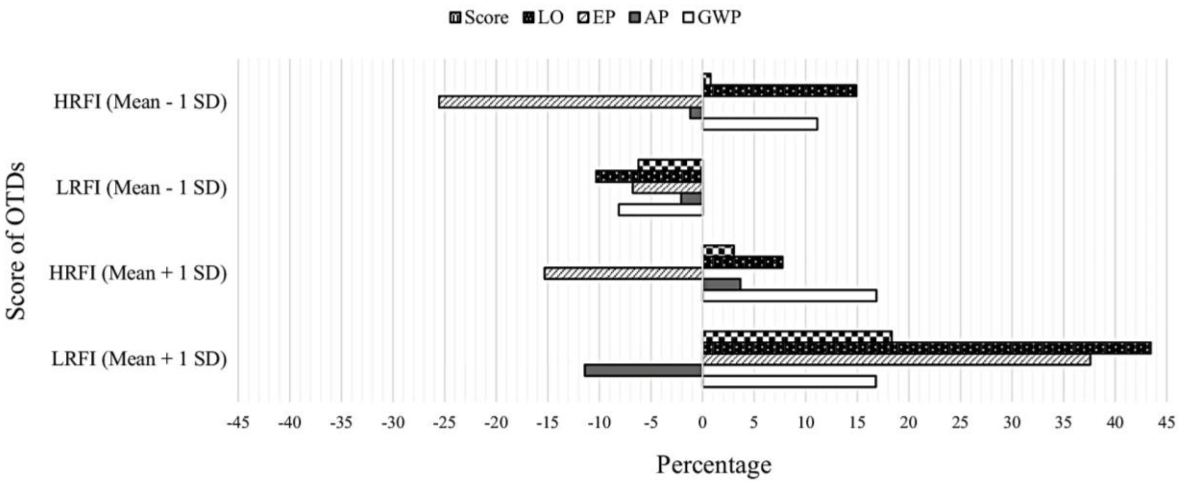

Fig. 2 Percentage changes in the environmental impacts and score of the optimised tailored diets for the high residual feed intake (HRFI) line and the low residual feed intake (LRFI) line when the representative requirements of the lines are changed by ± 1SD all-at-once in the diet-optimised formulation. GWP global warming potential, AP acidification potential, EP freshwater eutrophication potential, LO land occupation

environmental impact of the line optimised tailored diets. HRFI optimised tailored diet had increased GWP and LO after reduction of the requirements (> + 11%), and decreased EP (– 25%), whereas all environmental impacts were reduced for the LRFI optimised tailored diet when – 1SD was applied to the requirements, from 6 (EP) to 10% (LO), with very limited change in AP. Based on these sensitivity results, GWP, EP and LO were most sensitive to the changes in requirements. The environmental scores were affected by the changes in requirements mainly in the LRFI line, with a decrease of 6.2% when the requirements were reduced and an increase by 18% when they were increased.

To evaluate the sensitivity of the optimised tailored diet score to variations of environmental impact weights, a one-at-a-time sensitivity analysis was performed (Fig. 3). Altogether, the sensitivity of the optimised tailored diet environmental score to the score weight changes was relatively low, and only found for LRFI optimised tailored diet: the main sensitivity was found for increases in the LRFI optimised tailored diet scores in relation to LO, EP and AP reduced weights (increases > 6%), and LRFI optimised tailored diet scores when the weights for AP and GWP were increased.

3.4 Simulated individual trait responses to the line optimised tailored diets

The performance responses of all individual pigs to the line optimised tailored diets were simulated with InraPorc® up to the 120 kg BW. Table 4 gives the resulting mean and SD of the performance traits for each line. Significant differences between the lines were observed for feed intake ($P < 0.05$), energy conversion ratio ($P < 0.001$), protein weight at slaughter ($P < 0.0001$), backfat thickness ($P < 0.0001$), body lipids at slaughter ($P < 0.0001$), with lower average values in the LRFI line, and age at slaughter ($P < 0.05$) and ratio body

Table 4 Mean and standard deviation (SD) of growth performance traits and body composition for the low residual feed intake (LRFI) line and high residual feed intake (HRFI) line fed their corresponding optimised tailored diet, simulated by InraPorc®

Traits	Mean LRFI	Mean HRFI	SD LRFI	SD HRFI	P^1
ADG fattening (kg/day)	0.78	0.81	0.09	0.07	0.061
ADFI fattening (kg/day)	2.04	2.13	0.21	0.16	< 0.05
FCR fattening (kg/kg gain)	2.61	2.64	0.19	0.18	0.55
ECR fattening (MJ/kg gain)	24.56	25.84	1.81	1.77	< 0.001
Fattening duration (days)	119.5	112.9	16.3	11.8	< 0.05
BW slaughter (kg)	121.37	121.26	0.43	0.43	0.34
Age slaughter (days)	191.05	185.12	15.26	11.36	< 0.05
PD fattening (g/day)	127.8	128.2	14.0	11.3	0.76
BL (kg)	24.70	28.08	3.09	2.65	< 0.0001
BFT slaughter (mm)	16.20	17.50	1.15	0.99	< 0.0001
BP (kg)	19.38	18.89	0.44	0.37	< 0.0001
BP/BL at slaughter	0.79	0.68	0.11	0.07	< 0.0001

BW body weight, *ADG* average daily gain, *ADFI* average daily feed intake, *FCR* feed conversion ratio, *ECR* energy conversion ratio, *PD* protein deposition, *BFT* back fat thickness, *BP/BL* ratio of body protein weight/body lipid weight at slaughter, *BP* body protein content, *BL* body lipid content

[1] *P* were calculated via a t-test on the line effect

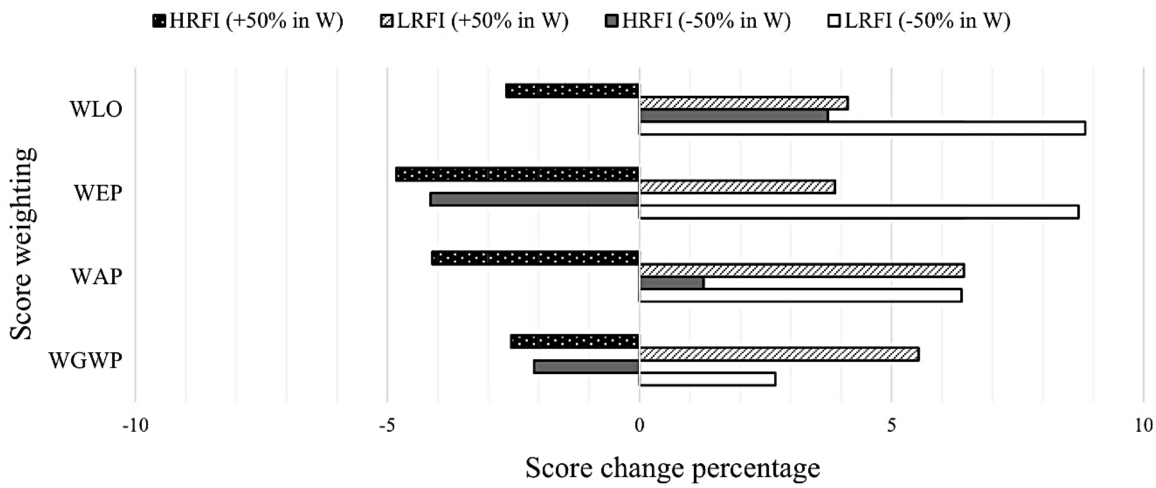

Fig. 3 Percentage changes in the environmental score of the optimised tailored diets of the high residual feed intake (HRFI) line and the low residual feed intake (LRFI) line when the weights (wGWP, wEP, wAP and wLO) were changed by ± 50% one-at-a-time for the diet-optimised formulation. wGWP weight for global warming potential, wEP weight acidification potential, wEP weight fresh water eutrophication potential, wLO weight land occupation

Table 5 Mean and standard deviation (SD) of four environmental impact categories calculated per kg of body weight of pig at the farm gate (120 kg body weight) through individual LCA using the ReCiPe 2016 Midpoint (H) V1.13 method for the low residual feed intake (LRFI) line and the high residual feed intake (HRFI) line fed their optimised tailored diet (OTDs) and conventional diet (Con)

Impact category	Unit	Mean LRFI OTD	Mean HRFI OTD	SD LRFI OTD	SD HRFI OTD	P^1_{OTDS}	Mean HRFI Con	Mean LRFI Con	SD LRFI Con	SD HRFI Con	P^1_{Con}
Global warming potential	kg CO_2 eq	1.96	2.00	0.098	0.092	< 0.05	2.21	2.07	0.124	0.124	< 0.0001
Acidification	g SO_2 eq	35.6	36.5	2.37	2.22	< 0.05	40.0	36.8	2.783	2.797	< 0.0001
Eutrophication	g P eq	1.27	1.39	0.077	0.081	< 0.0001	1.24	1.16	0.077	0.077	< 0.0001
Land occupation	m^2a crop eq	3.53	4.17	0.21	0.24	< 0.0001	4.58	4.30	0.30	0.30	< 0.0001

P phosphorous, *m^2a crop eq* area time

[1] *P* were calculated via a *t* test on the line effect

proteins/body lipids at slaughter ($P < 0.0001$), with higher values in the LRFI line.

3.5 Environmental assessment of the overall farm feed efficiency approach

To assess the environmental impacts of producing 1 kg of live pig through feeding the line optimised tailored diets, an individual LCA was performed in SimaPro for each pig fed its line optimised tailored diet, based on the performance traits simulated with InraPorc®. Table 5 lists the resulting four impact categories for the two lines. In response to their optimised tailored diet, all impact categories differed significantly ($P < 0.05$) between lines, the HRFI line having systematically larger impacts than the LRFI line (from + 2.04 for GWP to + 18.13% for LO). The lines with the conventional diet differed significantly in all impact categories ($P < 0.0001$), with a minimum difference in LO (+ 6.5%) and maximum difference in AP (+ 8.7%) in HRFI relative to LRFI (Table 5). The environmental impacts of the lines fed their optimised tailored diets are shown together with their environmental impacts with the conventional diet in Fig. 4, with reference to the scenario with least environmental impacts (LRFI line fed its optimised tailored diet). Feeding the lines with their optimised tailored diets reduced all environmental impacts compared to when fed the conventional diet ($P < 0.0001$), with the exception of EP

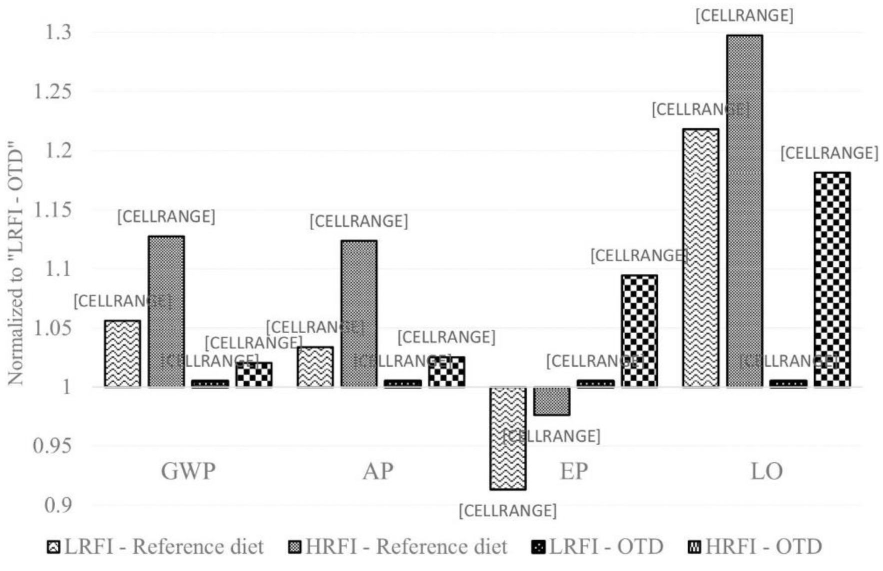

Fig. 4 Four environmental impact categories for the low residual feed intake (LRFI) line and high residual feed intake (HRFI) line fed their optimised tailored diet (OTD) and the conventional diet, presented relative to the impacts of the LRFI line fed its OTD. GWP global warming potential, AP acidification potential, EP freshwater eutrophication potential, LO land occupation. [1]For each impact category, different superscripts in Latin letters indicate significant differences at $P < 0.05$ for pairwise *t* test comparisons of impacts of the LRFI line fed different diets; different superscripts in Greek letters indicate significant differences at $P < 0.05$ for pairwise *t* test comparisons of impacts of the HRFI line fed different diets; different number superscripts indicate significant differences at $P < 0.05$ for pairwise *t* test comparisons of impacts of the LRFI line fed the conventional diet and the HRFI line fed the OTD

which increased ($P < 0.0001$). For all environmental impact categories, a bigger decrease was found with the line optimised tailored diet for the HRFI genetic line than the LRFI genetic line, with the exception of LO, which remained quite high. Altogether, feeding the HRFI line its optimised tailored diet led to a scenario with less environmental impacts than the LRFI line fed the conventional diet, with the exception of EP.

3.6 Correlations between growth performance traits and impact categories

To gain more insight into the relationships between growth performance traits and environmental impacts when the lines where fed their optimised tailored diet, phenotypic correlations were computed between the individual performances and the individual LCA results in each line fed its own optimised tailored diet (Supplementary Material S4). According to the 95% confidence interval of the correlation estimations, no difference between lines could be inferred for these correlations, except for RFI whose correlation with environmental impacts was 0.49 in the LRFI line, whereas it was 0.11 in the HRFI line. A principal component analysis (PCA) was performed to illustrate these correlations between traits and environmental impacts. Figure 5 shows the projection of the traits and EIs on the two first dimensions. All the impact categories were highly correlated with FCR, with correlations higher than 0.82, driving the first dimension of the PCA. Impact categories also had moderate to high negative correlations with traits related to protein deposition BP/BL ratio, BP, PD and ADG, with the absolute values higher than 0.42 for both lines.

4 Discussion

In this study, the reduction of environmental impacts of pig production due to improvement in overall farm feed efficiency was assessed through LCA. Genetic selection for feed efficiency, formulation of diet tailored to each line, and environmental diet optimisation were combined to achieve better production efficiency with reduced environmental impacts.

4.1 Environmental assessment of overall farm feed efficiency

Performing individual LCA on the two genetic lines of pigs fed their optimised tailored diet markedly improved the environmental score, demonstrating the value of the overall farm feed efficiency approach for environmental optimisation of pig production. In this study, the objective was to demonstrate that optimized combinations of genetics and diets are a path to reduce the environmental burden of pig production. From this

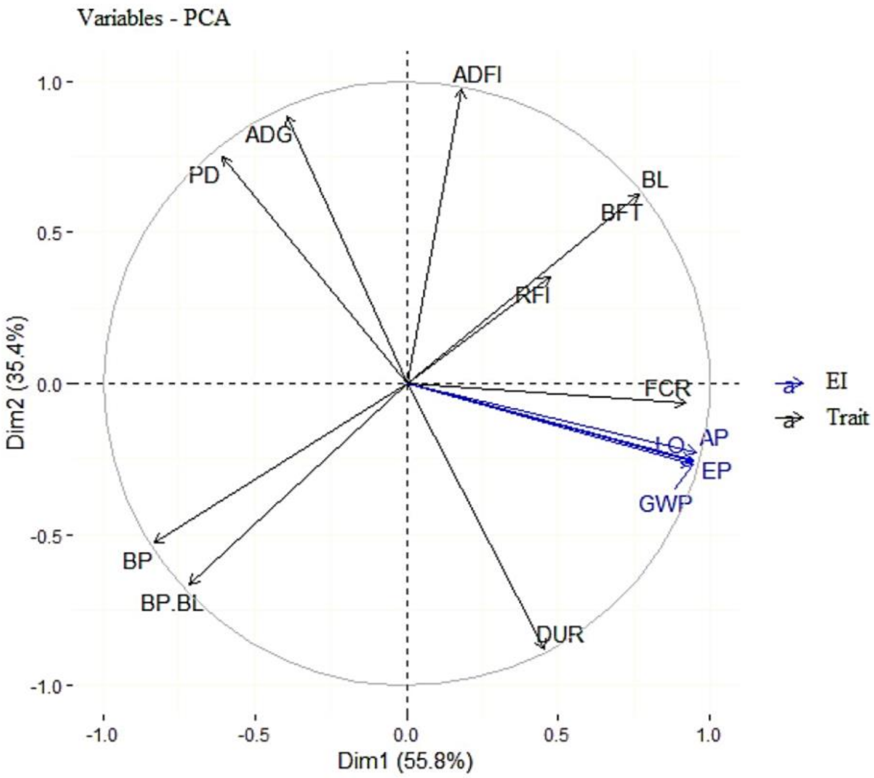

Fig. 5 Projection of the traits and environmental impacts (EI) on the two first dimensions of a principal component analysis applied to the correlation matrix between and the environmental impacts and the traits after adjustment for the line effect ($N = 114$ pigs with data). DUR duration, ADFI average daily feed intake, ADG average daily gain, BP body protein at slaughter, BP.BL ratio of body protein-to-body lipid at slaughter, PD average daily protein deposition, BFT back fat thickness, FCR feed conversion ratio, RFI residual feed intake, BL body lipid content at slaughter, GWP global warming potential, AP acidification potential, EP freshwater eutrophication potential, LO land occupation

simulation study, changes in the assumptions and conditions of the model could affect the outcomes of each scenario. However, most deviations from the current assumptions would have a similar effect for all the compared scenarios. For instance, it is expected that variations in the supply chain of the ingredients (e.g. origin), database inventories, manure management and application, farm operations, pig survival rate, and other methodological choices would modify the magnitude of the impacts for all scenarios, while the general conclusions about the scenario differences would hold robust. The results of this study are limited to the simulation tools and further field studies will be required to confirm these outcomes. With weights of 1 for the four impact categories in the environmental score and our list of ingredients, the lines fed their optimised tailored diet had lower GWP, AP and LO than the lines fed a single conventional diet, but not higher EP. Since the phosphorous content of the optimised tailored diets was lower than in the conventional diet, the increased EP in the two lines could be explained by the higher EP of the optimised tailored diet, via higher EP of their ingredients, rather than by increased excretion and leaching of phosphorous during manure storage and spreading. The substitution of the synthetic fertilisers by the N, P and K of the manure has partly alleviated the environmental burdens of the pig production. The differences in environmental impacts between the LRFI and HRFI lines fed their optimised tailored diet were smaller than the differences when they were fed the conventional diet, even if only a limited list of ingredients to be incorporated was considered in our study. Including a larger variety of ingredients, for instance with lower environmental impacts and lower amino acid concentrations relative to NE, as HRFI pigs had lower representative requirements, could further limit the environmental impacts of the less efficient pigs in a population. Furthermore, as previously reported by Soleimani and Gilbert (2020) with the same model applied to the lines fed the conventional diet, correlations between performance traits and environmental impacts appear to be robust to changes in the animals' genetic potential, and the present study shows that they are also robust to the diet. Thus, the high correlations between all environmental impacts and FCR and protein deposition related traits make them good candidates for the definition of an environmentally oriented selection index.

4.2 Formulation of diets tailored to each line and environmental multiobjective optimisation

A number of studies have been dedicated to optimising diets to achieve different objective functions. Pomar and Pomar (2012) considered the reduction in N and P excretions as the objective function, and Nguyen et al. (2012) targeted cost as the objective function, and GWP and EP as the constraints. Tallentire et al. (2017) minimised a single impact as the objective function along with the constraint of limiting the increase in the cost of the diet compared to a least cost diet. Mackenzie et al. (2016) included four environmental impact categories in their objective function, and combined predictions of excretion corresponding to each dietary nutrient. Finally, Garcia-Launay et al. (2018) presented a multiobjective formulation method to include feed costs and environmental impacts in the objective function using weighting factors. In our study, we capitalised on these approaches to implement a multi-objective diet formulation combining environment, cost and line nutritional requirements. More specifically, the choice of an environmental score is critical, along with the choice of which environmental impacts to include, the choice of normalization factors to standardise the magnitude of the environmental impacts in the score, and the choice of weights to combine them. First, the four highest environmental impacts at the pig production level were retained. Energy demand for instance, as one of the main impacts of diet productions, could be added to the model later (Basset-Mens et al. 2005; Leinonen et al. 2012). Second, we normalized the diet impacts to the environmental impacts of the least cost diet for each line (Garcia-Launay et al. 2018), so all environmental scores can be interpreted with respect to this reference. Third, equal weights were considered for all impact categories in the definition of the environmental score to minimise (Mackenzie et al. 2016). Diet optimisation for a single environmental impact may increase other impact categories (Tallentire et al. 2017). Giving equal weights is an arbitrary choice, and, depending on the societal context and on the load of the different impacts on the territory, different weights could be applied. However, the sensitivity analysis results showed that changes in the environmental impact score are difficult to predict when the weights are modified, as previously reported by Garcia-Launay et al. (2018): a higher value for a given weighting factor does not ensure a major reduction in the intended impact, and may increase other impacts. Finally, rather than considering the estimated emissions and excretions after diet consumption in the diet optimisation (Mackenzie et al. 2016), our formulation approach was constrained to the NE content of the resulting diet. This choice ensures consistency with the expected intakes, and hence related emissions and excretions at the pig farm level. Simultaneously minimising the environmental impacts and constraining cost is a multi-objective optimisation problem, with the issue of having a different scale for each objective. Different approaches have been proposed to solve this problem in the context of combining environmental impacts and costs, such as monetising the environmental impacts to combine all objectives in a cost function (Eldh et al. 2006), or normalizing the impacts, and weighting them in a single score (Mackenzie et al. 2016). To avoid assumptions on the costs of the different environmental impacts, we chose the second option in this study, and combined it with a constraint on the increase in cost. Environmental diet optimisation can increase the cost of the diet, which is the biggest production cost for owners of pig farms. Relative to the conventional diet, the optimised tailored diets cost less and had lower environmental impact scores, per kg of feed and per unit of NE. However, minimising the environmental impacts had a cost at the level of the diet, which in our study was higher for the HRFI optimised tailored diet than for the LRFI optimised tailored diet. Increasing the number of ingredients, and diversifying them towards incorporation of by-products, would certainly provide more flexibility in the diet optimisation and minimisation of environmental impacts. However since the main concern of the study was to develop and demonstrate the approach towards overall farm feed efficiency, a limited number of new ingredients was tested. In addition to the environmental assessment of overall farm feed efficiency strategies proposed in this study, further economic assessments would be needed to provide complementary insights into their sustainability.

4.3 Choice of nutritional requirements for each line and performance responses of individual pigs to their optimised tailored diet

The representative requirements of the LRFI were higher than those of the HRFI, as previously reported by Gilbert et al. (2017) for the same genetic lines. Respecting the high correlations between the five representative requirements, the all-at-once sensitivity analysis showed that environmental impacts were quite sensitive to representative requirements, especially when they were increased by + 1SD. Due to switches between ingredients to respond to the new requirements, the effects on the environmental impacts were quite varied, both in direction and magnitude. However, when summed in the environmental score, the main changes were changes in LRFI representative requirements. The higher baseline requirements for LRFI might reflect the higher sensitivity of impacts to higher requirements and underlines the need to adequately capture the nutritional requirements of the targeted animals.

The performance traits showed a decrease in growth rate in both lines with the optimised tailored diets compared to the conventional diet (Soleimani and Gilbert 2020), leading to approximately three more days required for the pigs to reach 120 kg BW. This is certainly related to the choice of representative requirements to formulate the line constraints: considering the average maximum nutritional requirements in each line would lead to the nonsatisfaction of the requirements in about half the animals in the early stage of the growing phase. In our dataset, this was limited to the very first days of the growing period, but could create a longer delay in reaching slaughter body weight. In an environmental perspective, the reduction in growth rate could be considered to be offset by the reduction in the environmental impacts to produce 1 kg of live pig in both lines. One possible way to alleviate this reduction in growth performance would be to increase the representative requirements, considering the 75% quantile of the maximum pig requirements per line, rather than the average maximum. Increased environmental impacts would certainly result from this strategy, especially in the more efficient genetic line, as shown by the sensitivity analysis. However, this could be reduced by formulating optimised tailored diets for different growth stages using multiphase feeding. In addition, individually tailored diet formulation and optimisation would certainly offer higher overall farm feed efficiency through precision feeding of individual pigs (Pomar and Remus 2019) selected for feed efficiency. However, a further economic assessment would reveal to what extent cost is compromised by switching from a conventional diet to optimised tailored diets at the farm level.

5 Conclusion

Animal selection for feed efficiency, formulation of diets tailored to the requirements of a genetic line, and environmental optimisation of the diet have separate potential for improving farm feed efficiency to reduce environmental impacts. Our study shows that combining these levers in an overall farm feed efficiency approach would remarkably reduce the environmental impacts of pig production systems. The real-time diet formulation tailored to the requirements of each individual selected for feed efficiency, integrated in real time optimisation according to an objective or multi-objective environmental function, would be a complementary tool to mitigate the environmental impacts of pig production. Although environmental optimisation of the production system was achieved in our study, economic evaluations of the full production system including different ranges of genetic and dietary options will be necessary to achieve selection and formulation decisions that tackle the necessary trade-offs between economic and environmental objectives of a sustainable pig production system.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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