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Efficient pigs do not always have less environmental impacts: insights from an individual-based model to assess environmental, economic and technical performances

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Highlights

- **It is possible to assess individual environmental and economic performances of pigs.**
- **Individual feeds were formulated to cover specific amino acids requirements.**
- **Efficient pigs with high amino acids requirements had high environmental impacts.**
- **Feed contribution varied by type of environmental impact, affecting pig rankings.**
- Nutrient-demanding pigs showed trade-offs between economic and environmental goals.

Abstract

Pig production is facing economic and environmental challenges. In previous studies, the environmental impacts of pig farming have mainly been assessed with group-feeding strategies. A feeding strategy applied to a group of pigs results in unequal animal responses and environmental impacts due to inter-individual variability in lean growth potential and nutritional requirements. The present work aimed at fairly evaluating pigs' responses in a given production system. We designed a methodological approach able to (i) virtually assess technical, economic and environmental performances of each fattened pig within a population; and (ii) help determine the pig characteristics resulting in contrasted environmental performances in a conventional system including feedstuffs classically used on French commercial farms. For that purpose, experimental data collected on 732 entire Large White males were used to adjust growth profiles using InraPorc® software and to estimate amino acid (**AA**) requirements of pigs. Each individual profile was used to generate a virtual population of 1 000 pigs. For each population, technical performances were simulated with an individual-based model, economic and environmental evaluations were applied to these performances, and then averaged to assess the individual performance of each of the 732 original pigs. Climate change, use of fossil resources, acidification, eutrophication potentials and land use impacts were evaluated per kg live body weight at farm gate through life cycle assessment. A principal component analysis was applied to the correlation matrix between environmental and economic performances to identify their main drivers. Hierarchical clustering was used to group pigs with similar responses. Three clusters of pigs were distinguished. Cluster 1, with best environmental and economic performances, combined low feed conversion ratios, relatively low-impact feeds and high protein deposition potential (**PDm**). Clusters 2 and 3 displayed worst environmental performances. Cluster 3 had similar feed efficiency and economic performances as Cluster 1, but higher initial AA requirements, resulting in high-impact feeds and a lower protein deposition. Cluster 2 had the lowest-impact feeds due to the lowest initial AA requirements, and were the least efficient. Feed efficiency, PDm and AA requirements of pigs at the beginning of fattening were the main factors affecting environmental performances. Contrary to previous studies where group feeding was modelled, we show that feed efficiency alone cannot be retained to identify pigs with the lowest impacts. Other pig characteristics such as AA requirements, PDm and environmental impacts should be accounted for to lower the environmental impacts of pig production.

Keywords: Fattening unit, System modelling, Life Cycle Assessment, Individual simulation, Multiperformance

Implications

The environmental impacts of pig production are usually evaluated for groups of animals provided with feeds covering the average nutritional requirements of the population. We propose an individual-based modelling approach applied at the system scale to assess the environmental, economic and technical performances of each pig. We identified feed efficiency, digestible amino acid requirements at the beginning of fattening, and protein deposition potential as key traits to identify pigs with the lowest environmental impacts. Feed efficiency alone is not sufficient to identify pigs with low impacts. These other traits should be considered when selecting pigs to reduce their environmental footprint.

Introduction

Among livestock, pig production has been reported to be a significant contributor to various environmental impacts (Basset-Mens, 2005). Environmental concerns have arisen about pig production due to greenhouse gases, nitrogen and phosphorus emissions through air, soil and water, and the consumption of fossil resources (Steinfeld, 2006). Pig production contributes to some 14% of greenhouse gas emissions from livestock (FAO, 2023). Emissions from manure in pig and cattle barns, as well as during storage, have been identified as the main contributors to ammonia emissions from livestock (Groot Koerkamp et al., 1998). De Vries and de Boer (2010) showed that among livestock products (chicken, pork, beef, milk and eggs), pork production rates second after beef in terms of impact per kg of edible protein for global warming (kg CO_2-eq), acidification (kg SO_2-eq), eutrophication (kg PO_4^{3-}-eq), energy use (MJ) and land use (m^2) impacts in the main European producer countries. In addition, pig meat is one of the most highly produced protein sources worldwide (Gill et al., 2021). Over the past 20 years, many studies have assessed the environmental impacts of pig farming systems (Gislason et al., 2023). In most of them, environmental impacts of groups of animals (batch, entire farm, genetic line, etc.) were evaluated to compare feeding (de Quelen et al., 2021; Méda et al., 2021) and manure management strategies (Pexas et al., 2020; Rudolph et al., 2018) and, more generally, to assess the impact of pig farming systems (Dourmad et al., 2014; Halberg et al., 2010). In these studies, based either on simulations or experimental data collected on farms, animals were fed a diet formulated according to the group's average nutritional requirements. In this practice, commonly used in commercial farms, the individual variations in nutritional requirements are therefore not considered. Consequently, some pigs receive more amino acids than needed while others are, at least partly, restricted. The over-coverage of the requirements leads to increased pig protein intake and reduced N retention efficiency (Andretta et al., 2016), resulting in higher nitrogen emissions to the environment (Pomar et al., 2019). Conversely, providing feeds that do not cover the requirements of the most demanding pigs over a more or less long period of time tends to reduce N retention efficiency and lean deposition compared to pigs whose needs are met by feed (Méda et al., 2021). Due to inadequate protein supply, resulting in decreased protein deposition and increased lipid deposition, pigs can then have lower growth rates and therefore higher feed conversion ratios (Gaillard et al., 2020) with subsequent negative effects on the feeding costs and the emissions per kg of weight gain. In these conditions, individual pig performances are not fairly evaluated, impairing the ranking of pigs and the identification of the best individuals for both production and environmental performances. Consequently, the effect of individual characteristics cannot be disentangled from that of the feeding level. For an unbiased characterisation of individual technical, economic and environmental performances, it can therefore be assumed that the performance of each pig should be assessed individually, with feeds formulated to meet its own requirements.

In addition, previous studies showed that a systemic approach is needed to integrate all factors affecting the environmental and economic performance of production systems (Bonneau et al., 2008). It is also widely accepted that the environmental assessment of pig production should include the production of feedstuffs, transportation, animal housing and manure management. We therefore hypothesised that combining evaluations at the individual level (feeds formulated to meet individual requirements) with an evaluation at the production system level is necessary to properly assess the individual economic and environmental impacts.

This study aimed to design a methodological workflow to investigate the technical, environmental and economic performance of individual pigs. By applying this workflow, the objective was therefore to determine the characteristics of pigs that achieve different environmental performances and their link with economic outcomes in a conventional system representative of a French commercial farm. The proposed strategy was to consider each individual as the average profile of a given population and simulate the fattening of its population with a feed formulated to specifically cover the nutritional requirements of that pig. This approach ensured that the feeding strategy was the same for each pig, and made it possible to assess the technical, economic and environmental performances of each individual with indicators at the fattening-unit level.

Material and methods

Methodological approach

The strategy developed in this study aimed at ranking each single pig issued from an *in vivo* population (Déru et al., 2020) according to its simulated technical, economic and environmental performances, in a given production system characterised by a set of available feedstuffs commonly used in France. The issue was to phenotype each individual pig via the evaluation of the environmental impacts obtained for a pig production system if this pig becomes the average animal of the population. Indeed, we hypothesised that the ranking of pigs, especially in terms of environmental impacts, would be different with feeds designed to meet each pig's requirements (Option 1, Fig. 1) compared to feeds classically formulated to cover the nutritional requirements of the average pig of the population (Option 2, Fig. 1). The approach (Option 1, Fig. 1) comprised four main stages described in Fig. 2. We simulated a hypothetical situation where each pig growth profile (referred to as parent profile) obtained from the *in vivo* population (growth profile adjustment) (Step 1, Fig. 2) was used as the average profile to generate a virtual population of 1 000 pigs (referred to as son profiles) (Step 2, Fig. 2). Within each virtual population, the individual growth performance and environmental footprint of son profiles were then assessed under a feeding strategy based on diets formulated either (1) to meet the specific needs of the parent profile (Step 3, Fig. 2), or (2) to meet the needs of an average profile established over the whole population of parent profiles (Step 3 in orange, Supplementary Fig. S1). With option (1), it is possible to assess the performance of each single pig when fed with feeds formulated to cover its own requirements. We compared options (1) and (2) to validate our hypothesis that individual feed formulation is needed to fairly evaluate individual impacts. Simulations of technical, economic and environmental impacts were performed with a pig-fattening unit model (Step 4, Fig. 2) that accounted for the individual variability of intake and growth potentials among pigs. This pig-fattening model was used to formulate feeds according to the pigs' requirements, to simulate pig growth using feed intake and growth prediction equations from InraPorc®, to assess economic results from the resulting technical outcomes and to evaluate environmental impacts using a cradle-to-farm gate life cycle assessment. The whole experimental simulation design was tested for a conventional system representative of a typical French commercial farm. The following sections aim at describing the full model and the different stages of the approach, as illustrated in Fig. 2.

Description of the pig fattening-unit model

We used the individual-based model developed by Cadéro et al. (2018) and Davoudkhani et al. (2020) to simulate technical, economic and environmental performances of fattened pigs. We used the version of the model from Davoudkhani et al. (2020) that corresponds to the model developed by Cadéro et al. (2018), with the addition of a feed formulation module. This version combines a feed formulation module, a pig growth simulation module based on the InraPorc® equations (van Milgen et al., 2008), and an evaluation module for assessing economic and environmental performances. The model operates on a daily time step. The whole unit is represented in the model by the following pig characteristics: feed intake and growth potential; initial body composition; the nutritional values of the feeds distributed to the pigs; as well as the characteristics of the fattening rooms, and the farmers' management practices. Inputs included all pig profiles, the feed rationing plan, the feed sequence plan and feed composition, plus several pieces of information related to farm management (pig allocation to pens, manure storage strategy, shipping to slaughterhouse strategy, etc.) and building characteristics (number of fattening rooms, pens, animal density, etc.).

Individual animal characteristics

Pig growth profiles are defined individually by five parameters (from the InraPorc® model) describing their intake and growth potentials: initial body weight, mean protein deposition (**PDm**), shape parameter of the Gompertz function describing the evolution of pig protein deposition as a function of age (BGompertz), and two parameters describing the feed intake curve (a and b) (Brossard et al., 2006). These variables can be used to simulate feed intake, growth and nutrient excretion according to the feeding strategy. The general functioning of the model is further described in Supplementary Material S1.

Environmental evaluations

Environmental impacts of each slaughtered pig are estimated in the model using a cradle-to-farm gate life cycle assessment. System boundaries comprise the production and transport of feed from the arable land to the feed plant and the farm, and all of the processes on the pig farm including pig production and manure management. It includes the cultivation of feedstuffs and the production and transport of inputs needed, as well as the transport of feedstuffs from field to feed factory and their processing at the plant. The evaluated pig production includes the whole farrowto-finish period (i.e., production of gilts and piglets, post-weaning and fattening phases), and pigs were considered to be raised on fully slatted floors. The functional unit is 1 kg of live body weight at the farm gate. In accordance with the latest recommendations of the European Commission on impact assessment, the Environmental Footprint 3.0 method was used to calculate the impacts. The environmental impacts considered are those usually taken into account for pig production (McAuliffe et al., 2016): climate change (**CC**) (in kg CO_2-eq/kg); acidification potential (**AC**) (in molc H^+-eq/kg); freshwater eutrophication potential (**EUfreshw**) (in kg P-eq/kg); terrestrial eutrophication potential (**EUter**) (in mol N-eq/kg); marine eutrophication potential (**EUmar**) (in kg N-eq/kg); resource use for fossil energies (**RU**) (in MJ/kg); and land use (**LU**) (in Point/kg). More details about environmental assessment are provided in Supplementary Material S1, and a more detailed description of the model and its operation are available in Cadéro et al. (2018).

Growth profile adjustment

In this first step of the approach (Fig. 2), each parent profile was characterised for its growth and feed intake potentials.

First, a database comprising individual longitudinal data of body weight and feed intake for 874 Large White pigs (entire males) bred between 2017 and 2018 at the INRAE phenotyping station UE3P (UE 3P. 2018 - https://doi.org/10.15454/1.5573932732039927E12) France Génétique Porc (Le Rheu, France) was used (Déru et al., 2020). This pig population was representative of the individual variability observed in a commercial selected population. Fattening began at 9 weeks of age and lasted until slaughter, with a target slaughter weight fixed at 115 kg live body weight. Pigs were fed with a two-phase dietary sequence and had *ad libitum* access to feed and water. The population was fed a conventional diet (9.6 MJ NE/kg feed) that covered the energy and amino acid requirements of all pigs so as not to restrict pig growth. Thus, these data were suitable for adjusting growth profiles (Brossard et al., 2009). The daily feed intakes and live body weights were recorded daily per individual through single place automatic feeders equipped with a weighing system in each pen of 14 pigs (Genstar, Skiold Acemo). Individual growth profiles were then defined from 70 days of age to slaughter from daily feed intake kinetics and recordings of live body weight for each pig. The parameters BGompertz and PDm for the Gompertz function for potential protein deposition were fitted, as well as the parameters a and b of the gamma function of the maintenance requirement used to predict feed intake in net energy (**NE**) per day. Fitting was performed using InraPorc® software in its population version to serially adjust the profiles for all pigs, with the feeding strategy originally applied to the pigs. Pigs with unrealistic values or calibration failures ($R^2 < 0.99$) were excluded, namely 17 profiles. In total, 857 adjusted profiles constituted the database and were considered as average profiles (referred to hereafter as parent profiles) in the following step.

Virtual population generation

In the second step, a virtual sub-population was generated with R software (version 4.3.2) considering each parent profile as the average profile of its sub-population. A variance-covariance matrix of the growth profile parameters of the real population was computed (Supplementary Table S1). Each of the adjusted growth profiles (parent profile) was used as an average profile to generate the profiles of a virtual sub-population of 1 000 pigs (referred to hereafter as son profiles) using the computed variance-covariance matrix following the multinormal distribution in Equation (1): this returned 857 virtual populations of 1 000 son profiles.

$$\begin{pmatrix} a_{i_n} \\ b_{i_n} \\ PDm_{i_n} \\ BGomp_{i_n} \\ BWinit_{i_n} \end{pmatrix} \sim N\left(\begin{pmatrix} a_i \\ b_i \\ PDm_i \\ BGomp_i \\ BWinit_i \end{pmatrix}, \begin{pmatrix} \sigma^2{}_a & \sigma_{a,b} & \sigma_{a,PDm} & \sigma_{a,BGomp} & \sigma_{a,BWinit} \\ & \sigma^2{}_b & \sigma_{b,PDm} & \sigma_{b,BGomp} & \sigma_{b,BWinit} \\ & & \sigma^2{}_{PDm} & \sigma_{PDm,BGomp} & \sigma_{PDm,BWinit} \\ & & & \sigma^2{}_{BGomp} & \sigma_{BGomp,BWinit} \\ & & & & \sigma^2{}_{BWinit} \end{pmatrix}\right) \quad (1)$$

where a_i, b_i, PDm_i, $BGomp_i$ and $BWini_i$ are the parameters of the parent profile i; and a_{i_n}, b_{i_n}, PDm_{i_n}, $BGomp_{i_n}$ and $BWinit_{i_n}$ are the parameters of the son profile n in the population centred on the parent profile i, with n ranging between 1 and 1 000.

Son growth profiles were sampled until 1000 consistent profiles were obtained for each parent profile: only profiles with positive values for parameters a, b and BGompertz and values of PDm lower than 270 g/d were retained (Vautier et al., 2013; Saintilan et al., 2015; L. Brossard. personal communication). Each virtual population (set of 1 000 combinations of the five growth parameters centred on the parameters of a given parent) was considered as a batch for simulation with the individual-based fattening-unit model.

Feed formulation for each individual parent profile

In the third step, pig diets were least-cost formulated to meet 100% of the nutritional requirements of the parent profile (i.e., minimum and maximum content for amino acids and net energy) at the beginning of the growing phase (from 30 kg to 65 kg) and of the finishing phase (from 65 kg until slaughter). For that purpose, the model considered the digestible amino acid requirements of the parent profile to formulate feeds for its virtual population of son profiles, leading to the coverage of the requirements of 50% of the son profiles at the beginning of each feeding phase, as previously established by Brossard et al. (2009). Nutritional requirements were determined by simulating lipid and protein depositions with InraPorc® software from previously adjusted growth profiles. Digestible amino acid requirements were predicted from the evolution of protein deposition. Among the 857 pigs, it was not possible to formulate the growing feed for 80 of them because of very high or even abnormal initial digestible lysine requirements (from 10.9 to 62.5 g digestible lysine/kg feed). Such amino acid requirements were linked to the pigs with the higher precocity parameter (BGompertz around 9.00 day^{-1} and below).

The method previously described was applied to a conventional pig-fattening unit, characterised by a set of feed ingredients commonly used in these units in France (Supplementary Table S2) according to the feed conjuncture reports issued by the

French Pig Technical Institute (IFIP, 2019-2021), Wilfart et al. (2018) and de Quelen et al. (2021). It included cereals and their coproducts traditionally used to feed pigs, as well as oilseed crops, fats and meals. The prices of feedstuffs were averaged over the 2019-2021 period on the basis of monthly ingredient prices of the conjuncture reports issued by the IFIP. Supplementation with synthetic amino acids, vitamins and minerals was provided to cover the pigs' requirements. Information on the nutritional values of feed ingredients was extracted from the French nutritional table, INRA-CIRAD-AFZ (2017, available at https://www.feedtables.com/). Incorporation constraints and nutritional constraints related to resource availability or known anti-nutritional factors were established according to the literature (Cadéro et al., 2018; de Quelen et al., 2021; Méda et al., 2021) (Supplementary Tables S2 and S3).

Technical, economic and environmental performance simulation

The model was parameterised to simulate a breeding system representative of a French commercial pig fattening farm. A single batch was simulated for each parent population with *ad libitum* feed supply. Performances of a total of 777 batches of 1 000 pigs were then simulated independently. Pigs were sent to slaughter when at least 10% of the batch was ready for shipment, with a maximum of 112 days after the start of fattening (more information is provided in Supplementary Material S1). Mortality was set to 0 as there is no *a priori* knowledge about the survival potential of the different profiles, so that all 1 000 son profiles were slaughtered. The simulation process was thus deterministic. Pigs were raised on a fully slatted floor. The 2019-2021 period was selected to set the selling price of pigs, and the premium per kg of carcass was calculated according to the French payment grid (Uniporc grid) reviewed in 2021.

Environmental impacts of feed ingredients, comprising the same impacts as those assessed per kg live body weight plus water use impact using the Environmental Footprint 3.0 method (m^3 deprivation), were taken from the last version of the AGRIBALYSE database (v.3.0) available on SimaPro® software (SimaPro® v.9.3.0.3) (Supplementary Table S4). Background data for the impacts of road transport, electricity, light fuel oil and natural gas were updated from the last version of the EcoInvent v3.8 database used in AGRIBALYSE. Impacts of the transport of feed ingredients to the feed factory were based on the distances assumed by Garcia-Launay et al. (2018) and Méda et al. (2021). Impacts related to the breeding of sows (farrowing phase) and the production of piglets (weaning and post-weaning phases) were extracted from the AGRIBALYSE database (version 3.0), considering average life cycle inventories for conventional production in France.

Finally, each parent profile performance was estimated in a breeding system with feeds formulated in the third step according to its own nutritional requirements. Individual technical, economic and environmental performances (Supplementary Table S5) resulting from the simulation were aggregated at the population level to characterise the parent profile as the mean and standard deviation of its son profile performances. Among the 777 profiles simulated, 40 parent profiles had no performance data due to model failure to simulate the performance of at least one son profile among its virtual population (for a parent profile with a PDm of 189 g/day, some of its son profiles reached a PDm above 245 g/day), and were thus excluded.

Another five profiles resulting in extreme values of environmental impacts (± 4 sd) were excluded. Finally, the performances of the 732 parent profiles were analysed. Altogether, 30 indicators of technical, environmental and economic performances at the animal (/kg) and feed (/kg feed) levels were obtained (see Supplementary Table S5 for units and abbreviations).

Technical, economic and environmental performance simulation with an average feed

In order to validate our hypothesis that individual feed formulation is needed to fairly evaluate individual impacts, we compared the proposed individual feed formulation to the standard average feed approach. For this purpose, the technical, economic and environmental performances were also simulated with an average feed to meet the needs of an average profile established over the whole population of parent profiles (Supplementary Fig. S1). The individual daily feed intakes and live body weights recorded for the 732 parent pigs between 70 days of age to slaughter were averaged on a daily basis. These daily average values and the feeding strategy applied during the experiment were used to define the average growth profile of the parent population with InraPorc® software. Two feeds (referred to hereafter as average feeds) were least-cost formulated to meet 100% of the nutritional requirements of the average profile at the beginning of the growing phase (from 30 kg to 65 kg) and of the finishing phase (from 65 kg until slaughter). For each son population, the virtual experiment settings were the same as those previously described, to simulate the responses. The performances of the 732 son populations were then obtained with this unique average feed, and for each parent pig, new performances were calculated as the average of its son population results.

Statistical analyses

Statistical analyses aimed at investigating the relationships between technical, environmental and economic performance indicators for each parent profile, and at analysing to what extent the ranking of the parent profiles is modified according to the level at which the feeds are formulated (i.e., parent profile or average profile) and the indicator considered (e.g., climate change impact per kg body weight and feed conversion ratio). First, to confirm our work hypothesis, pig rankings were compared for every indicator between the approach where the son populations are fed the average feed and our proposal to feed them individually-adjusted feeds. For that purpose, we computed Spearman rank correlations, which are adequate for testing a monotonic relationship between two variables, when the purpose is to highlight the potential reranking of individuals (Becker et al., 1988). All the following statistical analyses were only performed on the data obtained with individually-adjusted feeds. Pearson correlations obtained between all individual indicators were computed using R software (version 4.3.2) in order to understand their covariations, with all variables being normally distributed (normality was checked visually). Correlations between the environmental impacts of pigs (seven impacts), the economic indicators (five indicators) and the impacts of feeds (eight impacts) were represented with a principal component analysis (PCA function from FactoMineR package in R software (Lê et al., 2008)). A hierarchical clustering (HCPC function from the FactoMineR package in R software) was applied to all components of the principal component analysis to group pig profiles with similar economic and environmental performances. Ward's criterion was used to decompose the total variance (the sum of variances of all components from the principal component analysis) and aggregate individuals into clusters so that the total within-cluster multidimensional variance was minimised. The number of clusters retained was determined from the hierarchical tree calculated from the Euclidean distance matrix using Ward's method, with the higher relative loss of within-cluster inertia. For variables that were not included in the principal component analysis, the differences between clusters were tested on mean values with Welch-ANOVAs for unequal variances (function welch_anova_test of the library rstatix, R software (Kassambara, 2023)) followed by Tukey's test with a Bonferroni correction of the p-values for multiple outcomes (function glht of the library multcomp, R software (Hothorn et al., 2008)) to highlight differences in pig responses and feed, and to understand the main drivers of the environmental impacts.

Results

Average environmental and economic performances of the population

Descriptive statistics of the environmental, economic and technical performances of the 732 parent profiles are displayed in Table 1. For all environmental impacts, values were slightly dispersed around the mean, as indicated by coefficients of variation ranging between 3.92% and 8.06%. Acidification, freshwater and terrestrial eutrophication impacts varied the most compared to other impacts (CV > 7.00%). No major variation was observed for economic results (CV < 10.0%) or technical performances (CV < 9.87%). Selling prices were quite homogenous due to low variability in lean meat percentages and slaughter weights (CV = 3.30% and 2.83%, respectively). More heterogeneity was observed for total feed cost, in line with a greater variability in average daily gain (**ADG**) and average daily feed intake (**ADFI**) (CV = 9.10% and 8.73%, respectively). Consequently, gross margin varied the most among other economic indicators (CV = 9.92%).

To confirm that virtual populations were true representations of the experimental pigs (parent profiles), the consistency of the outcomes with real data obtained by Déru et al. (2020) on the same dataset was checked. For instance, ADG was, on average, 991g/d in the virtual populations with the mean of the standard deviations of the son populations equal to 107 g/d. In Déru et al. (2020) on the true experimental population, ADG was 1027 g/d with a standard deviation of 86 g/d. For feed conversion ratio (**FCR**), it was 2.52 ± 0.15 with experimental data, and in our study, the average mean was 2.41 and the mean of the standard deviations of the son populations was 0.16 kg/kg.

Rank correlations between individual feeding and group feeding

Rank correlations between performance indicators were obtained when the son populations were fed the average feed; individual feeds are presented in Table 2. Some consistency was found in the ranking of several indicators with the two feeding approaches: for economic and technical indicators, rank correlations exceeded 0.79 and 0.84, respectively. However, pigs ranked differently for all impact categories (rho < 0.92), and reranked more for climate change (CC), freshwater eutrophication (EUfreshw), fossil resource use (RU) and land use (LU) impacts (0.46 < rho < 0.82).

Correlations between environmental impacts and economic performances

The correlations between environmental impacts, economic results at the pig level and feed prices are shown in Supplementary Table S6. When used to represent the variables in a principal component analysis (Fig. 3), the factorial plan defined by the first two axes accounted for more than 89% of the dataset inertia, with the first axis representing 49.8% of the total inertia. All of the active variables significantly contributed to the plan (> 5.73%), largely above 1/21 (4.76%, 21 being the total number of variables). Variables with the greatest contributions to the first principal component were three environmental impacts per kg live body weight (CC: 7.10%; EUfreshw: 9.38%; RU: 6.12%), and all of the variables related to the feeds (feed cost: 6.90%; CC: 8.12%; AC: 7.90%; EUfreshw: 8.12%; EUter: 7.67%; marine eutrophication (EUmar): 7.62%; RU: 7.81%; LU: 7.62%), with the exception of water use (WU) impact (3.34%).

The second axis was driven by the economic variables (selling price: 9.73%; premium: 9.73%; margin: 11.31 %; revenue: 9.43%; total feed cost: 5.73%) and the other environmental impacts per kg of live body weight (AC: 9.23%; EUter: 9.48%; EUmar and LU: 8.20%), with a strong opposition between the economic and environmental indicators. Indeed, correlations (Supplementary Table S6) were generally negative between environmental impacts and economic indicators, from low (-0.05 for EUfreshw with the selling price) to high values (-0.88 for EUter with margin), except for feed cost, which had moderate to high positive correlations with all impacts (from 0.37 to 0.74). These results indicated that the higher the environmental impacts of a pig, the lower its selling price (per kg carcass), revenue and margin. On the other hand, high positive correlations were estimated between all environmental impacts per kg live body weight. Pairwise Pearson's correlations between environmental impacts per kg live body weight (Supplementary Table S7) ranged from 0.53 (between terrestrial and freshwater eutrophication impacts) to 0.99 (between EUmar and AC impacts).

All environmental impacts of feeds, except water use impact, were highly correlated with each other and with the feed cost (price per kg feed), with correlations ranging between 0.87 and 0.99. Water use impact was moderately correlated with other impacts (from 0.50 to 0.76) and feed cost (0.60). However, impacts of feeds showed moderate correlations with impacts per kg live body weight (from 0.03 to 0.64), except for EUfreshw (> 0.84).

Correlations between technical performances of pigs and their environmental impacts and economic results

The lean meat percentage (**LMP**) and mean protein deposition (**PD**) were highly and positively correlated with the economic indicators (selling price, premium, margin and revenue) (Fig. 3), with correlations ranging from 0.64 to 0.96 for LMP, and 0.50 to 0.97 for protein deposition, whereas the FCR had strongly negative correlations with these indicators, ranging from -0.81 to -0.97. More efficient pigs tended to depose more protein and less fat, thus having higher LMP, resulting in better selling prices and premiums with the French payment grid. Those pigs also had better environmental impacts per kg live body weight since negative correlations were estimated for LMP and protein deposition with all environmental impacts per kg live body weight (from -0.02 with EUfreshw to -0.76 with EUter). The FCR and nitrogen emissions were strongly positively correlated with all environmental impacts per kg live body weight, except EUfreshw (0.07 and 0.44), with Pearson's correlations ranging from 0.46 with CC to 0.86 with EUter for FCR, and between 0.67 and 0.93 for nitrogen emissions. The ADFI was moderately correlated with the environmental impacts of the pigs (from 0.06 with EUfreshw to 0.31 with EUter), and the margin (-0.20), highly correlated with the selling price and the premium (-0.68), and its correlations with revenue did not differ from 0 (*P* > 0.05). The total feed cost was highly correlated with ADFI (0.80) and FCR (0.60), and moderately with ADG (0.40) and slaughter weight (0.38). Thus, pigs that consumed less feed had a lower feed cost and were slaughtered heavier (*P* < 0.001), in relation to higher protein deposition. Environmental impacts of feeds were lowly to moderately correlated with the technical performances of pigs, with low correlations between -0.12 and 0.19 for ADFI and N emissions, and above 0.19 in absolute values for FCR, ADG, LMP, protein deposition, lipid deposition and P emissions.

Distribution of environmental and economic responses of pigs

A hierarchical ascending classification performed on principal component analysis results for environmental and economic performances of pigs and feeds distinguished three clusters of pigs (Fig. 4). Environmental impacts for 1 kg live body weight and 1 kg feed, as well as economic performances, varied between clusters (Table 3). The distributions of CC, AC, EUfreshw and RU impacts per kg of pig, as well as the revenue and the feed cost for all parent profiles are illustrated in Supplementary Fig. S2. Cluster 1 (blue in Fig. 4) included most of the pigs (n = 403), and Cluster 2 (n = 164) (yellow in Fig. 4) and Cluster 3 (n = 165) (red in Fig. 4) had similar numbers.

Environmental performances

Pigs in Cluster 1 were characterised by the lowest environmental impacts per kg of live body weight compared to Cluster 2 and Cluster 3 (Table 3 and Supplementary Figs. S3 and S4). On average, the environmental impacts of Cluster 1 were about 0.64 standard deviations below the average impacts of the whole population. In general, environmental impacts of feeds in Cluster 1 were intermediate between those of Clusters 2 and 3, except for EUfreshw that was similar to Cluster 2. Per kg live body weight, CC, EUfreshw and RU impacts were lower for Cluster 2 than

Cluster 3, but the highest for AC, EUter and EUmar impacts (Supplementary Figs. S3 and S4). Indeed, environmental responses to global (CC, RU) and local impacts (AC, EU) differed between clusters. Pigs in Cluster 2 were fed with lower impact feeds compared to other clusters. Pigs included in Cluster 3 had higher CC, EUfreshw, RU and LU impacts at the pig level compared to other clusters, and intermediate AC, EUter and EUmar impacts, as well as higher-impact feeds.

Economic performances

On average, Cluster 1, along with Cluster 3, displayed the best revenue compared to Cluster 2. The higher margin in Cluster 1 than in Cluster 3 was related to a difference in the feeding costs. The total feed cost of Cluster 1 was 0.47 standard deviations below the population. Pigs in Cluster 2 (n = 164) had the poorest economic results. The selling price was, on average, 11 and 10 centimes lower per kg carcass than Cluster 1 and Cluster 3, respectively, i.e., 1.27 standard deviations lower than the whole population. The margin and the revenue of Cluster 2 were around 1.34 and 1.22 standard deviations lower than the whole population. The total feed cost was higher than in the other two clusters (on average, €3.3 more per pig than Cluster 1 and €1.3 more than Cluster 3, i.e., 0.81 standard deviations lower than the whole population). Economic results for the selling price, the premium and the revenue of Cluster 3 (Table 3 and Supplementary Fig. S2) did not differ from Cluster 1. Pigs in Cluster 3 were associated with intermediate margins and total feed costs compared to the two other clusters.

Factors affecting the environmental and economic performances of the three clusters

The low CC, AC and EUfreshw impacts per kg live body weight of pigs in Cluster 1 resulted from the combination of low -impact feeds and low to intermediate FCR values (Supplementary Fig. S3). Environmental impacts of feeds from Cluster 1 did not exceed 0.51 kg CO_2-eq/kg feed for CC, 7.86 x 10^{-3} mol H^+-eq/kg feed for AC and 0.19 g P-eq/kg feed for EUfreshw, whereas the majority of feeds from Cluster 3 had impacts above those values. Feeds from Cluster 1 and Cluster 2 shared similar ranges of impacts. Pigs included in Cluster 1 were characterised by lower FCR ($P <$ 0.001, Table 4 and Supplementary Fig. S3) compared to Cluster 2, but not different from Cluster 3 ($P > 0.05$). They showed lower ADFI and nitrogen emissions than the other two clusters ($P < 0.05$), explaining their better environmental performances per kg live body weight. They also had higher ADG, LMP and slaughter weights than Cluster 2 ($P < 0.001$), but comparable to Cluster 3 (Table 4), in line with better economic results. For pigs with higher CC, AC and EUfreshw impacts per kg live body weight, two distinct patterns were observed (Supplementary Fig. S3): pigs in Cluster 2 had the lowest-impact feed but the highest FCR, whereas pigs in Cluster 3 had low to intermediate FCR but the highest-impact feeds. The similar technical results between pigs in Clusters 1 and 3 indicated that the highest impact values per kg live body weight of pigs in Cluster 3 were mainly due to high-impact feeds. Pigs in Cluster 3 also showed intermediate nitrogen emissions ($P < 0.001$, Table 4), which was another explanatory lever to the impacts of these pigs. In addition, they consumed more feed than other clusters, with the highest ADFI ($P < 0.001$). Contrary to Clusters 1 and 3, pigs in Cluster 2 had significantly worse FCR, ADG, ADFI, LMP, slaughter weights and nitrogen emissions ($P < 0.05$) on average, explaining their poor economic and environmental performances, despite low-impact feeds. The same observations were made for EUter, EUmar, RU and LU impacts (Supplementary Fig. S4).

Pig characteristics affecting environmental and economic performances in relation to feed characteristics

Growth profiles

Parameters a, BGompertz and PDm were properly projected in the first principal component analysis plan ($\cos^2 > 0.06$, Fig. 3), contrary to initial body weight and parameter b ($\cos^2 < 0.05$). The PDm of pigs was moderately and negatively correlated with all environmental impacts of pigs (from -0.24 to -0.57). Pigs with higher PDm had significantly lower nitrogen emissions (-0.35) and higher protein deposition (0.67), resulting in lower environmental impacts and better economic results (correlations ranging from 0.14 to 0.60). In particular, pigs in Cluster 1 had higher PDm than pigs in Cluster 3 ($P < 0.05$, Table 4), which had higher PDm than pigs in Cluster 2 ($P < 0.05$). Pigs with higher parameter values (Cluster 2) had significantly higher ADFI ($P < 0.001$), associated with higher feed costs ($P < 0.001$). No significant difference for the second parameter of the ingestion curve (b) was found between clusters ($P > 0.05$). Pigs in Cluster 3 had on average higher BGompertz values than Cluster 1 and Cluster 2 ($P < 0.001$), indicating a higher precocity of protein deposition.

Nutritional requirements of pigs and feed characteristics

Lysine requirements at the beginning of the growing phase were highly correlated with the environmental impacts of feeds (0.57 with WU and above 0.80 with other impacts), and lowly correlated with the impacts of pigs (< 0.25) and economic results (< 0.41), except for CC (0.48), EUfreshw (0.72) and RU (0.44). On average, pigs in Cluster 1 had intermediate lysine requirements compared to other clusters ($P < 0.001$), with the pigs in Cluster 3 having the highest ones ($P < 0.001$), around 10 to 11 g digestible lysine/kg feed (Supplementary Fig. S2), and pigs in Cluster 2 having on average the lowest ones ($P < 0.001$). Thus, pig profiles with feeds with the best impact values corresponded to pigs with lower nutritional requirements. In addition, feeds with the highest environmental impacts corresponded to feeds with higher lysine content, as indicated by correlations between impacts per kg of feed and lysine content above 0.80 (except 0.58 for WU impact), and higher crude protein content (correlations between impacts per kg of feed and crude protein content of feeds above 0.73 and 0.37 for WU impact). They were also the most expensive ones, with correlations between impacts per kg of feed and formula prices above 0.87 (0.60 for WU impact). Those results indicated that pigs with higher nutritional requirements would eat high-impact and high-price feeds, resulting in high impacts per live body weight.

Average feed composition

To understand the differences in environmental impacts between feeds in the three clusters, the formulas were analysed in more detail. The composition of feeds for the 732 profiles, sorted in ascending order according to the digestible lysine requirements of the pigs within a cluster at the start of the fattening period, is presented in Fig. 5. Mean values for each category of ingredients that differed between clusters are displayed in Table 5. Feeds corresponding to pigs from Cluster 3, with the highest environmental impacts, incorporated more soybean and sunflower meal, more synthetic amino acids (lysine, methionine, threonine and tryptophan), and less protein seeds (spring pea) and distiller's dried grains with solubles (**DDGS**) compared to other clusters (around 10% for both ingredients) ($P < 0.001$, Table 5): on average, they contained about 3.0 ± 2.2% soybean meal, 5.0 ± 1.3% sunflower meal, 7.0 ± 1.6% spring pea and 7.0 ± 1.1% DDGS. In comparison, feeds of Clusters 2 and 1 incorporated 3.0 ± 1.0% and 4.0 ± 0.1% sunflower meal, respectively, and less than 1% soybean meal. Incorporation of cereals did not differ between clusters, except for maize, which was more incorporated into the feeds of Cluster 3 ($P < 0.001$), and represented, on average, 51.0 ± 1.3% of the formulas (vs. 48.0 ± 1.9% and 49.0 ± 1.1% for Cluster 2 and Cluster 1, respectively). No major differences were found for other coproducts of cereals, with incorporation rates of around 1% for all clusters (wheat gluten feed, wheat bran, maize bran and wheat middlings). Higher-impact feeds incorporated more sunflower and soybean meals, which are high-impact feedstuffs, and less spring pea and cereal coproducts (DDGS, wheat middlings, wheat gluten feed) that are associated with lower environmental impacts (Supplementary Fig. S5).

Discussion

The methodological workflow developed in this study made it possible to simulate the technical, economic and environmental performances of individual pigs within a population, considering their specific growth profiles. With this approach, the relationships between pig characteristics, composition and environmental impacts of feed, as well as the associated economic results and the environmental impacts of pigs, were investigated in a conventional production system. On the basis of the outputs, we were able to determine that the feed conversion ratio and the environmental impacts of feeds have a major influence on the environmental results of pigs. For all impact categories, pigs with the lowest environmental impacts were among the most efficient ones, with moderate nutritional requirements, resulting in relatively low-impact feeds (Cluster 1). However, the most demanding pigs (pigs with the highest digestible AA requirements at the start of the fattening period) (Cluster 3) were found to be efficient as well, but to cover their digestible AA requirements, high-impact feedstuffs were recruited, resulting in a considerable environmental footprint. Similar economic results were obtained by efficient pigs in Cluster 1 and Cluster 3, highlighting a trade-off between economic and environmental performances for the most demanding pigs. For the less demanding pigs (pigs with the lowest digestible AA requirements at the start of the fattening period) (Cluster 2), the environmental benefit of their low-impact feeds was offset by poor feed efficiencies and protein deposition, resulting in higher global impacts than other pigs.

Simulating individual performances with feed covering individual requirements

Formulating feeds that cover 100% of the mean requirements of a population implies that the requirements of about 50% of the individuals are not met at the start of the feeding phase (Brossard et al., 2009). Since lysine requirements decrease over time, around 94% of the animals have their requirements met at the end of each feeding phase for a two-phase feeding strategy (Brossard et al., 2009). Consequently, only the most demanding pigs will still have a digestible AA supply lower than their requirements. Depending on the level and duration of the digestible AA supply deficit, some pigs may not be able to compensate for it. Consequently, these pigs cannot express their growth potential, affecting their growth performances (ADG, FCR, protein-to-lipid deposition ratio) and their resulting environmental indicators (Le Floc'h et al., 2014; Poullet et al., 2019). Our results confirm the initial hypothesis, i.e., that the ranking of pigs according to their environmental performances is affected by the level at which feeds are formulated (group vs. individual), since reranking was observed for the seven impact categories. Reranking was mainly associated with Cluster 3, for which the individual feeds differed the most from the average ones (Supplementary Fig. S6). The increased reranking for CC, EUfreshw, RU and LU impacts can be related to higher sensitivity of these impacts to feed production and transport (Supplementary Table S8). Thus, it is necessary to fully cover each pig's digestible amino acid requirements in order to assess the individual environmental performance.

Simulating performances of actually tested pigs

The methodological approach proposed in this study aims to evaluate the individual environmental impacts of real pigs, provided that their growth and ingestion profiles are known. To obtain individual performances for each profile, small virtual son populations were simulated, using parameters derived from the existing phenotypic variability of the initial population. In agreement with previous works (Ali et al., 2018; Monteiro et al., 2021), adjusted growth profiles were used to simulate feed intake, protein and lipid deposition of each pig, considering dietary nutritional composition and the resulting growth and excretion. The resulting simulated technical and economic performances were consistent with technical data recorded in growing-finishing French farms (IFIP, 2016) and previous simulation studies (Cadéro et al., 2018). The centesimal composition of average feeds was comparable to those of commercial feeds formulated in 2021 (IFIP, 2019-2021). Orders of magnitude of environmental impacts (per kg live body weight) were comparable with published studies reviewed in Gislason et al. (2023). The approach is then robust to capture the variability of individual responses in a large population, offering options to sort pigs according to all their performances. Among the entire experimental population, it was not possible to evaluate the performance of 16% of the individuals. This may have slightly affected the ability to represent the population variability, but the final dataset included pigs with requirements ranging from 0.61 g lysine/MJ NE (5.95 g lysine/kg feed) to 1.11 g lysine/MJ NE (10.9 g lysine/kg feed), which was consistent with the data in the literature (Brossard et al., 2009; Hauschild et al., 2010; Remus et al., 2020). Especially, pigs with requirements above 10.9 g digestible lysine/kg feed would probably have had similar responses to those in Cluster 3.

In our simulations, one context of prices was simulated. Feed ingredient prices corresponded to values averaged from 2019 to 2021, which prevented the risk of picking a context specific to extreme marginal fluctuations. However, the variability in feed ingredient prices has a major effect on the centesimal composition of feeds formulated on a least-cost basis principle (Mackenzie et al., 2016). Prices can soar differently for different types of ingredients because price variations are the result of various factors: the demand from the food sector or other livestock sectors and for biofuel production, the competition for arable land, lower crop yields due to climate change and political crises (Woyengo et al., 2014). Depending on the ingredients impacted by a price fluctuation and the extent of the fluctuation, pigs may be differently affected by changes in feed compositions. For instance, if the price of oilseed meals rises, alternative sources of protein would be recruited to replace soybean, sunflower and rapeseed meals in feed formulas. In this situation, pigs in Cluster 3 would be more impacted than pigs in Cluster 1 since meals represent a greater proportion of their feeds. Since feed has a major effect on the environmental impacts of pigs, it can lead to possible reranking. A question to be addressed in a future work is therefore: How sensitive is pig ranking on environmental performances to changes in ingredient prices? It would be relevant in a future work to evaluate the sensitivity of the model outcomes to such variations.

The most efficient pigs may not be the most environmentally-friendly

Few previous studies have carried out individual life cycle assessments to explore correlations between environmental impacts and performance traits. Soleimani and Gilbert (2020) reported moderate to high correlations between environmental impacts (global warming potential, AC, EU and land occupation) and FCR. Monteiro et al. (2021) captured even higher correlations between impacts (CC, AC, EU, land occupation) and FCR (> 0.99). These findings suggested that efficient pigs always have lower environmental impacts and better economic results than less efficient ones. In our study, environmental impacts were more moderately correlated with FCR since pigs with similar technical performances could have contrasted environmental impacts (Cluster 1 and Cluster 3). Covering the AA requirements of the most demanding pigs at the beginning of each feeding phase led to highest incorporations of feedstuffs with high environmental impacts (Wilfart et al., 2016) and to a greater contribution of feed to the environmental impacts expressed per unit of kg live body weight. In that case, feed efficiency can be offset by high nutritional requirements. In line with Méda et al. (2021), less efficient pigs (Cluster 2) had the poorest environmental performances despite the use of feed with a lower environmental impact to meet their requirements. This result suggests that the environmental benefits of low impact diets may be offset by poor feed efficiency potential. Individuals with the highest economic indicators (Cluster 1 and Cluster 3) had on average lower FCR. However, Cluster 3 displayed significant environmental impacts and a slightly reduced margin compared to Cluster 1, in relation with higher feed costs. Our results highlight the fact that the most efficient pigs with moderate nutritional requirements have the best environmental and economic performances in a conventional system. They confirm that a trade-off between the production, economic and environmental dimensions of the multiperformance should be considered. In combination with digestible AA requirements, higher BGompertz values in Cluster 3 compared to Cluster 1 correspond to higher precocity of protein deposition and faster development. Besides having different nutritional requirements at the start of the growing phase, the two clusters also had different trajectories of their requirements during growth: Cluster 3 had a faster decline of lysine requirements than Cluster 1. We can suppose that the environmental performances may be adversely affected by the precocity of the pigs, which cannot be reflected in the technical performances calculated over the whole fattening period. Growing feeds usually have higher environmental impacts than finishing feeds (van der Werf et al., 2005). Early maturing pigs ate different proportions of growing over finishing feed than late maturing pigs: On average, Cluster 3 had a lower proportion of growing feed than Cluster 1 and Cluster 2. Differences in the dynamics of nutritional requirements may accentuate the heterogeneity between pigs in terms of environmental impacts linked to feed.

Cluster 3 was also characterised by intermediate PDm and N emissions compared to the other two clusters. The digested proteins supplied by feed are converted into amino acids used for protein synthesis, with some losses in urine, especially when supplied in excess. For a given intake, higher protein deposition is then linked to lower nitrogen emissions and lower environmental impacts (Monteiro et al., 2021), which is consistent with our results. In addition to feed efficiency, traits related to protein deposition are thus also important features to consider in an evaluation procedure to determine the most environmentally-friendly pigs since efficient pigs with moderate protein deposition potential will result in higher environmental impacts when fed high-quality feeds.

The identification of three different clusters of pigs, based on economic and environmental results at feed and animal levels, revealed that a significant environmental footprint can be achieved by different combinations of animal- and feed-related factors depending on the impact categories. Efficient pigs in Cluster 3 had the poorest values for CC, EUfreshw and RU impacts (per kg live body weight and kg feed), but intermediate values of AC, EUter and EUmar impacts. The highest values of AC, EUter and EUmar impacts were reached by the less efficient pigs of Cluster 2, with feeds characterised by lowest impacts. These results can be explained by different contributions of feed, housing and manure management to CC, EUfreshw and RU impacts vs. AC, EUter and EUmar. Indeed, the last ones were more sensitive to emissions occurring at housing and during manure storage than emissions from feed production and transport (Supplementary Table S8), as previously shown by McAuliffe et al. (2017) and Ottosen et al. (2020).

Due to the reranking of pigs between impacts, the choice of a unique score (choice of impacts and their weightings) to characterise a global environmental performance is complex. Further work is needed to find a robust metric since no consensus has yet been established in the literature (Mackenzie et al., 2016).

Future applications

Testing pig responses to different feeding strategies

Changes in the profile of feed resources available for pig farming have already been observed over the past years, in response to multiple issues related to the mitigation of the environmental impacts of the livestock sectors, maintaining the competitiveness of farms in terms of the competition between food, feed and fuel. This has led to the incorporation into pig rations of more locally-produced resources (Sasu-Boakye et al., 2014), coproducts of cereals (Shurson et al., 2022), and forage on organic farms, supported by European legislation (Åkerfeldt et al., 2019). In parallel, a global framework has been initiated to redesign current agricultural models for more sustainable food systems (Dumont et al., 2019; Rauw et al., 2020). These prospective studies suggest major changes in feed formulas, such as replacing imported plant proteins for animal feed by alternative protein sources (Stødkilde et al., 2023), or feeding pigs with by-products that are non-edible for humans (Karlsson et al., 2017; van Hal et al., 2019). The individual environmental responses of pigs currently fed with these new formulas need to be assessed. Judging from our study, it seems that the most demanding pigs may have a greater potential for impact reduction in future systems that promote low-impact resources, as opposed to less demanding pigs. Provided that these alternative low-impact feed resources can cover their high digestible AA requirements, such feeding resources could be used to lower the impacts of the most demanding pigs. Since less demanding pigs can already be fed with low-impact feeds in conventional systems, these different options for improvement can lead to the possible reranking of individual pigs between systems. The model could also be used to test the impact of multi-phase feeding strategies on the variability of pig response since, in this case, pig requirements are met more often than with a two-phase feeding strategy.

Genetic selection

Current selection objectives in pigs include large weights on feed efficiency, among other traits. Our results suggest that some efficient pigs, likely to be used as future breeding stock, would have considerable environmental impacts. A main issue will then be to distinguish them from the best pigs on the basis of both production and environmental criteria (Cluster 1), implying the necessity of having access to their performance for traits not routinely assessed, in order to achieve more sustainability. Dedicated genetic analyses will be needed to evaluate whether or not specific environmental weights are needed in addition to the usual traits used in breeding indexes to sort out the differences between pigs from Clusters 1 and 3.

In addition, as more diversified pig breeding and feeding systems are expected in the future (van der Heide et al., 2021; Zijlstra and Beltranena, 2022), further work is needed to identify if the best pigs in a conventional system remain the best in other production systems, such as organic farming and locally-based feeding strategies. If those best pigs were not the best in other systems, it would indicate genotype-by-system interactions, leading to the potential revision of selection strategies to address the challenge of reranking economic and environmental performances across farming systems.

Ethics approval

The experimental data were obtained in a trial conducted in accordance with the French legislation on animal experimentation and ethics. The certificate of Authorization to Experiment on Living Animals was issued by the French Ministry of Higher Education, Research and Innovation to conduct this experiment under reference number 2017011010237883 at INRA UEPR – France Génétique Porc phenotyping station (UE 3P. 2018 - https://doi.org/10.15454/1.5573932732039927E12, Le Rheu, France).

Data and model availability statement

The scripts of the model that support the study findings and input files to perform the simulations described in this paper are publicly accessible on the repository Hal Inrae (https://hal.inrae.fr/hal-05038622). Launching the file 'Simulations_parallelization_code.R' using R software will reproduce the simulation outputs, and the final database is obtained with the file 'Data_simu.R'. Information can be made available from the authors upon request.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors did not use any artificial intelligence-assisted technologies in the writing process.

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Declaration of interest

None.

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Tables

Table 1

Environmental impacts per kg live BW and economic results of pigs (mean, SD and coefficient of variation of performances averaged over the 732 parent profiles).

Simulated performances	Mean	SD	CV (%)
Environmental impacts (per kg live BW)			
Climate change (kg CO_2-eq)	1.87	0.095	5.07
Acidification (mol H^+-eq x 10^{-3})	45.4	3.39	7.47
Freshwater eutrophication (g P-eq)	0.41	0.032	8.06
Terrestrial eutrophication (mol N-eq x 10^{-3})	0.20	0.015	7.55
Marine eutrophication (g N -eq)	12.2	0.53	4.38
Resource use (MJ)	15.3	0.6	3.92
Land use (Point)	161	6.7	4.20
Economic results			
Price (€/kg carcass)	1.48	0.063	4.24
Premium (€/kg carcass)	0.05	0.063	-[a]
Margin (€/pig)	93.9	9.32	9.92
Revenue (€/pig)	211	8.2	3.88
Total feed cost (€/pig)	54.6	2.58	4.73
Technical performances			
FCR (kg feed/kg live BW)	2.41	0.131	5.44

ADG (kg/day)	0.99	0.090	9.10
ADFI (kg feed/day)	2.39	0.208	8.73
Lean meat percentage (%)	57.4	1.90	3.30
Slaughter weight (kg)	124	3.5	2.83
N excreted (kg/pig)	2.90	0.286	9.87
P excreted (kg/pig)	0.49	0.047	9.71

Abbreviations: FCR = feed conversion ratio; ADG = average daily gain; ADFI = average daily feed intake.

[a] Premium had a mean close to zero as it can take negative and positive values, which is not appropriate to extract a meaningful coefficient of variation.

Table 2

Spearman rank correlations of environmental impacts, technical performances and economic results between pigs when fed with feeds covering their specific nutritional needs and when fed with a unique feed formulated to cover the nutritional needs of the average profile.

	Spearman correlation	95% Confidence Interval	
Performances		Lower limit	Upper limit
Environmental impacts (per kg live BW)			
Climate change (kg CO_2-eq)	0.70	0.66	0.75
Acidification (mol H^+-eq x 10^{-3})	0.92	0.90	0.93

Freshwater eutrophication (g P-eq)	0.46	0.39	0.52
Terrestrial eutrophication (mol N-eq x 10^{-3})	0.92	0.90	0.94
Marine eutrophication (g N -eq)	0.88	0.86	0.90
Resource use (MJ)	0.76	0.72	0.79
Land use (Point)	0.82	0.79	0.85
Economic results			
Price (€/kg carcass)	0.91	0.89	0.93
Premium (€/kg carcass)	0.91	0.89	0.93
Margin (€/pig)	0.85	0.83	0.88
Revenue (€/pig)	0.79	0.75	0.82
Total feed cost (€/pig)	0.92	0.90	0.94
Technical performances			
FCR (kg feed/kg)	0.84	0.81	0.87
ADG (kg/day)	0.91	0.89	0.91
ADFI (kg feed/day)	0.99	0.99	0.99
Lean meat percentage (%)	0.91	0.88	0.92
Slaughter weight (kg)	0.91	0.89	0.92
N excreted (kg/pig)	0.92	0.90	0.93

P excreted (kg/pig)	0.85	0.82	0.88

Abbreviations: FCR = feed conversion ratio; ADG = average daily gain; ADFI = average daily feed intake.

Table 3

Means and SDs of averaged environmental performances (per kg live BW and per kg feed) and averaged economic results (per pig or per kg carcass) of each son population of the three clusters built by hierarchical clustering.

	Cluster 1 n = 403		Cluster 2 n = 164		Cluster 3 n = 165	
item	Mean	SD	Mean	SD	Mean	SD
Environmental impacts (per kg live BW)						
CC (kg CO_2-eq)	1.80	0.048	1.92	0.061	1.97	0.078
AC (mol H^+-eq x 10^{-3})	43.3	1.84	49.1	2.58	46.7	3.12
EUfreshw (g P-eq)	0.39	0.015	0.41	0.019	0.45	0.024
EUter (mol N-eq x 10^{-3})	0.19	0.008	0.22	0.011	0.20	0.014
EUmar (g N -eq)	11.9	0.29	12.8	0.40	12.5	0.47
RU (MJ)	14.9	0.33	15.6	0.44	15.9	0.51

LU (Point)	157	3.5	167	5.1	167	5.7
Environmental impacts (per kg feed)						
CC (kg CO_2-eq)	0.44	0.025	0.43	0.023	0.54	0.043
AC (mol H^+-eq x 10^{-3})	7.50	0.128	7.44	0.130	8.00	0.202
EUfreshw (g P-eq)	0.16	0.010	0.16	0.010	0.20	0.015
EUter (mol N-eq x 10^{-3})	32.1	0.453	31.9	0.461	33.8	0.718
EUmar (g N -eq)	4.89	0.101	4.85	0.089	5.20	0.131
RU (MJ)	5.11	0.163	5.00	0.190	5.67	0.235
LU (Point)	69.9	1.83	69.1	1.710	75.5	2.14
WU (m^3)	1.76	0.030	1.74	0.060	1.82	0.036
Economic results						
Price (€/kg carcass)	1.51	0.037	1.40	0.059	1.50	0.050

Premium (€/kg carcass)	0.08	0.037	-0.03	0.059	0.07	0.050
Margin (€/pig)	98.2	5.48	81.4	7.47	96.0	7.27
Revenue (€/pig)	214	5.4	201	7.54	214	5.73
Total feed cost (€/pig)	53.4	1.68	56.7	2.79	55.4	2.5

Abbreviations: CC = Climate change; AC = Acidification; EUfreshw = Freshwater eutrophication; EUter = Terrestrial eutrophication; EUmar = Marine eutrophication; RU = Resource use (fossils); LU = Land use; WU = Water use.

Table 4

Least Squares Means (LSMean) and SEs of averaged pig growth profile parameters and technical results of each son population of the three performance clusters built by hierarchical clustering.

	Cluster 1	Cluster 2	Cluster 3
	n = 403	n = 164	n = 165

Item	LSMean	SE	LSMean	SE	LSMean	SE	RMSE	Adjusted *P*-values[1]
Technical performances								
FCR (kg feed/kg)	2.36^{a}	0.004	2.59^{b}	0.007	2.37^{a}	0.007	0.092	< 0.001
ADG (kg/day)	0.99^{b}	0.004	0.96^{a}	0.007	1.01^{b}	0.007	0.088	< 0.033
ADFI (kg feed/day)	2.34^{a}	0.010	2.49^{c}	0.016	2.40^{b}	0.016	0.200	< 0.010
Lean meat percentage (%)	58.1^{b}	0.07	55.1^{a}	0.11	58.1^{b}	0.11	1.41	< 0.001
Slaughter weight (kg)	124^{b}	0.2	122^{a}	0.3	124^{b}	0.3	3.4	< 0.001
Pig emissions and nutritional requirements								
Lysine requirement[2] (g/kg feed)	8.95^{b}	0.033	8.53^{a}	0.052	10.2^{c}	0.052	0.665	< 0.001
N excreted (kg/pig)	2.74^{a}	0.011	3.21^{c}	0.017	2.98^{b}	0.017	0.212	< 0.001
P excreted (kg/pig)	0.47^{a}	0.002	0.55^{b}	0.003	0.47^{a}	0.003	0.034	< 0.001
Growth profile parameters								

A	4.21^{a}	0.030	4.72^{b}	0.047	4.33^{a}	0.047	0.600	< 0.001
B	13.7^{a}	0.17	13.9^{a}	0.27	14.2^{a}	0.27	3.45	> 0.568
PDm (g/day)	166^{c}	0.7	153^{a}	1.1	162^{b}	1.1	14.2	< 0.006
BGompertz (10^{-3}/day)	11.3^{a}	0.22	13.3^{b}	0.34	12.6^{b}	0.34	4.31	< 0.006
Initial BW (kg)	30.0^{b}	0.21	28.8^{a}	0.33	29.2^{a,b}	0.33	4.22	0.005

Abbreviations: FCR = Feed conversion ratio; ADG = Average daily gain; ADFI = Average daily feed intake; N = Nitrogen; P = Phosphorus; A and B = two parameters describing the feed intake curve; BGompertz = shape parameter of the Gompertz function for protein deposition; PDm = Mean protein deposition.

[1] Welch's one-factor ANOVA followed by Tukey's test were performed on each variable; the *P*-values correspond to the adjusted *P*-values with a Bonferroni adjustment analysis of multiple outcomes (multiplication factor of 39; three comparisons per indicator).

[2] Digestible lysine requirement at the beginning of fattening at 70 days of age.

[a,b,c] Values within a row with different superscripts differ significantly at $P < 0.05$ according to Tukey's test.

Table 5

Least Squares Means (LSMean) and SEs of feedstuff incorporation rates (kg/kg feed) in feeds formulated for parent pig profiles of the three clusters built by hierarchical clustering.

	Cluster 1 n = 403		Cluster 2 n = 164		Cluster 3 n = 165			
Item	LSMean	SE	LSMean	SE	LSMean	SE	RMSE	Adjusted *P*-values[1]
Maize grain	0.49^{b}	0.001	0.48^{a}	0.001	0.51^{c}	0.001	0.014	< 0.001
Triticale	0.10^{a}	< 0.001	0.10^{a}	< 0.001	0.10^{a}	< 0.001	0.000	> 0.176
DDGS	0.10^{b}	0.001	0.10^{b}	0.001	0.07^{a}	0.001	0.007	< 0.001
Wheat middlings	0.10^{b}	< 0.001	0.09^{b}	< 0.001	0.10^{a}	< 0.001	0.003	< 0.001
Wheat gluten feed	$< 0.001^{a}$	0.001	0.01^{b}	0.001	0.00^{a}	0.001	0.010	< 0.001

Wheat bran	0.01^{b}	< 0.001	0.01^{b}	0.001	< 0.01a	0.001	0.007	< 0.001
Spring pea	0.10^{b}	< 0.001	0.10^{b}	0.001	0.07^{a}	0.001	0.012	< 0.001
Rapeseed meal	0.00^{b}	< 0.001	0.00^{b}	< 0.001	0.001^{a}	< 0.001	0.001	< 0.001
Soybean meal	$< 0.01^{a}$	0.001	$< 0.01^{a}$	0.001	0.03^{b}	0.001	0.010	< 0.001
Sunflower meal	0.04^{b}	0.001	0.03^{a}	0.001	0.05^{c}	0.001	0.010	< 0.001

Abbreviations: DDGS = Dried distillers' grains with solubles from wheat distillation.

Only ingredients with incorporations above 1% are displayed.

[1] Welch's one-factor ANOVA followed by Tukey's test were performed on each variable; the *P*-values correspond to the adjusted *P*-values with a Bonferroni adjustment analysis of multiple outcomes (multiplication factor of 81; three comparisons per ingredient).

[a,b,c] Values within a row with different superscripts differ significantly at $P < 0.05$ according to Tukey's test.

Figure captions

Fig. 1. Distributions of digestible lysine requirements at the beginning of fattening of a parent population with emphasis on pig A (red) and pig B (black) (Option 0) and comparison of relative distributions of digestible lysine requirements of populations centred on pigs A and B with feeds formulated for each pig (Option 1) or feeds formulated for the average pig of the parent population (Option 2).

Abbreviations: NE = net energy.

Fig. 2. Diagram of the methodological approach used to assess technical, economic and environmental performances of each fattened pig within a database of N individuals using longitudinal experimental data for growth and feed intake; rectangular boxes with thick lines represent outputs of the simulation model; rectangular boxes with thin lines represent inputs of the simulation model; rectangular boxes with dashed lines represent the simulation models.

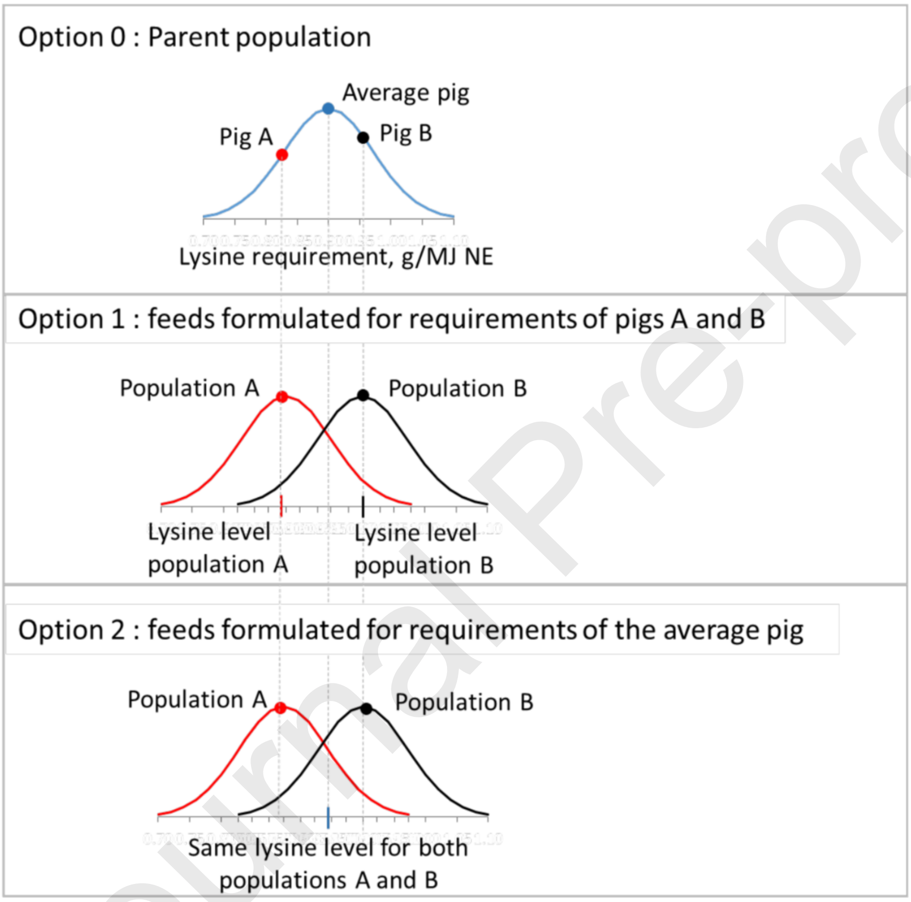
Abbreviations: ADFI = daily feed intake.

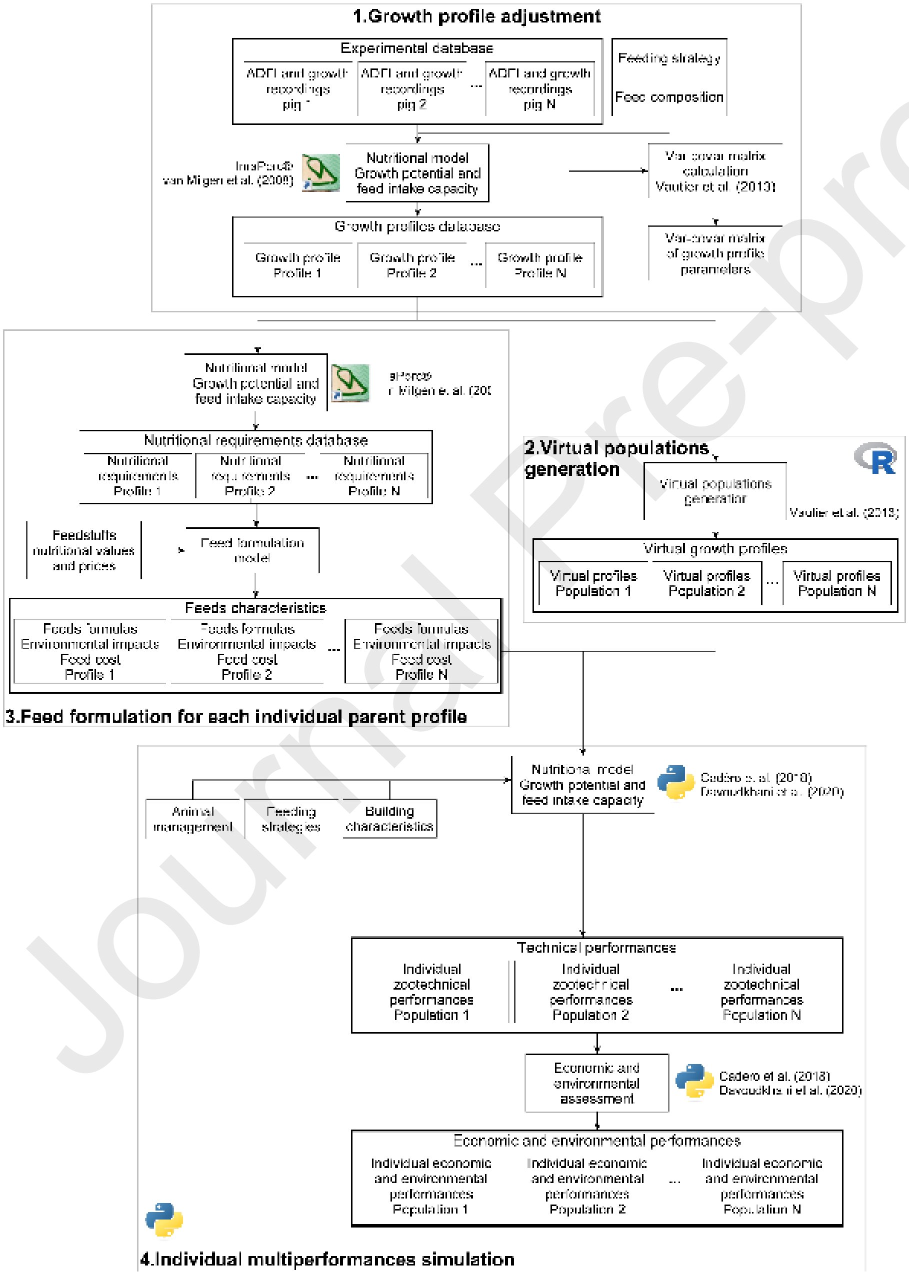
Fig. 3. Correlation circles in the two-first-axes-dimensional space of the principal component analysis runs on economic and environmental performances of pigs and environmental impacts of feeds (n = 732: mean value of 732 virtual populations), with explanatory variables associated with growth profiles and growth performance. Solid black arrows represent active variables (TotFeed_cost: price per kilogram of feed multiplied by total feed intake; CC_kgLBW: climate change impact per kg live BW; AC_kgLBW: acidification potential per kg live BW; EUfreshw_kgLBW: freshwater eutrophication potential per kg live BW; EUter_kgLBW: terrestrial eutrophication potential per kg live BW; EUmar_kgLBW: marine eutrophication potential per kg live BW; RU_kgLBW: use of fossil resources per kg live BW; LU_kgLBW: land use impact per kg live BW; CC_feed: climate change impact per kg feed; AC_feed: acidification potential per kg feed; EUfreshw_feed: freshwater eutrophication potential per kg feed; EUter_feed: terrestrial eutrophication potential per kg feed; EUmar_feed: marine eutrophication potential per kg feed; RU_feed: use of fossil resources per kg feed; LU_feed: land use impact per kg feed; WU: water use in m^3 per kg feed; Feed_cost: price per kg feed). Blue dotted arrows represent explanatory variables with $\cos^2 > 0.06$ (ADFI: average daily feed intake; DFI = daily feed intake; Lysreq: digestible lysine requirement per MJ of net energy at the beginning of the growing phase; PD: protein deposition in kg/pig; N_emit: nitrogen emissions in kg/pig; FCR: feed conversion ratio; LMP: lean meat percentage; A: parameter of the gamma function predicting ADFI from BW; BGomp: precocity parameter of the Gompertz function predicting protein deposition; PDm: mean PD).

Fig. 4. Projection of individuals in the two-dimensional space of the principal component analysis run on the economic and environmental performances of pigs (n = 732). Individuals are coloured according to clusters resulting from the hierarchical

ascendant clustering performed on the principal component analysis (pigs in Cluster 1 in blue, Cluster 2 in yellow and Cluster 3 in red).

Fig. 5. Composition of feeds (average growing-finishing feeds) formulated at least-cost for each of the 732 pig profiles in the simulated conventional system. Profiles were sorted along the x-axis according to the digestible lysine requirements of the pig at the start of the fattening period within cluster, from low values (left) to higher values (right).




1.Growth profile adjustment
Experimental database
ADFI and growth recordings pig 1
ADFI and growth recordings pig 2
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ADFI and growth recordings pig N
Feeding strategy
Feed composition
InraPorc®
van Milgen et al. (2008)
Nutritional model Growth potential and feed intake capacity
Var-covar matrix calculation Vautier et al. (2013)
Growth profiles database
Growth profile Profile 1
Growth profile Profile 2
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Growth profile Profile N
Var-covar matrix of growth profile parameters
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Nutritional requirements database
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Nutritional requirements Profile N
Feedstuffs nutritional values and prices
Feed formulation model
Feeds characteristics
Feeds formulas Environmental impacts Feed cost Profile 1
Feeds formulas Environmental impacts Feed cost Profile 2
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3.Feed formulation for each individual parent profile
2.Virtual populations generation
Virtual populations generator
Vautier et al. (2013)
Virtual growth profiles
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Cadéro et al. (2018)
Davoudkhani et al. (2020)
Animal management
Feeding strategies
Building characteristics
Technical performances
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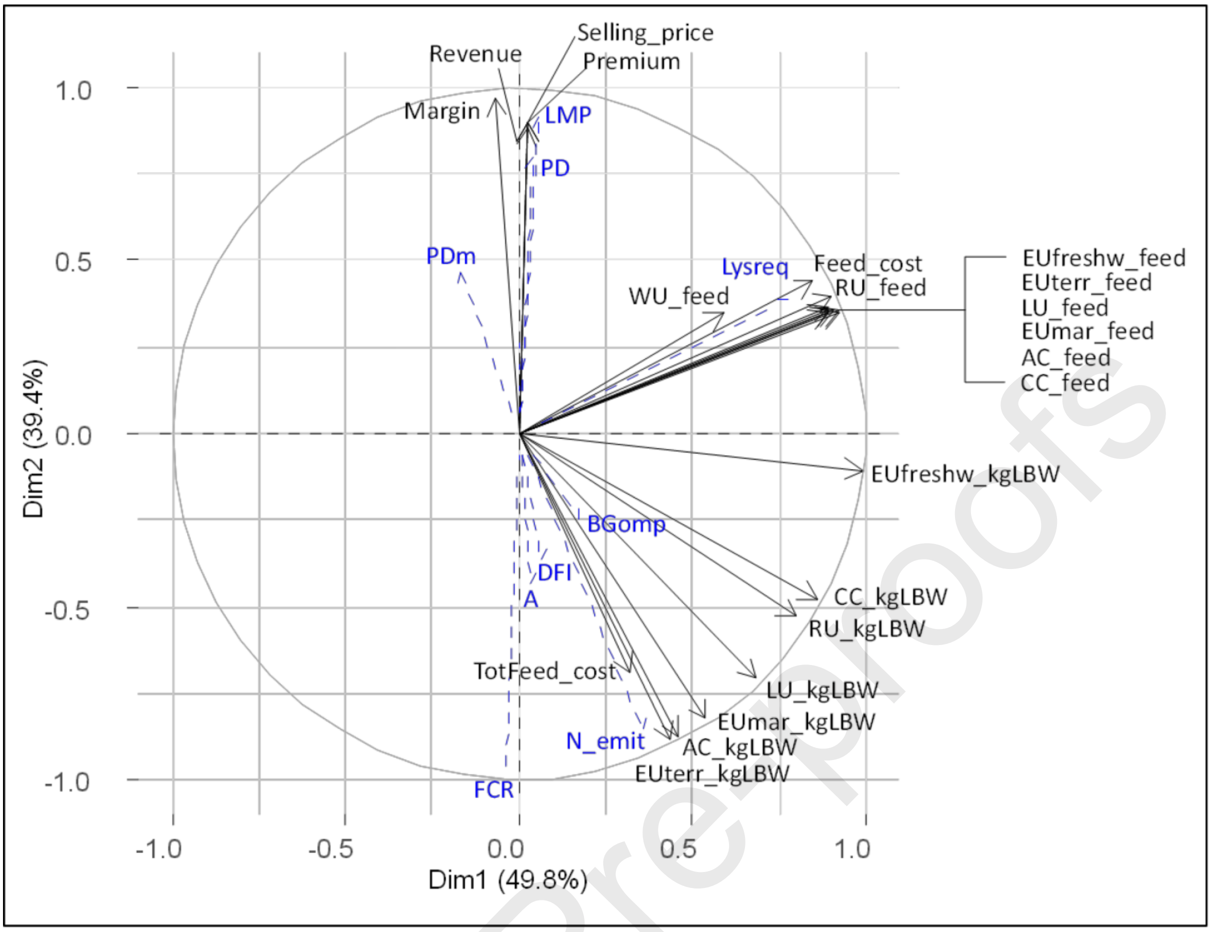
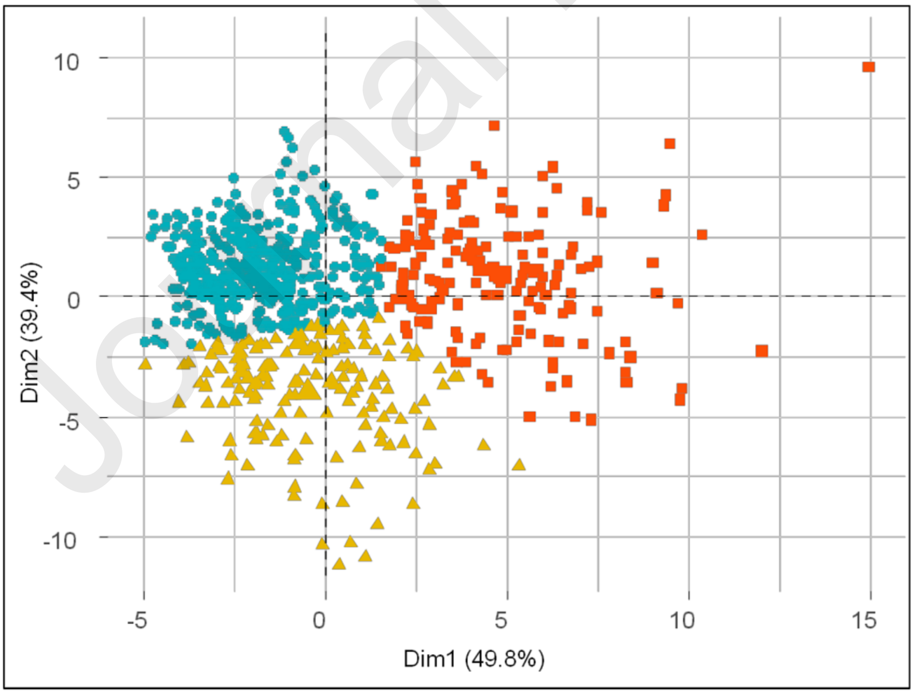
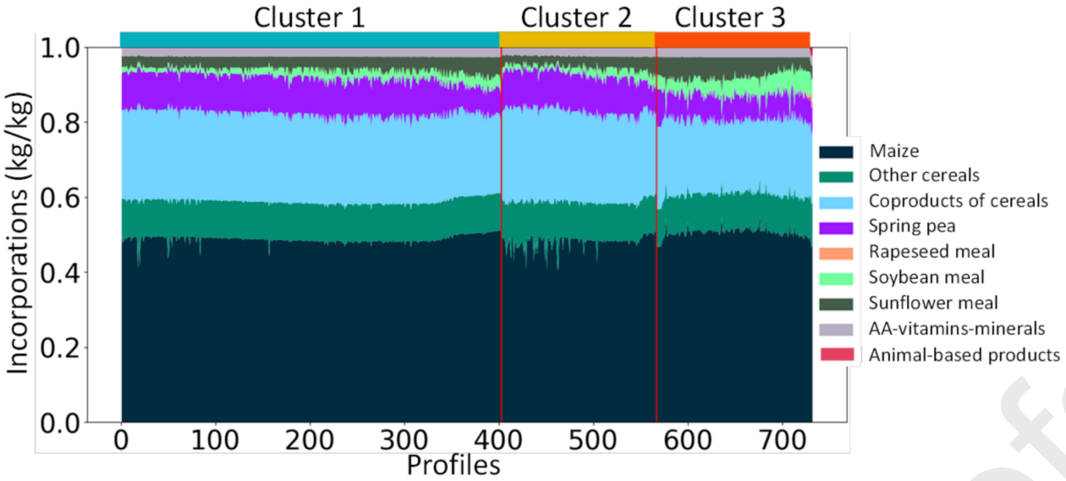
Individual zootechnical performances Population N
Economic and environmental assessment
Cadéro et al. (2018)
Davoudkhani et al. (2020)
Economic and environmental performances
Individual economic and environmental performances Population 1
Individual economic and environmental performances Population 2
...
Individual economic and environmental performances Population N
4.Individual multiperformances simulation


Selling_price
Premium
Revenue
Margin
LMP
PD
PDm
Lysreq
Feed_cost
RU_feed
WU_feed
EUfreshw_feed
EUterr_feed
LU_feed
EUmar_feed
AC_feed
CC_feed
EUfreshw_kgLBW
BGomp
DFI
A
CC_kgLBW
RU_kgLBW
TotFeed_cost
LU_kgLBW
EUmar_kgLBW
N_emit
AC_kgLBW
EUterr_kgLBW
FCR
1.0
0.5
0.0
-0.5
-1.0
Dim2 (39.4%)
-1.0
-0.5
0.0
0.5
1.0
Dim1 (49.8%)


10
5
0
-5
-10
Dim2 (39.4%)
-5
0
5
10
15
Dim1 (49.8%)


Cluster 1
Cluster 2
Cluster 3
Incorporations (kg/kg)
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
600
700
Profiles
Maize
Other cereals
Coproducts of cereals
Spring pea
Rapeseed meal
Soybean meal
Sunflower meal
AA-vitamins-minerals
Animal-based products