Changes in the Environmental Impacts of Pig Production Systems in Great Britain over the last 18 Years

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Abstract:	The aims of global pig production systems include a reduction of their environmental impacts, which can be achieved through an increase in outputs whilst minimising inputs. The aim of this paper was to develop a novel method to enable estimation of the changes in the environmental impacts based on sparse data from the British pig production industry over ~20 years. To achieve this, we developed a Life Cycle Assessment (LCA) method capable of dealing with sparse historical data from livestock systems. We applied it, for the first time, to estimate the temporal changes in environmental impacts of British pig production systems caused by changes in production performance. Performance data available from industry-held databases for indoor and outdoor bred pigs in Britain were used to estimate nutrient requirements through animal performance modelling, and feed composition through least-cost formulation. The cradle to farm-gate LCA model developed, included manure management and the full life cycle of the pigs and its functional unit was 1 kg of live weight pig at farm-gate. Sensitivity analyses were conducted to investigate the potential influence of changes in animal performance and feed prices on the estimated changes in environmental impacts. The higher growth rates and increased leanness over the period considered led to substantial reductions in energy requirements. Overall, the system changes led to reductions, for indoor and outdoor bred systems respectively, of 37.0 % and 35.4 % for Global Warming Potential, 21.2 % and 16.4 % in Terrestrial Acidification Potential, 22.5 % and 22.3 % in Freshwater Eutrophication Potential, 15.8 % and 16.8 % in Agricultural Land Use and 16.5 % and 16.1 % in Fossil Resource Scarcity. The sensitivity analyses showed that trends in feed composition were influential on the environmental impact outcomes, and that the LCA model was more sensitive to the change in feed composition than to the changes in animal performance over the time period considered. Knowledge of temporal changes to the environmental impacts of livestock systems and the drivers of changes to date should guide future decisions to mitigate these impacts.
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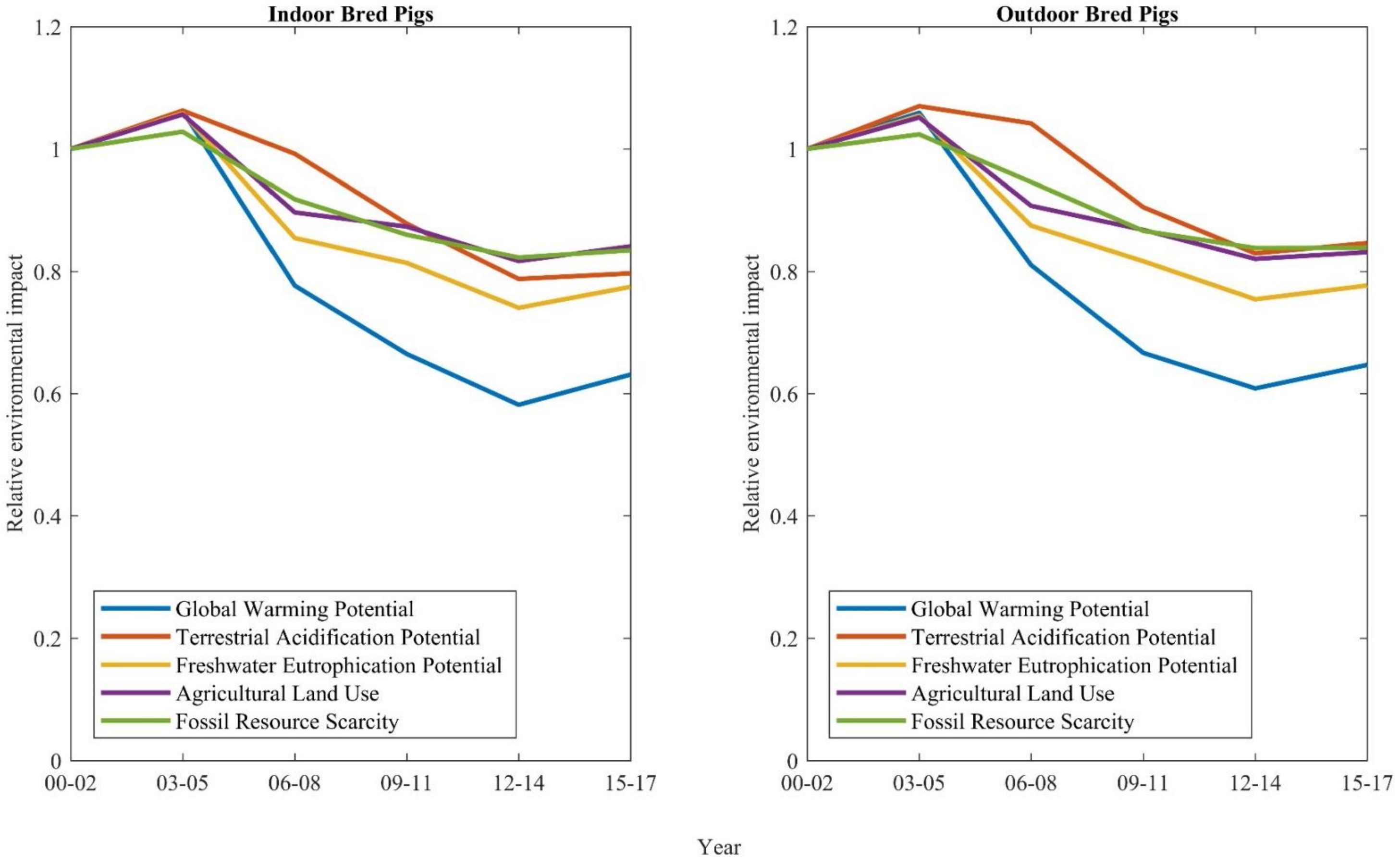
Highlights

- Livestock systems, including pig production need to reduce their environmental impacts to ensure long-term sustainability
- We aimed to develop a method to estimate the changes in environmental impacts of British pig production over 18 years from sparse historical data
- All environmental impacts were reduced, including a 37%/35% reduction in Global Warming Potential for indoor and outdoor bred pigs respectively
- The LCA model was more sensitive to changes in feed composition over time than changes in animal performance
- Historical LCA studies can aid decision making to reduce impacts from livestock systems by analysing the consequences of production trends

Graphical Abstract



Graphical Abstract: The temporal development in the relative environmental impact per 1 kg of live pig at farm gate from 2000 to 2017 from indoor and outdoor bred pig systems in Great Britain. The baseline (1 unit) is the environmental impact of the systems during the time interval 2000-2002. The environmental impact categories shown are consistent with LEAP (FAO, 2018b) recommendations. The change in the environmental impacts over the study period as a mean and standard deviation of model outcomes with constant prices set to each individual year (Price sensitivity analysis). The impacts are: Global Warming Potential (GWP), Terrestrial Acidification Potential (TAP), Freshwater Eutrophication Potential (FEP), Agricultural Land Use (ALU) and Fossil Resource Scarcity (FRS).

Abstract

The aims of global pig production systems include a reduction of their environmental impacts, which can be achieved through an increase in outputs whilst minimising inputs. The aim of this paper was to develop a novel method to enable estimation of the changes in the environmental impacts based on sparse data from the British pig production industry over ~20 years. To achieve this, we developed a Life Cycle Assessment (LCA) method capable of dealing with sparse historical data from livestock systems. We applied it, for the first time, to estimate the temporal changes in environmental impacts of British pig production systems caused by changes in production performance. Performance data available from industry-held databases for indoor and outdoor bred pigs in Britain were used to estimate nutrient requirements through animal performance modelling, and feed composition through least-cost formulation. The cradle to farm-gate LCA model developed, included manure management and the full life cycle of the pigs and its functional unit was 1 kg of live weight pig at farm-gate. Sensitivity analyses were conducted to investigate the potential influence of changes in animal performance and feed prices on the estimated changes in environmental impacts. The higher growth rates and increased leanness over the period considered led to substantial reductions in energy requirements. Overall, the system changes led to reductions, for indoor and outdoor bred systems respectively, of 37.0 % and 35.4 % for Global Warming Potential, 21.2 % and 16.4 % in Terrestrial Acidification Potential, 22.5 % and 22.3 % in Freshwater Eutrophication Potential, 15.8 % and 16.8 % in Agricultural Land Use and 16.5 % and 16.1 % in Fossil Resource Scarcity. The sensitivity analyses showed that trends in feed composition were influential on the environmental impact outcomes, and that the LCA model was more sensitive to the change in feed composition than to the changes in animal performance over the time period considered. Knowledge of temporal changes to the environmental impacts of livestock systems and the drivers of changes to date should guide future decisions to mitigate these impacts.

Words: 10625

Changes in the Environmental Impacts of Pig Production Systems in Great Britain over the last 18 Years

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- We aimed to develop a method to estimate the changes in environmental impacts of British pig production over 18 years from sparse historical data
- All environmental impacts were reduced, including a 37%/35% reduction in Global Warming Potential for indoor and outdoor bred pigs respectively
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The aims of global pig production systems include a reduction of their environmental impacts, which can be achieved through an increase in outputs whilst minimising inputs. The aim of this paper was to develop a novel method to enable estimation of the changes in the environmental impacts based on sparse data from the British pig production industry over ~20 years. To achieve this, we developed a Life Cycle Assessment (LCA) method capable of dealing with sparse historical data from livestock systems. We applied it, for the first time, to estimate the temporal changes in environmental impacts of British pig production systems caused by changes in production performance. Performance data available from industry-held databases for indoor and outdoor bred pigs in Britain were used to estimate nutrient requirements through animal performance modelling, and feed composition through least-cost formulation. The cradle to farm-gate LCA model developed, included manure management and the full life cycle of the pigs and its functional unit was 1 kg of live weight pig at farm-gate. Sensitivity analyses were conducted to investigate the potential influence of changes in animal performance and feed prices on the estimated changes in environmental impacts. The higher growth rates and increased leanness over the period considered led to substantial reductions in energy requirements. Overall, the system changes led to reductions, for indoor and outdoor bred systems respectively, of 37.0 % and 35.4 % for Global Warming Potential, 21.2 % and 16.4 % in Terrestrial Acidification Potential, 22.5 % and 22.3 % in Freshwater Eutrophication Potential, 15.8 % and 16.8 % in Agricultural Land Use and 16.5 % and 16.1 % in Fossil Resource Scarcity. The sensitivity analyses showed that trends in feed composition were influential on the environmental impact outcomes, and that the LCA model was more sensitive to the change in feed composition than to the changes in animal performance over the time period considered. Knowledge of temporal changes to the environmental impacts of livestock systems and the drivers of changes to date should guide future decisions to mitigate these impacts.

Key words

Environmental Impact, Great Britain, Historical Data, Life Cycle Assessment, Sensitivity Analysis, Swine.

1. Introduction

Livestock industries, including pig production, are under scrutiny regarding their environmental impacts (FAO, 2018a). Although the environmental impact contribution per unit of meat from pig systems is relatively low (de Vries and de Boer, 2010), pig meat is the meat type most produced and consumed globally (FAOSTAT, 2019) and thus contributes significantly to several forms of environmental impacts. In 2013 it was estimated that the total contribution of pig systems to Greenhouse Gas (GHG) emissions was 668 million tonnes CO_2-eq (Gerber et al., 2013), i.e. 9 % of the GHG emissions produced by livestock systems. In addition, pig systems are considered to be major contributors to the acidification and eutrophication of the environment due to emissions of N and P from manure storage and spreading (de Vries and de Boer, 2010).

The issue of sustainability of pig production systems has only relatively recently become the focus of pig breeders and producers (Neeteson-van Nieuwenhoven et al., 2013). Previous genetic selection has aimed at increasing growth rate, improving carcass traits, such as reduced fatness, and improving the reproductive performance of sows (Knap and Rauw, 2009). In addition, much research has focused on the use of more sustainable feeding strategies, such as the use of home grown protein sources (Mordenti et al., 2012; Rauw et al., 2020; Sakkas et al., 2019) and enhancing the management of animals, for example through the introduction of precision feeding (Pomar and Remus, 2019). However, this paper hypothesises that previous breeding goals of improving economic outcomes have already contributed to reductions in the environmental impacts of pig systems. The objective of this study was to quantify changes in the environmental impacts of the average GB pig production system between year 2000 and year 2017; this was done through the integration of a nutritional requirement and feeding model into a Life Cycle Assessment (LCA) framework. Historical LCA exercises such as presented here, enable the livestock sector to understand which trends in production practices such as breeding and feeding have led to reductions in environmental impacts. As such, the knowledge they generate can aid decision making in efforts to further reduce the environmental impacts, in this case for pig production.

This task, which involved the use of historical data, presented several challenges which included: acquiring data on both the inputs and outputs of the national pig production system and modelling the changes to the production system over the years. For the GB pig systems, the only such dataset available was held by the National Levy Board (Agricultural and Horticultural Development Board – AHDB Pork) and consists of national average performance data for growing pigs and sows (https://pork.ahdb.org.uk/prices-stats/costings-herd-performance/). As such, there was a lack of information on: 1) the production of pigs and inputs to the system at a national level; 2) typical pig feeds used, even at a national scale over a given period, and 3) nutrient requirement recommendations, especially as pig performance changes relatively rapidly. This lack of information is not unique to GB as similar issues exist for other pig systems across Europe, albeit to varying extents.

We overcame these challenges first by estimating animal requirements based on a simple animal performance model for growing pigs and an extended model for sows. Second, the feed composition for each production phase was estimated by least cost feed formulation; excreted manure composition was estimated from nutrient balance. The former is a deviation from previous approaches where ‘typical’, historical feed formulations have been used for this purpose (i.e. Vergé et al., 2009a). Finally, the environmental impacts from each year and each growth phase were estimated through a holistic LCA model based on the above three sub-models (requirements, feed composition and manure management). Since data on many inputs and outputs of the pig production system were not available for GB, the internal dynamics between the sow and the growth phases of the pig needed to be estimated.

A substantial number of sows are bred outdoors in GB (up to 40%), as opposed to indoor breeding practiced in most European pig producing countries (AHDB, 2017), so we applied our approach to both indoor and outdoor breeding systems. Given that our approach identified several uncertainties in the estimation of environmental impacts, we applied sensitivity analyses to differentiate the effects of changes in feed ingredient prices and animal performance over the period. The novelty in our methodological approach lies in the combination of these previously independent models into an integrated historical LCA that can tackle the uncertainty of the sparse input datasets available for GB pig systems.

2. Material and methods

To test our hypothesis, we built a detailed LCA model of pig production systems in GB, using farm performance data during the 18-year period 2000-2017; this was the most current and complete dataset available for GB pig production. Since only national average pig performance data was available, multiple intermediate steps from the input data to the environmental impacts were taken to estimate the changes to the environmental impacts per kg of live weight pig produced over the investigated period (see Fig. 1). In brief, after transforming the data to accommodate a four phase production system (i.e. early weaner, late weaner, grower, and finisher), the animal requirements for energy and protein were estimated for each phase and period. These requirements were used to estimate feed composition for each phase, followed by an LCA model which used the pig performance data and the estimated feed composition to estimate environmental impacts. Each of the steps taken are described below.

Commonly applied terminology in pig production will be utilised in this article: the gilt is the female pig until first insemination; the sow is a reproducing female pig going through the stages of gestation (116 days), lactation (28 days) and weaning to insemination (function of litters per sow per year); piglets are the new-born pigs until weaning and the production pig is a common term used to encompass early and late weaners, growers and finishers. Reproducing male pigs were not considered since previous studies have shown that their proportional contribution of environmental impacts to the pig production systems are insignificant due to the great number of offspring produced over the boar lifetime (Ottosen et al., 2020). Pigs which were produced by sows breed outdoors will be termed outdoor bred whereas pigs produced by sows bred indoors will be termed indoor bred. 2.1. Data acquisition and transformation

Average data on GB pig performance from 2000 to 2017 was acquired from AHDB (see Fig. 2). The data were collected in self-reported schemes through the AgroSoft commercial software, which tracks performance of the majority of pigs in GB (AgroSoft, 2020), and the data had previously been reported by the InterPig network (Hoste, 2017). Although this dataset clearly has its limitations, no other database has a comparable coverage of pig systems in GB.

The initial dataset contained information for two phases of the production pig (source used the terminology ‘rearing’ and ‘finishing’ for the two stages which will be capitalised (REARING and FINISHING) below when referring to source terminology) and performance for indoor and outdoor sows (see Fig. 2). From 2000 to 2017, the average production pig in GB had slightly increased Average Daily Gain (ADG) especially during the FINISHER phase. Its mortality rate was highest between 2002 to 2006, but returned to initial levels by the end of the period under consideration. During this period the slaughter weight increased from 93.4 kg to 110.9 kg. Sow replacement rates increased, but to a lesser extent for outdoor sows. Although there was an increase in piglets born alive for both indoor and outdoor sows, litters per sow per year and sow cumulative feed intake (CFI) did not change during the period considered.

The performance traits ADG and Feed Conversion Ratio (FCR, kg feed use per kg weight gain) contained in the primary dataset, were used to estimate the number of days and the CFI respectively for each phase for the production pigs, which were then used as inputs into the requirements model. To implement the four feeding phases, the REARING phase was split into an early weaner (5 kg BW gains, 7 kg feed, 11 days) and a late weaner phases (the remaining BW gains, CFI and time). The initial FINISHER phase in the dataset was split into a grower (BW gains from end of late weaner until 60 kg, 85 % of allocated feed according to FCR and 35 days) and a finisher phases (BW gains until slaughter, remaining feed, remaining time). Mortality rates were estimated for early weaner, late weaner, grower and finisher phases using the square root of the survivability of the initial REARING and FINISHER phases respectively. A gilt phase was created from the finisher phase starting at slaughter weight until typical weight at service (BPEX, 2010), 90 % growth rate and 130 % FCR of the finisher. To reduce the effect of annual fluctuations, the performance data was averaged over three year periods which also removed the problem with missing sow performance data for 2001 and 2003

2.2. Animal models

To estimate the protein and energy requirements for all stages of production, a phase-specific model of the production pig and a detailed day-to-day model of the sow were constructed. The production pig model was used to estimate requirements for the production pig and the gilt over the relevant production phase based on four principles: conservation of energy, conservation of protein, conservation of body mass, and allometry between lipid and protein. On the other hand, as sows lose both lipid and protein during lactation, a detailed day-to-day model was needed to estimate their requirements. Both models predicted energy requirements in terms of metabolizable energy (ME) (Noblet, 2013). Standardized Ileal digestible (SID) protein and the principle of ideal essential amino acids distribution were implemented in the model to simulate protein requirements (NRC, 2012). As in previous models (Dourmad et al., 2008; NRC, 2012; van Milgen et al., 2008), energy maintenance was calculated from the metabolic bodyweight (BW) with a 0.6 exponent for production pigs (Van Milgen and Noblet, 1999) and a metabolic BW with a 0.75 exponent for sows (Kleiber, 1947).

2.2.1. Production pig model

The production pig energy and protein requirements were estimated by solving equations 2, 4, 6 and 8 below (see parameters in Table 1).

The conservation of energy in each growth phase was based on the assumption that ME intake was used by the animal for either maintenance or deposition of protein and lipid:

$$ME_{intake} = ME_{used} (MJ) \tag{1}$$

$$CFI * ME_c = \frac{\Delta Pr * HC_{Pr}}{k_{ME(F \to \mathrm{Pr})}} + \frac{\Delta L * HC_L}{k_{ME(F \to L)}} + \sum_{t=ti}^{tf} ME_{maint}\, (MJ) \tag{2}$$

where CFI (kg) is the cumulative feed intake during the phase, ME_c (MJ/kg) is the concentration of metabolizable energy in the feed during a phase (ME concentration), ΔPr (kg) is the protein gain during a phase, ΔL (kg) is the lipid gain during a phase and maintenance energy (ME_{maint}) (MJ) during a phase estimated from metabolic BW (Table 1); HC_{Pr} (MJ/kg) is the heat of combustion of protein, $k_{ME(F\to Pr)}$ is the energetic efficiency of protein retention, HC_L (MJ/kg) is the heat of combustion of lipid and $k_{ME(F\to L)}$ is the energetic efficiency of lipid retention.

In a similar manner, the conservation of protein in each phase was based on the assumption that SID protein intake in each phase was used either for protein maintenance or for growth:

$$SID\ Pr_{intake} = SID\ Pr_{used} (kg) \tag{3}$$

$$CFI * SID\ Pr_c = \frac{\Delta Pr}{k_{\mathrm{Pr}(F \to Pr)}} + \sum_{t=ti}^{tf} Pr_{maint} + CFI * k_{DM} * EL_{Pr}\ (kg) \tag{4}$$

where SID Pr_c (kg/kg) is the concentration of SID protein in the feed of the phase (Pr concentration) and Pr_{maint} (kg) is the protein maintenance estimated from BW; $k_{Pr(F\to Pr)}$ is the protein efficiency of protein retention, k_{DM} is the average dry matter concentration in the feed (kg/kg) and EL_{Pr} (kg/kg) is the endogenous loss coefficient.

Body weight gain in each phase consisted of gains in protein, lipid, water and ash (Wellock et al., 2003):

$$BW_f = Pr_f + L_f + Ash_f + Water_f\ (kg) \tag{5}$$

$$BW_f = \frac{(\mathrm{Pr}_i + \Delta \mathrm{Pr}) + (L_i + \Delta L) + \left(k_a * (\mathrm{Pr}_i + \Delta Pr)\right) + \left(k_{w1} (\mathrm{Pr}_i + \Delta Pr)^{k_{w2}}\right)}{k_{eBW}}\ (kg) \tag{6}$$

where BW_f (kg) is the final body weight in a phase, Pr_i, L_i, Ash_i and $Water_i$, and Pr_f, L_f, Ash_f and $Water_f$ (kg) are the initial and final protein lipid, ash and water weight respectively; k_a is the allometric coefficient that relates body ash to body protein, and k_{w1} and k_{w2} are the two allometric coefficients that relate body water to body protein.

The lipid to protein ratio at maturity was assumed to decrease linearly from the 1.75 in 1994 (latest year reported by Knap (2000)) to 1.25 in 2017. Protein mass at maturity was assumed to be constant throughout at 60 kg (Knap, 2000), which was consistent with equation 6 and with reported mature BW. The lipid mass at the end of each phase was determined through its allometric relationship to the protein mass at the end of a phase (Emmans and Kyriazakis, 1997; Wellock et al., 2003):

$$L = L_m \left(\frac{Pr}{Pr_m}\right)^d \ (kg) \tag{7}$$

where L_m and Pr_m (kg) are the lipid and the protein mass at maturity respectively. Eq. 7 was applied at the end of each phase in the model by adding L and Pr and their respective growth ΔL and ΔPr:

$$(L_i + \Delta L) = L_m \left(\frac{Pr_i + \Delta Pr}{Pr_m}\right)^d \ (kg) \tag{8}$$

The d-exponent in Eq. 7 and 8 was evaluated as a function of protein and lipid at maturity according to Emmans (1997):

$$d = 1.46 \left(\frac{L_m}{Pr_m}\right)^{0.23} \tag{9}$$

Equations 2, 4, 6 and 8 were solved for energy and protein requirements, and growth of lipid and protein.

2.2.2. Sow model

A brief description of the sow energy and protein requirement model is given here. The full model description with all parameters can be found in the supplementary materials S5.

The model simulates the requirements of a sow depending on performance and local environmental conditions. This model was based on the concepts outlined in the InraPorc sow model (Dourmad et al., 2008) adapted to comply with the principles of conservation of protein.

The model predicted for each day how much energy and protein were available for growth after obligatory losses (maintenance and piglet requirements) were accounted for:

$$Growth_{nut} = Available_{nut} - Maintenance_{nut} - Export_{piglet_{nut}} \tag{10}$$

Where $Growth_{nut}$ is either energy or protein available for growth, $Available_{nut}$ is either the energy or protein made available through intake and mobilisation, $Maintenance_{nut}$ is either the maintenance cost in energy or protein and Export_piglet$_{nut}$ is either the energy or protein needed for the conceptus or for milk production.

Nutrients were used with priority to fulfil the maintenance requirements (although there may be weight loss, as explained below):

$$SIDPr_{Maintenance} = k_{DM} * FI_{daily,} * El_{Pr} + \beta * BW^{0.75}\ (kg/day) \tag{11}$$

$$ME_{maintentance} = (a_{basal} + a_{therm} * DT + a_{active} * H) * BW^{0.75} (MJ/day) \tag{12}$$

Where SIDPr$_{Maintenance}$ is the SID daily requirement for protein maintenance, k$_{DM}$ is the standard dry-matter concentration in the feed, EL$_{Pr}$ is the endogenous SID Pr loss, β is the SID Pr turnover maintenance metabolic coefficient, ME$_{maintenance}$ is the ME for daily maintenance, a$_{basal}$ is the ME for basal heat production, a$_{therm}$ is the thermal maintenance coefficient, DT is the difference between the thermoneutral temperature (16 °C for gestation, 10 °C for lactation, (Dourmad et al., 2008)) and the monthly average ambient temperature if this difference is positive and zero otherwise, a$_{active}$ is the ME activity cost coefficient and H is the daily activity level of the specific stage of reproduction.

The thermoregulation component in Eq. 12 only applied for outdoor systems and was estimated from the annual temperature in East Anglia (Met Office, 2019) where the majority of sows reside in GB (APHA, 2017). The activity component in Eq. 12 was smaller for the indoor sows since they have fewer opportunities for activity than the outdoor sows (Buckner et al., 1998).

In addition to the utilisation of intake for maintenance, nutrients for piglets were diverted to the conceptus and to milk production: the conceptus grew as a function of gestation stage, average piglet BW at birth and total litter size; the milk output was a function of litter average daily gain, live-born litter size and days during lactation. If any nutrients were available for growth, they were first used to maximise protein growth, and the remaining energy was deposited as lipid.

During lactation, body weight was lost since the energy and protein requirements for maintenance and milk production exceeded energy and protein intake. The protein needed for milk production that could not be provided from the feed, was derived from body protein reserves. The energy required for milk production that could not be provided from the feed, was derived mainly from body lipid degradation, but 5 % came from degradation of protein (Dourmad et al., 2008):

$$\Delta L_{lactation} = \frac{ME_{milk} - ME_{F-M}}{HC_L * k_{ME(B-M)} * k_{ME(B)}} * 0.95\ (kg/day) \tag{13}$$

$$\Delta \mathrm{Pr}_{lactation} = \frac{Pr_{milk} - Pr_{F-M}}{k_{\mathrm{Pr}(B-M)}} + \frac{ME_{milk} - ME_{F-M}}{HC_{Pr} * k_{\mathrm{ME}(B-M)} * k_{ME(B)}} * 0.05\ (kg/day) \tag{14}$$

Where ΔL and ΔPr are the loss of body lipid and protein under lactation respectively, ME_{milk} and Pr_{milk} are the energy and protein required to be delivered in the milk, ME_{F-M} and Pr_{F-M} are the milk content of energy and protein intakes respectively, HC_L and HC_{Pr} are the heat of combustion of lipid and protein respectively, and $k_{ME(B-M)}$, $k_{ME(B)}$ and $k_{Pr(B-M)}$ are the efficiencies in providing body energy to the milk, degrading body energy and providing body protein to the milk respectively.

The changes in body reserves of protein and lipid were calculated each day, and the respective growth or loss was added to the current weight, to predict the body components of the next day:

$$Pr_{t+1} = Pr_t + \Delta Pr_t\ (kg) \tag{15}$$

$$L_{t+1} = L_t + \Delta L_t\ (kg) \tag{16}$$

The total body weight of t+1 was estimated as the sum of the predicted protein and lipid mass and the predicted water and ash according to Eq. 6. During gestation, the weight of the conceptus was included in the total sow body weight and thereby accounted for in the maintenance calculations. The sow ME and SID Pr feed concentrations were evaluated to allow the expected BW growth of a third parity sow.

2.3. Feed formulation

In formulating the feeds for each year, a list of ingredients was selected to simulate the ingredients that an average farmer would have at their disposal; each chosen feed ingredient had a recorded price for each year it was considered available. Cereals included were wheat and barley, since oats were only available from producers during the autumn (Farmers weekly, 2017), and maize and rye were not available in sufficient quantities in GB (ABN, personal communication). Protein sources consisted of soybean meal and rapeseed meal, but whole soybeans were excluded since their primary use in GB was for human consumption (Young, 2017) and whole rape was excluded due to concerns regarding anti-nutritional effects (Rymer and Short, 2003). Micronized ingredients were used in some experimental and compound pig feeds in GB, but were not considered to be available in large enough quantities for inclusion in the feed ingredient list. Bakery co-products are used in many different forms in pig feeds in GB, but due to limited data availability, only two products, bakery and biscuit meal, were considered. Some ingredients were potentially available to pig producers, such as alfalfa, linseed and naked oats, but due to human consumption and use in ruminant feeds, prices were often disproportionally high for pigs. All commonly used pure amino acids were included in the list of available ingredients. Due to the 2001 EU ban on animal co-products in farm animal feeds (Regulation (EC) No 999/2001), such ingredients were not considered. The price list of the ingredients considered can be seen in Table 2.

Feed composition was based on least cost formulation subjected to constraints (NRC, 2012) using the Linprog function in MATLAB (MathWorks, 2017). Each ingredient had a maximum inclusion limit to prevent anti-nutritional effects according to industrial and scientific recommendations (Edwards, 2002; Mackenzie et al., 2016; Pork Information Gateway, 2010) (maximum inclusion limits can be found in the supplementary materials S2).

The nutritional properties of the feed ingredients were taken from the PremierAtlas (Premier Nutrition, 2014), including values needed to estimate gastric methane production (Philippe and Nicks, 2014; Tran et al., 2018) (see supplementary materials S6 for applied values).

The feeds were constrained to have sufficient concentration of ME and SID Pr to meet the animals requirements derived from the historical feed intake and performance data . Furthermore, Lysine requirements were assumed to be 6.8 % of SID Pr requirements (Goodband et al., 2014); the ratios of essential amino acids relative to Lysine and minerals per kg feed were taken from Dourmad et al. and van Milgen et al., (2008). The sum of oils had a maximum inclusion limit of 6 % (NRC, 2012) and to achieve an optimal dietary mineral balance around 250 milliequivalents (mEq) (NRC, 2012) only feeds within the range of 200-300 mEq were considered. Feed ingredient prices were averaged over each of the three-year periods in the same way as the performance data was.

2.4. LCA framework

The outcomes of the above sub-models were used to build an LCA model of the average GB pig production system. The *goal* of the LCA was to investigate how changes in animal performance have affected the environmental impacts of the GB pig production system. The *scope* of the work was to calculate the average environmental impacts of these production systems for every three years for the period 2000 to 2017. The *functional unit* was 1 kg of live pig at farm gate and the *system boundary* included a fully integrated farm with breeding unit, feed ingredients from growth to consumption and manure applied to fields replacing artificial fertilizers. The study estimated the environmental impact categories recommended by FAO LEAP guidelines (FAO, 2018b) based on the available data. Thus, included impact categories were Global Warming Potential (GWP), Terrestrial Acidification Potential (TAP), Freshwater Eutrophication Potential (FEP), Agricultural Land Use (ALU) and Fossil Resource Scarcity (FRS). Impact categories from the Life Cycle Impact Assessment (LCIA) methodology ReCiPe 2016 midpoint (H) were used in this study. All prices and pig performance data were national average values for the given years. However, the inventory data for feed ingredients were kept constant throughout – i.e. each ingredient had constant environmental impacts for all years.

Nutrient excretion and manure management methodology was implemented as in Ottosen et al. (2020) with present practice and emission factors for GB. The full description can be found in the supplementary material S4.

The LCA model was compiled in matrix as in Ottosen et al. (2020) and will therefore only be described here briefly. The estimation of environmental impacts was carried out using the relationship:

$$\boldsymbol{B} * \boldsymbol{A}^{-1} * \boldsymbol{f} = \boldsymbol{g} \tag{17}$$

Where **B** is the environmental matrix, $\mathbf{A}^{-1}$ is the inverse technology matrix, **f** is the functional unit and **g** is the result matrix (Heijungs and Suh, 2002). All feeds were inputted through the technology matrix together with animal feed intake, methane production, electricity consumption, and mortality rates adjusting the fraction of pigs going from one phase to the next. Since statistics on the ratio of culled pigs going to slaughter or being culled on farm were not available, the fate of their carcasses was unaccounted for. The early weaner process required the inflow of one piglet produced in the sow process; the gilt process required a finisher pig inflow and the sow replacement rate was accounted for by adjusting the inflow of gilts into the annual sow process to the replacement rate. All calculations were performed in MATLAB R2017a (MathWorks, 2017), and data on environmental impacts from feed production were sourced from Simapro 8.5.2.0 (Pre Consultants, 2017). Codes for all used models are available upon request.

2.5. Sensitivity analyses

Sensitivity analyses were conducted to understand the sensitivity of the model outcomes to variation in the estimated trends in animal performance and feed ingredient prices for GB pig production systems during 2000-2017. We investigated the sensitivity of the predictions to the following factors: 1) variation in feed ingredient prices; 2) changes and uncertainty on animal performance and resulting changes in the utilisation of feed and nutrient excretion. The outcomes of the sensitivity analysis were used to infer how influential trends in these areas of the model were in driving the overall trends in environmental impacts.

2.5.1. Sensitivity to feed ingredient prices

National-average feed formulations were estimated based on least cost to meet a set of nutritional requirements. As such, changes and trends in ingredient prices could have altered the environmental impacts caused by pig production. Since the data on feed ingredient prices could not be assumed to be normally distributed, multi-normal sampling was not a viable option. Instead, we assumed that the data on annual feed ingredient prices over the 18-year period were representative of the range possible annual price scenarios. For each of the six three-year periods, we applied the annual feed prices of all 18 possible prices one at a time and calculated the mean and standard deviation (SD) of the environmental impacts of each of the six three-year periods. This approach accounted for the empirical correlations and variance in the prices of the different ingredients from year to year. A larger temporal change in the mean of the environmental impacts from 2000 to 2017 than the SD of the environmental impact for each three-year period would suggest, that it was the changes in animal performance that drove the changes in environmental impacts of the pig system rather than changes in feed ingredient prices.

2.5.2. Sensitivity to animal performance

The effect of the observed changes to ingredient prices was tested while accounting for uncertainty in the estimated animal performance. The national and farm level of aggregation in the animal performance data did not allow computation of an animal-level variance-covariance matrix through which sampling of individual animal variation could be carried out. Instead, the data on average animal performance across each on the 18 years were used to estimate a variance-covariance matrix and a multivariate normal (MVN) distribution of the pig population. Latin Hypercube samples containing 100 possible realisations of the set of animal performance traits were generated for each of the six 3-year periods. The associated environmental impacts were calculated for each of the 100 realisations and their mean and

SD were estimated for each three-year period. For each realisation of animal performance, the price of feed ingredients and the feed composition still changed as described above. Hence, a larger temporal change in the mean environmental impacts from 2000 to 2017 than the estimated SD would suggest that the change to environmental impacts could have been influenced more strongly by the change in feed ingredient prices than the change or the uncertainty in animal performance.

3. Results

3.1. Feed composition

The predicted feed composition scaled to produce the functional unit of one kg of live pig at farm gate for both indoor and outdoor bred pigs can be seen in Fig. 3. The trends in the predicted energy and protein concentration of feeds based on historical data of feed intake and animal performance for the production pigs, gilts and both indoor and outdoor sows can be found in supplementary material S7, while the concentration of all feed ingredients for all scenarios can be seen in the supplementary materials S8. Major changes in feed composition happened over the period considered. The model showed a reduction in wheat and oil accompanied by an increase in barley and a number of co-products over the period considered. These changes were driven by an overall reduction in the energy concentration of feed for finisher pigs and gilts. In particular, finisher feed energy concentration reduced from 13.7 to 11.0 MJ ME/kg over the period considered reflecting a change to typical feed specifications over this period. Soybean meal inclusion was reduced, while the use of several pure amino acid supplements increased, although this was not the case for tryptophan and valine. Protein concentration of the feeds for production pigs were relatively stable over the analysed period (see S7), the trend to increased use of amino acid supplements came as they reduced in costs.

3.2. Environmental impacts

The trends in the predicted relative environmental impacts can be seen in Fig. 4 (the numeric results are in the supplementary materials S9). After an initial increase during 2003-2005, all environmental impacts decreased towards a plateau during 2015-2017. Over the whole period of 2000-2017, GWP per kg live weight from indoor bred pigs was reduced by 37.0 % (from 3.82 to 2.41 kg CO_2 eq/kg live weight), TAP by 21.2 % (from $99.6*10^{-3}$ to $78.5*10^{-3}$ kg SO^2 eq/kg live weight), FEP by 22.5 % (from $0.566*10^{-3}$ to $0.439*10^{-3}$ kg P eq/kg live weight), ALU by 15.8 % (from 4.21 to 3.55 m^2/kg live weight) and FRS by 16.5 % (from 0.249 to 0.208 kg oil eq/kg live weight).

During the same period, GWP per kg live weight from outdoor bred pigs was reduced by 35.4 % (from 3.82 kg to 2.47 kg CO_2 eq/kg live weight), TAP by 16.4 % (from 83.8*10^{-3} to 70.0*10^{-3} kg SO^2 eq/kg live weight), FEP by 22.3 % (from 0.575*10^{-3} to 447*10^{-3} kg P eq/kg live weight), ALU by 16.8 % (from 4.35 to 3.62 m^2/ kg live weight) and FRS by 16.1 % (from 0.252 to 0.212 kg oil eq/kg live weight).

The contributions of each phase to the impact categories can be seen in Fig. 5. Early weaner phase had minimal contribution to the overall environmental impacts of 5.35 %, 3.66 %, 5.68 %, 3.13 % and 5.70 % for GWP, TAP, FEP, ALU and FRS respectively due to the small feed intake of the phase. The finishing phase had the highest contribution for all environmental impacts with an average contribution of 31.6 %, 39.3 %, 36.5 %, 40.5 % and 38.7 % for indoor bred pigs and 31.0 %, 44.7 %, 35.6 %. 39.4 % and 37.9 % for outdoor bred pigs for the GWP, TAP, FEP, ALU and FRS impact categories respectively. The finishing phase also contributed to a major part of the reduction in GWP by contributing 41.4 % less in 2015-2017 than in 2000-2002. The reproduction phase was also associated with large reductions of 55.9 %, 39.1 %, 46.7 %, 41.4 % and 37.9 % for indoor bred and 49.3 %, 32.6 %, 44.3 %, 41.9 % and 34.8 % for outdoor breed between 2000 and 2017 for GWP, TAP, FEP, ALU and FRS respectively.

3.3. Sensitivity analyses

The results of the Feed Ingredient Prices sensitivity analysis and of the Animal Performance sensitivity analysis can be seen in Fig. 6 and Fig. 7 (numerical values can be found in supplementary materials S10). Both sensitivity analyses showed temporal reductions in all environmental impacts similar to those in the baseline indoor bred pigs, although the changes from across the three-year intervals were smaller than in the baseline outcomes. In the Price sensitivity analysis scenario, the SD of the environmental impacts had the same order of magnitude as the observed change in the mean environmental impacts from 2000-2017. This suggests that the effect of the changes in animal performance over that period were overshadowed by the variation in ingredient prices and the resulting feed compositions. In contrast, in the Performance sensitivity analysis, the SD was smaller in all periods than the magnitude of the change in the means between the period 2000-2005 and 2009-2017 with the exception of 2006-2008 which had higher SD than the other periods. This suggests that the changes in feed ingredients prices were an important driver of the changes in environmental impact over the time period considered.

4. Discussion

The objective of this study was to quantify changes in the environmental impacts of the average GB pig production system between year 2000 and year 2017. These evaluations were based on GB national average performance data used to estimate energy and protein requirements, feed formulation and manure nutrient content which, compiled into an LCA model, led to estimation of the environmental impacts in each of the three-year periods. Historical LCA studies of livestock production systems, such as that presented here, can provide insights to how trend practices within key areas such as feeding and breeding have influenced the environmental impacts of these systems over time. Proper analysis of these trends can aid future decision making aimed at reducing environmental impacts in these systems.

Many historical datasets for livestock systems, especially those dealing with larger regional or national systems, do not have detailed data on key aspects of animal production relevant to the estimation of environmental impact, such as feed composition, animal performance or manure management. The method proposed in this paper is a robust approach applicable to many animal production systems when trying to understand how their environmental impacts changes over time. It enabled us to estimate trends over time in animal requirements, accompanied by feed composition in the historical data sets. These steps were necessary to estimate the environmental impacts of GB pig systems detailed in the historical dataset.

4.1. Trends in feed composition

There were important changes in animal performance over time, the most significant being the increase in the ADG of the finisher pigs, an increase in the slaughter weight of the production pigs, an increase in the number of piglets born alive and an increase in the replacement rate of the sows. Over time, the increase in growth rate, which reduced both energy and protein maintenances, distributed the daily requirements over more feed through an increase in finisher CFI. However, an increase in slaughter weight raised both energy and protein maintenance cost and made the slaughtered animal less lean. These two trends counterbalanced each other, but supplemented with the effect of overall higher leanness in later years, they resulted in a reduction in energy concentration in feed over time while protein concentration remained stable. This ‘rebound’ effect with respect to feed conversion ratio and slaughter weight was also observed by Macleod et al. (2019) for wider pig systems in the EU in their analysis of the impact of animal breeding on GHG emissions.

Formulation of feeds per production phase was based on the principle of least cost formulation, subject to certain constraints (NRC, 2012), as this is the method preferred by most nutritionists and farmers (Saxena and Chandra, 2011). The implications of this approach will be discussed later. The estimated feed composition in our study were mainly based on wheat, barley, soybean meal and rapeseed meal, which is in line with the findings of Sprent (2014) for GB pig systems. There were two important trends in feed ingredient inclusion over time: oils were no longer present in the later years and barley replaced wheat, especially in sow feed. This was a reflection of the reduced energy requirements in the animal model, as discussed previously. Similarly, soybean meal was gradually replaced by rapeseed meal, which also has a lower energy content.

Some of the changes in the feed composition can also be explained by the changes in the prices of feed ingredients. Rapeseed meal inclusion became more dominant during the latter parts of the investigated period, since it had only a modest price increase compared to changes in the price of soybean meal. Inclusion of co-products such as bakery and biscuit meal in the feed increased as cereal prices increased, but their prices remained constant. Sunflower meal also became a significant protein source after it started being available in GB post 2009. It is possible that a higher concentration of co-products and alternative protein sources would have been included if their maximum inclusion limit had been set higher (Mackenzie et al., 2017), since they delivered cheaper nutrient resources than cereal and soy products, especially during the later investigated periods. These levels were taken from the literature and consultation with GB nutritionists, and they are likely to be conservative estimates. Higher co-product inclusion levels in pig feed have previously been shown to reduce environmental impacts of pig production systems (i.e. Ali et al., 2017; Mackenzie et al., 2017), thus resulting in both economic and environmental impact reduction benefits.

4.2 Trends in of the environmental impacts of pig production

All predicted environmental impacts decreased over time, which was consistent with our hypothesis that breeding trends have improved animal performance over time and thus reduced the environmental impacts of the system per functional unit. The degree of reduction varied between the environmental impact categories considered. As the majority of the environmental impacts were associated with the finisher component of the system, any reductions were mainly attributed to three main factors: 1) change in animal performance, which led (mainly) to a decrease in energy concentration of feed; 2) change in feed ingredient prices and inclusion of alternative, home grown ingredients in the ; and 3) increase in slaughter weight without an increase in inputs. Especially changes in 1) and 2) resulted in changes in feed composition, which drove the changes in the environmental impact of the systems considered.

GWP was the most sensitive impact category due to its high dependence on the inclusion of soybean meal in the feed, especially for the production pigs. Soybean is imported in the UK and comes mainly from South America; as a consequence it has a high GWP impact per kg of ingredient due to deforestation associated with its production and transport (Pre Consultants, 2017). Any reductions in its inclusion over time, as was the case here, would automatically lead to reduced GWP impacts. Reductions in the TAP and FEP impacts over time were more moderate, reflecting the fact that changes in these impact categories over time were minimal for the production pigs. The main contributors to the reduction in ALU were the higher inclusions of co-products and reduced CFI, which led to smaller relative reductions than in the other impact categories. The FRS impact category is more affected by ingredients with high energy inputs to processing (Mackenzie et al., 2016), ingredients such as animal co-product, pure amino acid and rapeseed meal are associated with high levels of FRS. The reductions in FRS due to decreases in cumulative feed intake were partly counterbalanced by the increasing inclusion of rapeseed meal over time.

In the reproduction component of the system, an increased litter size would be expected to reduce its environmental impacts. However, this was partly counter-balanced by an increase in the sow replacement rates and therefore only limited reductions in the environmental impact of this system component were seen. There were only small differences in the environmental impacts between the indoor and outdoor breeding component of the system, even though outdoor breeding requires more energy inputs. This can be attributed to the disproportionate higher feed intake and thereby lower energy concentration in the feed of outdoor sows compared to indoor sows.

The reproductive phase contributed more to the TAP impact of the system, than for any other impact category. The breeding sow has significantly lower protein requirements than the production pig, which necessitates the inclusion of high energy, but low protein feed ingredients. However, as the feed formulation was based on least cost, the resulting feed included high energy, but also relatively high protein ingredients, which is a usual challenge in the formulation of sow feed (Edwards et al, 2002). This resulted in oversupply of nitrogen in the feed, which led to over excretion of nitrogen in the manure from this system component.

4.3 Sensitivity Analyses

The proposed model had two main sources of data that contributed with substantial uncertainty: the feed ingredient prices and animal performance data. The variability estimated (shown as SD) of the environmental impacts from the Price sensitivity analysis were of the same magnitude or larger than the mean difference in environmental impacts between 2000 and 2017. This result meant that the impact of the trends in animal performance could not be observed when variability in ingredient prices was taken into account. This is contrary to the sensitivity analysis on animal performance, which for most three-year periods had a lower SD in environmental impact than the mean difference in the environmental impacts between 2000 and 2017. This suggested that the price of the feed ingredients, which reduced the concentration of soymeal in the feed, had a large effect on the environmental impacts, and that this effect in reducing the environmental impacts could be observed irrespective of variations to the trends in animal performance.

The sensitivity analyses in this study were not designed to test the true causal cause of historical changes in the environmental impacts, but only to investigate the sensitivity of trends to important input variables. Comparing the change in the mean with the SD can only indicate which input variables were most important between the two model components we examined. As such, one cannot definitively state that either changes in feed prices were the sole driver of reductions in environmental impacts, or that improved pig performance did not contribute to this development.

4.4 Comparison of the methodologies of other historical livestock LCA studies

Previous studies have indicated substantial reductions in environmental impacts from pork (Boyd et al., 2012; Cederberg et al., 2009; Matlock et al., 2014; Putman et al., 2018; Vergé et al., 2009a; Watson et al., 2018), poultry (Vergé et al., 2009b) and egg production systems (Pelletier, 2018; Pelletier et al., 2014) over periods of several decades. Historical LCA studies of livestock systems need to estimate changes in animal performance, feed composition and manure nutrient content to make comparisons at different points in time. In the aforementioned studies, animal performance was taken from different production systems representing ‘typical’ farms (Matlock et al., 2014; Putman et al., 2018) or national databases (Boyd et al., 2012; Cederberg et al., 2009; Vergé et al., 2009a; Watson et al., 2018). These studies derived feed compositions from either national statistics (Cederberg et al., 2009;

Vergé et al., 2009a), estimated them from recommendation for the period considered (Boyd et al., 2012; Putman et al., 2018), or based them on expert opinion (Watson et al., 2018). Lastly, these studies estimated emissions from manure either from statistics for the periods considered (Boyd et al., 2012; Cederberg et al., 2009; Putman et al., 2018), simple calculations based on feed intake and composition (Vergé et al., 2009a) or mass balance principles (Watson et al., 2018). All above studies made specific inventories for the upstream feed production for the investigated years, accounting for changes in crop yields, fertilizer application and other key factors that determine the environmental impact of animal feed.

Our model was designed to test our hypothesis that changes in animal performance, such as breeding for improved efficiency have resulted in reductions in the environmental impacts of pig systems. This test was applied to systems for which there were sparse available data on animal performance, feed composition and manure nutrient content. Given this context, we took different methodological approaches compared to the previous historical LCA studies; the advantages and limitations associated with methodological differences are discussed below.

I) We used a constant life cycle inventory for the production of feed ingredients and other upstream processes in the LCA model. For our purposes, this approach was preferable as it allowed us to eliminate changes and improvements in how feed is produced, especially over the relatively short time interval considered (<20 years). Due to this combination of methodological choice and limitation in the available data, our model is likely to be conservative in its presentation of the overall reduction in the environmental impacts from pig production systems. This is because it does not account for improvements in the efficiency of production for crops and other important feed inputs to pig production systems.

II) In contrast to basing feed compositions on national statistics or official recommendations, we calculated feed compositions based on least cost formulations using outputs of the animal requirement sub-model. In determining feed composition through least cost, we assumed that the pig producer is only interested in cost reduction when designing the feed.. In reality, the farmer also has some concerns over animal health and risk management (James, 2018), which are not accounted for by this method. However, the approaches of previous studies also have their limitations. For instance, feed compositions based on national statistics are difficult to apply to individual phases in the life cycle of the pig, since these data are often not available. As such, estimating feed composition based on national statistics makes it very difficult to estimate the manure nutrient content accurately. We suggest that the approach taken here is a reasonable trade-off between limitations and consequences.

4.5 Implications and conclusions

We estimated that GB pig production systems, indoor and outdoor bred respectively, reduced GWP by 37.0 % and 35.4 %, TAP by 21.2 % and 16.4 %, FEP by 22.5 % and 22.3 %, ALU by 15.8 % and 16.8 % and FRS by 16.5 % and 16.1 % over an 18-year period. Changes in feed ingredient prices, which reduce high-impact ingredient inclusion, were an important factor in determining these reductions and the outcomes of the LCA model were very sensitive to these. Change in performance and thereby animal nutrient resource requirements also contributed to the reductions in environmental impacts over time although trends in these data were less sensitive inputs to the model than feed composition. The method presented here for historical livestock LCA, where performance data is used to estimate requirements, feed composition and environmental impacts, can be applied to any animal system in the past, present and future, as long as data on animal performance and ingredient prices are available. This approach will give researchers opportunities to estimate environmental impacts for systems with sparse data availability, identify the main contributors to any changes in environmental impacts and propose improvements for systems in a less expensive and less time consuming manner. Further, this method might be an alternative strategy for studies on national environmental impact of different livestock systems. Currently, such studies rely heavily on registration of feed composition and intake, which are not always reliable at a national level.

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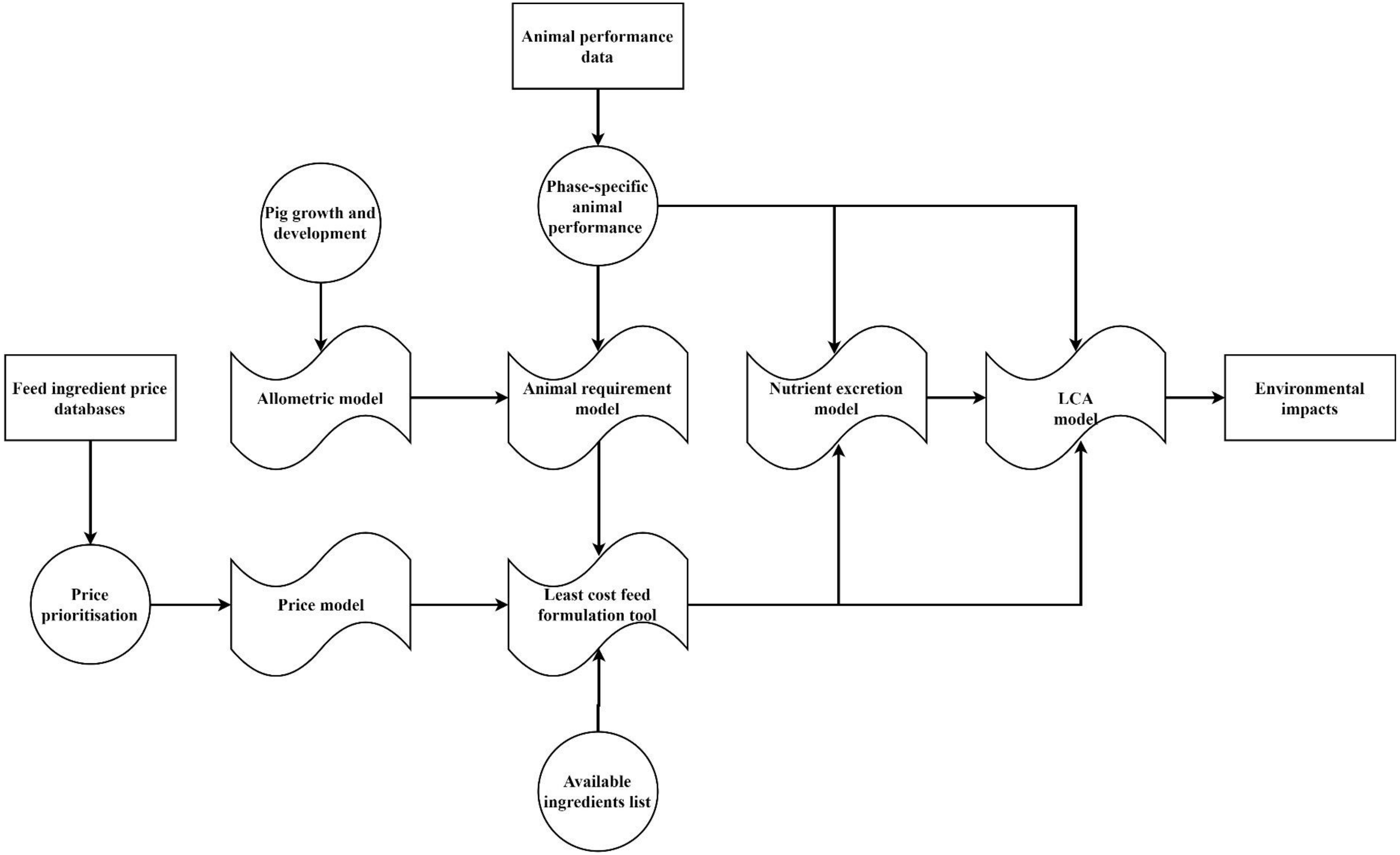

Figure 1: A Schematic representation of the Life Cycle Assessment model structure. Rectangular boxes are untransformed input and output data, circles are assumptions made during the modelling process and wavy boxes are sub-models. The animal performance data was used, to estimate their nutrient resource requirements. Available feed ingredients were assigned prices, with least cost formulation used to estimate the feed composition. Nutrient excretion is estimated from growth and nutrient intake, which are used to estimate the environmental impacts.

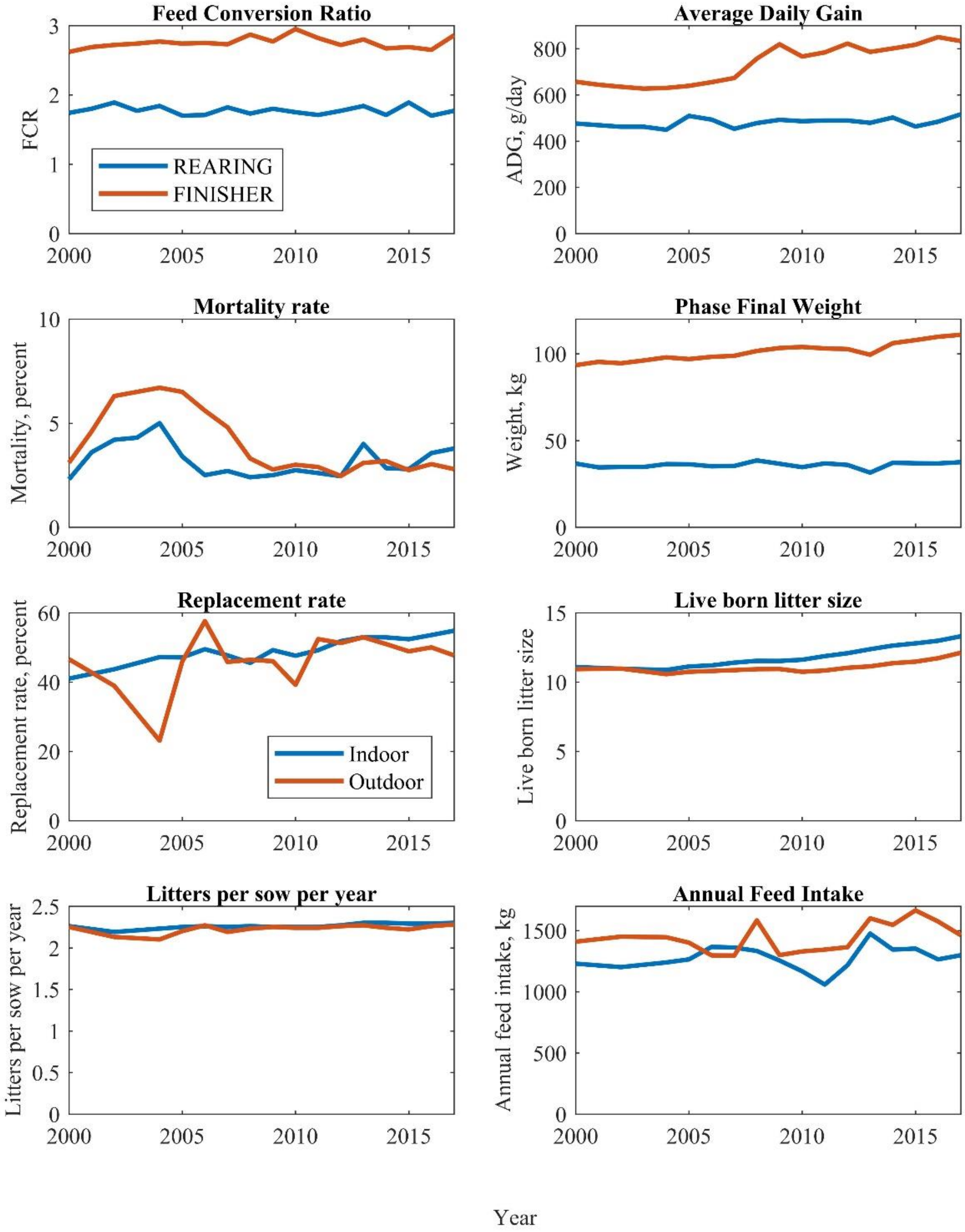

Figure 2: Average GB pig performance from 2000 to 2017, untransformed data. The different lines refer to the performance of the of the production pig (rearing vs finishing phases; top four panels), whereas they refer to the performance of the indoor and outdoor sow performance (bottom four panels).

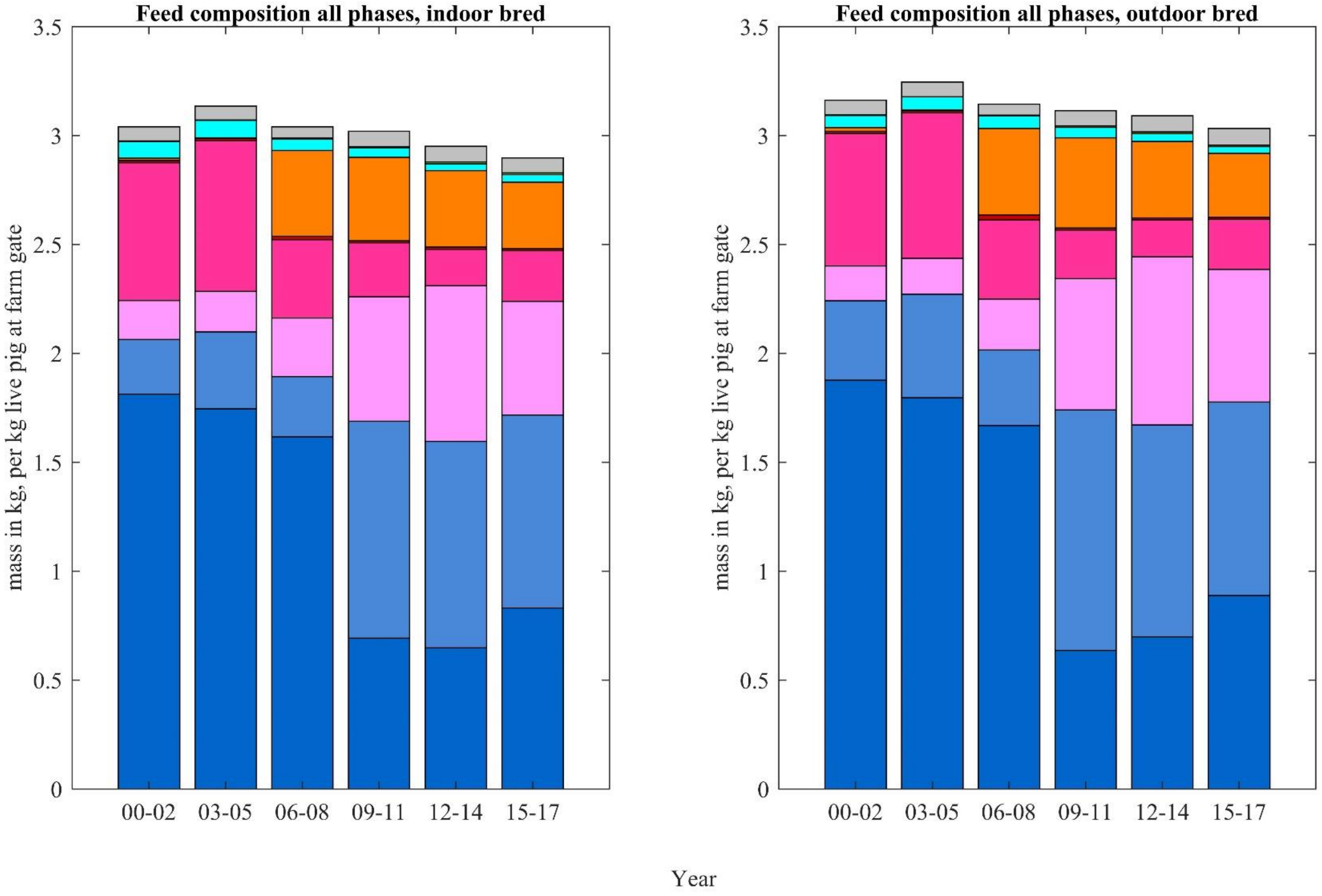

Figure 3: Overview of feed mass and composition required to produce one kg of live pig at farm-gate for indoor and outdoor breed pigs during 3-year intervals. 🟦 *wheat,* 🟦 *barley,* 🟪 *byproducts (bakery meal, biscuit meal, molassess, wheat bran, wheat midlings),* 🟪 *soy bean meal,* 🟥 *animal products (fish meal, skimm milk powder, whole milk powder, whey protein),* 🟧

alternative protein meals (rapeseed meal, sunfloser meal), 🟦 *oils (rapeseed oil, sunflower oil),* 🟩 *amino acid supplements (lysine, methionine, threonine, tryptophan, valine),* ⬜ *minerals (dicalcium phosphate, potassium cloride, salt).*

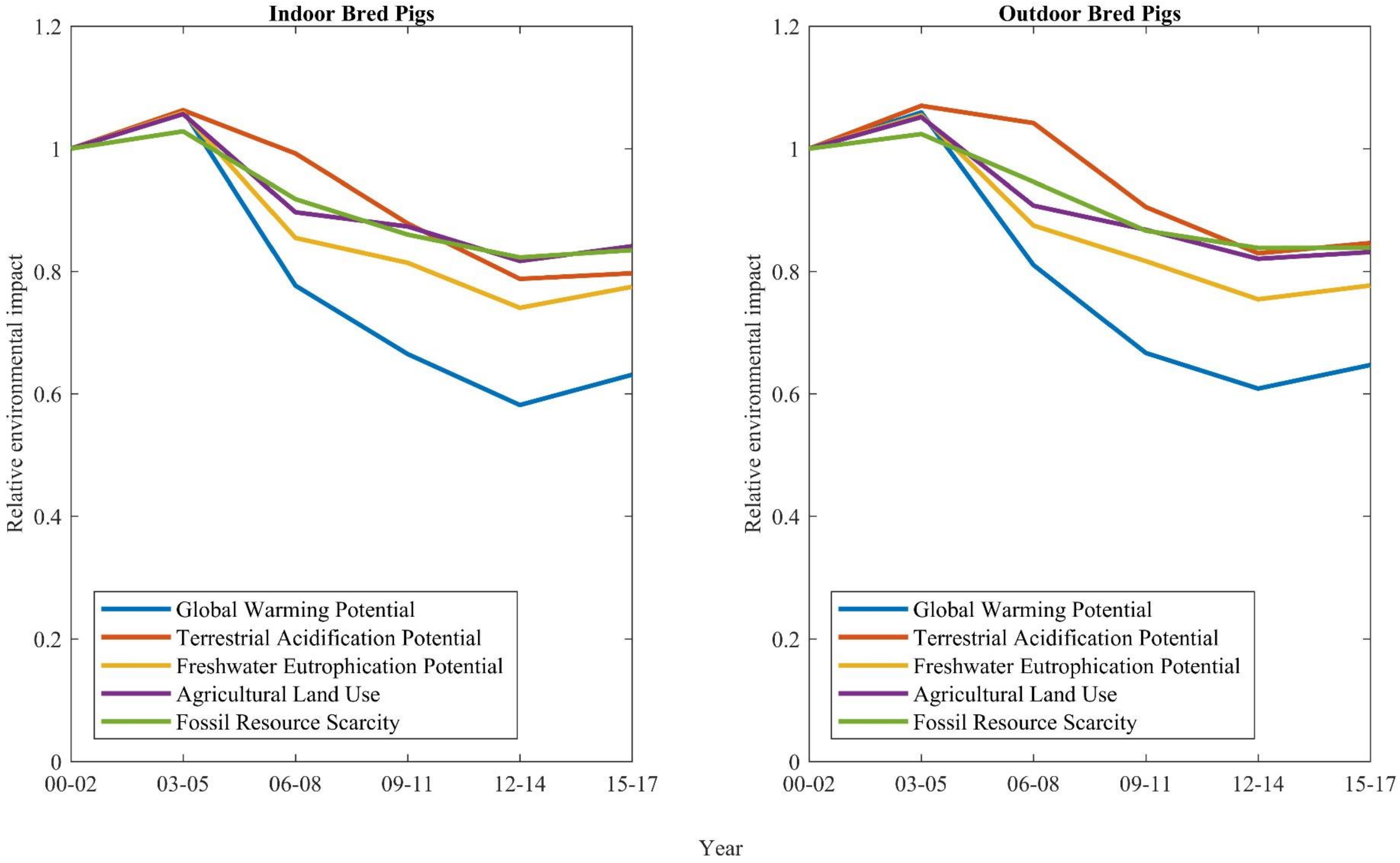

Figure 4: The temporal development in the relative environmental impact per 1 kg of live pig at farm gate from 2000 to 2017 from indoor and outdoor bred pig systems in Great Britain. The baseline (1 unit) is the environmental impact of the systems during the time interval 2000-2002. The environmental impact categories shown are consistent with LEAP (FAO, 2018b) recommendations.

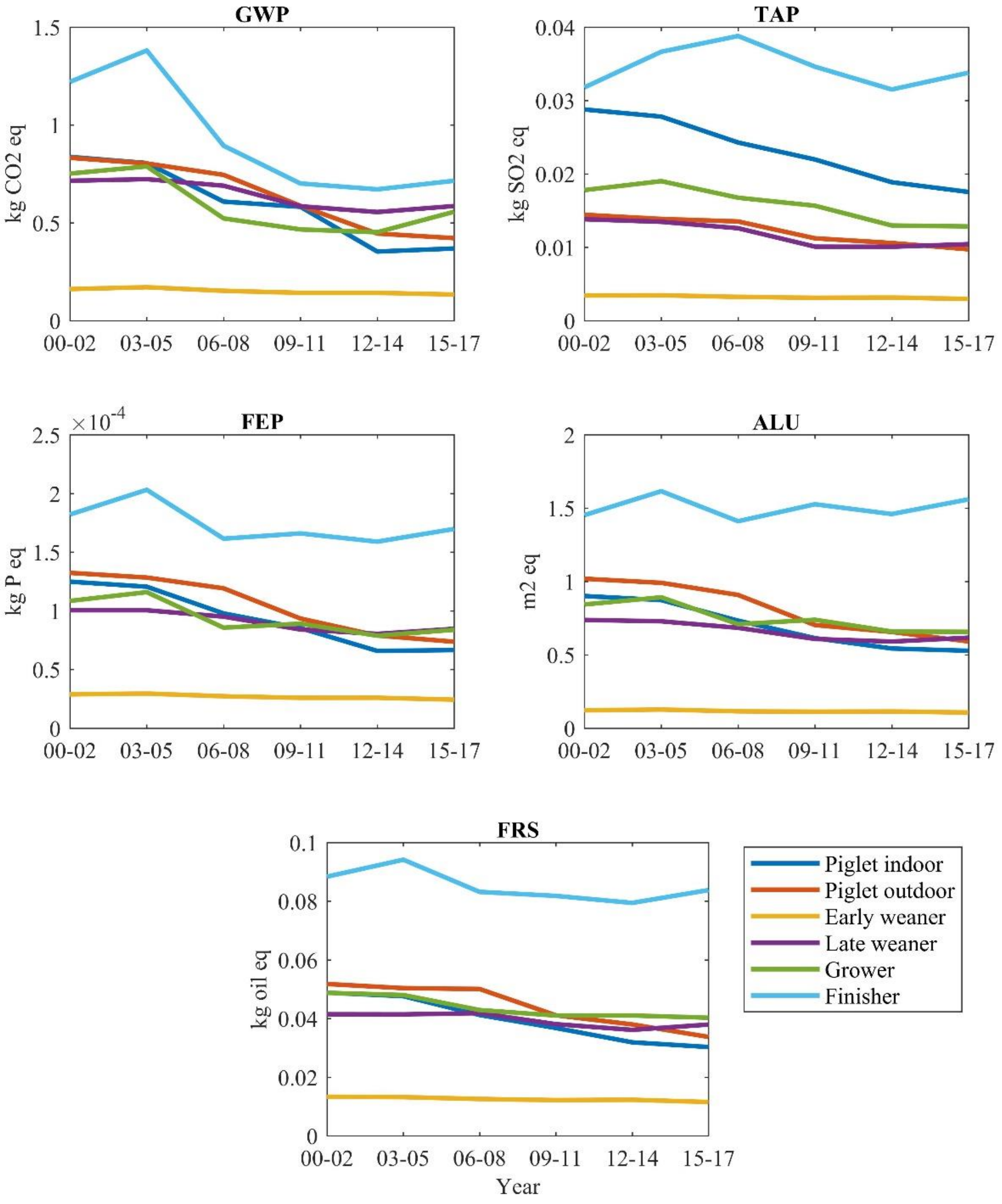

Figure 5 Contributions from the different pig production phases to Global Warming Potential (GWP), Terrestrial Acidification Potential (TAP), Freshwater Eutrophication Potential (FEP), Agricultural Land Use (ALU) and Fossil Resource Scarcity (FRS) from indoor and outdoor pig production in Great Britain. The piglet phase contains contributions from the full reproductive phase. Since indoor bred and outdoor bred early and late weaners are indistinguishable in the figure, only the indoor bred weaners are shown.

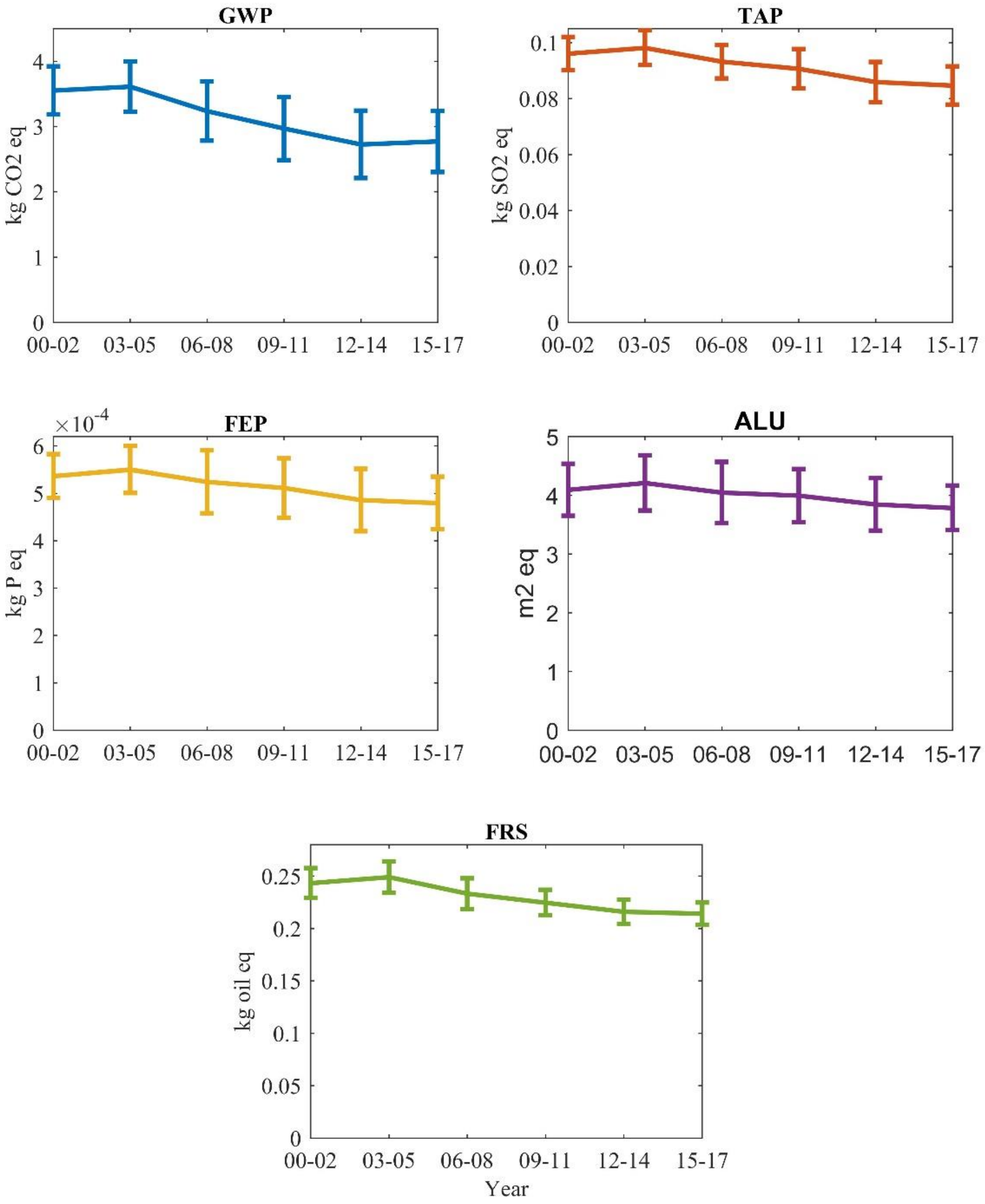

Figure 6: The change in the environmental impacts over the study period as a mean and standard deviation of model outcomes with constant prices set to each individual year (Price sensitivity analysis). The impacts are: Global Warming Potential (GWP), Terrestrial Acidification Potential (TAP), Freshwater Eutrophication Potential (FEP), Agricultural Land Use (ALU) and Fossil Resource Scarcity (FRS).

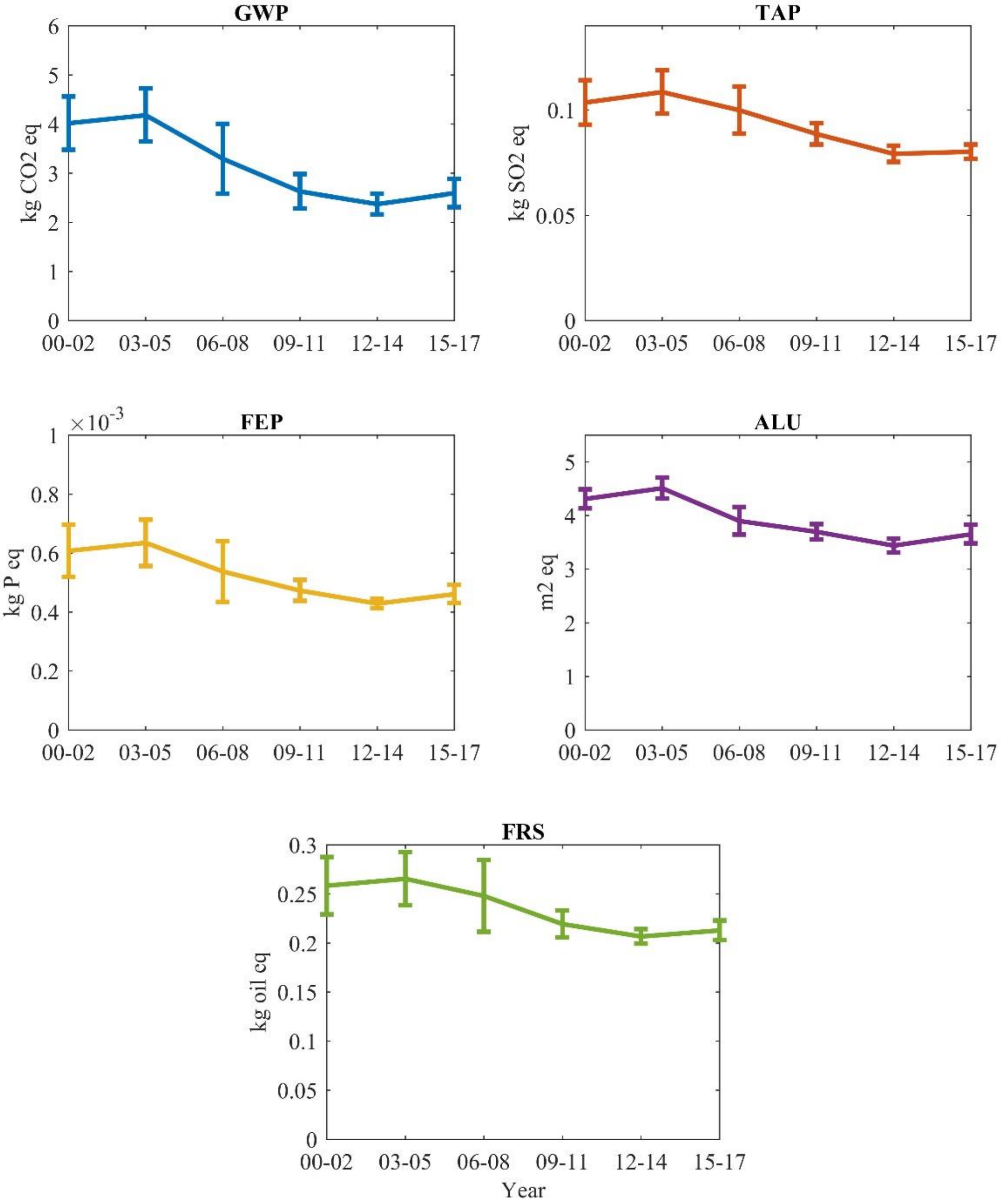

Figure 7: The change in the environmental impacts over the study period as a mean and standard deviation of model outcomes with sampled correlated animal performance for 100 iterations (Performance sensitivity analysis). The impacts are: Global Warming Potential (GWP), Terrestrial Acidification Potential (TAP), Freshwater Eutrophication Potential (FEP) , Agricultural Land Use (ALU) and Fossil Resource Scarcity (FRS).

Description	Value	Source
Heat of combustion of protein, MJ/kg	$HC_{Pr} = 23.8$	(Knap, 2008)
Heat of combustion of lipid, MJ/kg	$HC_L = 39.6$	(Knap, 2008)
Energetic efficiency of protein retention	$k_{ME(F\rightarrow Pr)} = 0.644$	(Noblet et al., 1999)
Energetic efficiency of lipid retention	$k_{ME(F\rightarrow L)} = 0.831$	(Noblet et al., 1999)
Daily energy requirements for maintenance, MJ ME	$ME_{maint}(t) = 1.068\ BW(t)^{0.60}$	(Noblet et al., 1999)
Protein efficiency of protein retention	$k_{\mathrm{Pr}(F\rightarrow Pr)} = 0.763$	(Sandberg et al., 2005)
Daily protein requirements for maintenance, kg	$Pr_{maint}(t) = 0.0004655 BW^{0.75}$	(Moughan, 1999; van Milgen et al., 2008)
Dry matter concentration in feed	$k_{DM} = 0.88$	(NRC, 2012)
Endogenous loss coefficient, kg/DM intake	$El_{Pr} = 0.008517$	(Sauvant et al., 2004)
Empty body weight to body weight ratio	$k_{eBW} = 0.95$	(Wellock et al., 2003)
Water allometry constants	$k_{w1} = 4.9$ $k_{w2} = 0.855$	(De Lange et al., 2003)
Ash allometry constant	$k_a = 0.19$	(Wellock et al., 2003)

Table 1: Parameters used in production pig requirement model. Parameters are required to ensure conservation of metabolizable energy, standardised ileal digestible protein, body weight and lipid to protein allometry

£/ton	**2000-2002**	**2003-2005**	**2006-2008**	**2009-2011**	**2012-2014**	**2015-2017**
Bakery meal	170	170	170	170	170	170
Barley	66	68	103	117	146	107
Biscuit meal	185	185	185	185	185	185
Dicalcium phosphate	200	250	275	275	275	275
fish meal	428	452	629	1019	1262	1273
Limestone	25	45	54	53	52	50
Lysine	883	1533	1615	1413	1210	1008
Methionine	1800	1950	2133	2333	2533	2733
Milk, dried skimmed	1437	1409	1836	1861	2232	1473
Milk, dried whole	1702	1711	2031	2266	2590	2114
Molasses beet	78	92	106	139	175	191
Potassium chloride	80	75	171	299	241	185
Rapeseed meal 00	92	107	139	184	238	195
Rapeseed oil	339	370	542	685	675	604
Salt	37	77	95	103	110	118
Soy bean meal	116	133	209	289	353	297
Soya oil	257	325	478	667	667	587
Sunflower meal	NaN	NaN	NaN	170	165	158
Sunflower oil	380	369	553	696	688	620
Threonine	2100	4367	4790	3725	2660	1595

Tryptophan	NaN	NaN	NaN	19000	19000	19000
Valine	NaN	NaN	NaN	NaN	5200	5200
Wheat	68	72	110	130	160	121
Wheat bran	53	55	82	99	124	89
Wheat feed midlings	NaN	80	116	131	162	133
Whey protein concentrate	1409	1409	1913	2027	2895	2217

Table 2: Estimated prices in £/ton for feed ingredients from 2000 to 2017. NaN refers to that no price was available and that the ingredient is therefore assumed not to be used in pig production (Defra, 2019; Edwards et al., 2002; Eurostat, 2019; FAOSTAT, 2019; Farmers weekly, 2017; Gordon, 2005; Hazzledine et al., 2011; IndexMundi, 2019; Tallentire et al., 2017)

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: