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Impact of animal breeding on GHG emissions and farm economics

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Executive Summary

This report reviews the existing evidence regarding the current and potential use of animal breeding to reduce GHG emissions. It also comments on the likely impact of breeding on farm economics, identifies barriers to achieving GHG reductions via breeding and highlights some future research needs.

The report focuses on the following livestock commodities within the EU-28: cattle meat, cattle milk, pigmeat, chicken meat and hen's eggs. Together these account for approximately 95% of the emissions from European livestock (measured from cradle to farm gate, i.e. including on-farm emissions plus emissions arising pre-farm from the production of inputs such as feed, fertiliser and fuel).

Beef and dairy cattle

The main sources of GHG emissions from European beef and dairy cattle production are enteric methane (CH_4) excreted directly by the animals and nitrous oxide (N_2O) and carbon dioxide (CO_2) arising from feed production. The rate of enteric methane excretion is a function of the amount of feed intake per unit of output and the rate at which methanogenesis takes place during digestion. Rates of methanogenesis depend on the gut microbiome, which can be influenced by genetics. Feed emissions are a function of (a) the emissions intensity (EI) of the feed and (b) the efficiency with which feed is converted into live weight gain or milk, i.e. the feed conversion ratio (FCR). While feed EI is unaffected by animal genetics, FCR is a function of a range of parameters, some of which can be strongly influenced by genetics, notably: cow fertility and milk yield, calf growth rates and the health status of both breeding and growing animals. Finally, the herd structure (the relative proportions of each animal type within the herd) influences the total amount of emissions and meat/milk produced, and the parameters that determine the herd structure (such as cow replacement rates or calf death rates) can also be influenced by genetics.

The trends in EU milk yield per cow imply that there is scope to significantly increase milk yield in the future. However, future reductions in EI from increasing milk yield in the EU are likely to be modest, i.e. in the range 0% to 0.5% per annum. For beef cattle, it has been argued that the relatively slow historic rates of genetic improvement represent an opportunity. It is estimated that a reduction in EI from genetic improvement of beef cattle of between 0% and 0.25% per annum could be achieved in the future. For both beef and dairy cattle, further reductions in EI may be achieved by targeting new traits, e.g. feed utilisation efficiency and rumen ecology. Recent evidence indicates that the genetic improvement of cattle can reduce emissions significantly at a negative cost, i.e. while providing net financial benefits.

Improved genetics may require increased use of concentrates to the detriment of fibre utilisation. Ruminants fill the niche of utilising fibre and non-protein nitrogen sources to produce food (meat and milk) for human consumption. Increased grain use will conflict with pig, poultry and, human food resources and biofuel production. Moving towards higher producing animals may have knock-on effects on essential fitness traits, which may negate reductions in EI.

Future research priorities include: (a) quantifying the changes in EI that are likely to arise from the forecast changes in performance once wider system level effects are included (b) identifying best practice of reducing EI via beef genetic improvement within the EU (c) investigating the extent to which new traits could reduce EI and be integrated into breeding goals (d) investigating the social acceptability of nascent technologies (e.g. transgenic modification versus gene editing) and the likely timescales for regulatory approval and (e) quantifying the effects of breeding for increased dairy cow milk yield on the EI of European beef as a whole.

Pigs

The main sources of emissions from European pig production are N_2O and CO_2 arising from feed production and N_2O and CH_4 from manure management. The FCR is one of the main determinants of pig emissions and is a function of a range of parameters, some of which can be strongly influenced by genetics (i.e. growth rates, body composition and health status). In addition there is a genetic basis of variation in N excretion that raises the possibility of reducing manure emissions by breeding for reduced N excretion.

Recent trends in European pig performance indicate significant increases in sow fertility but limited reductions in FCR. The slower than predicted improvement in FCR represents a rebound effect – improved genetics have reduced FCR at a given weight but this has also led to increases in weights at slaughter, offsetting the reductions in FCR. If rebound effects are avoided, sustaining the recent increases in growth rates and sow fertility should lead to a reduction in the emissions intensity of pigmeat via genetic improvement of around 0.3% per annum. This reduction should be achievable at low/no cost as the financial benefits of improved physical performance should outweigh the costs.

Genetic improvement should also lead to a range of social benefits, notably a reduction in the impacts associated with feed production and nutrient excretion. However, there may also be negative effects on animal health and welfare.

Future research priorities include investigating: (a) the trade-offs between improved nutrient use efficiency and disease resistance to identify the optimal combinations that can reduce EI while improving financial performance (b) non-production traits that can reduce EI by improving FCR (c) the extent to which practical barriers (such as the limitations of the production environment) and rebound effects may constrain the GHG reduction potential.

Broilers

The greenhouse gas emissions arising from broiler meat and egg production are largely associated to two sources, namely 1) feed production, processing and transport, and 2) manure emissions from housing and manure management. Therefore, it is clear that the traits associated with the feed efficiency of the bird are the key factors determining the changes in EI and how they can be affected by animal breeding. Improving the feed efficiency would reduce both the intake of feed (per unit output) and also the nutrient excretion of the birds (per unit output), thus affecting the emissions associated with both feed production and housing/manure management.

Since the beginning of the industrial broiler breeding programmes in the early 1950s, growth rate has been the main selection trait, and improvements in this trait have been spectacular and probably exceeded the achievements in any other production animal. To facilitate the faster growth, the daily feed intake of broiler birds has increased as a result of breeding. However, because the time to reach the slaughter weight has shortened, the overall feed efficiency of the birds has improved considerably and this has also reduced the GHG emission intensity, while also reducing the costs of broiler farming. The capacity to increase growth rate and daily feed intake also determines the future potential of breeding to reduce the GHG emissions arising from broiler production. Due to biological and physical limits in improvements in these traits, the future GHG reduction potential through breeding is relatively low, likely no more than 10% compared to the level of the current intensive broiler production.

As a result of "welfare-friendly" policies and changing consumer preferences, the fast growing broilers may not be the preferred trend in European countries in the future. Moving towards slower growing birds will necessary reduce the feed efficiency and therefore increase the GHG emissions and nutrient excretion. Further research needs include development of mechanistic models that link the environmental performance of different broiler genotypes to physical energy and mass balance calculations.

Layers

The European egg production industry has gone through major changes during the last decade. From 1 January 2012 keeping hens in conventional (battery) cages was prohibited in the EU, and egg producers had to change to either enriched cages or to one of the cage-free production systems. These changes have resulted in diversification in egg production, and have also affected the GHG emissions and costs of production. The new enriched cages may have resulted in even lower emission intensity compared to the old battery cages, while the lower feed efficiency and lower productivity in the alternative systems have increased the emissions.

Over decades, the potential productivity (i.e. the number of eggs per hen per year) has increased considerably as a result of breeding, and this has also improved the feed efficiency and reduced the GHG emission intensity. However, as productivity is approaching its biological limits, further reductions in emissions achieved through breeding are likely to be less than 10% compared to the current level. Furthermore, the likely future trend of moving away from the highly efficient cage system towards the less intensive free range and organic systems brings more challenges to the reductions of GHG emissions and nutrient excretion.

Future research needs include genetic studies required to better understand the limits of the laying capacity of the hen, and especially the duration of the period of maximum rate of lay. The traits related to bird behaviour, stress tolerance and shell strength would be key factors in alternative production systems, and their improvements are needed in order to keep productivity and feed efficiency at a high level. Furthermore, similarly as in broiler research, process-based energy and mass balance modelling approaches are needed to better understand the bird energy needs, energy flows and nutrient dynamics and their consequences on GHG emissions and other environmental impacts.

The abatement potential from livestock breeding in Europe

A preliminary estimate indicates that livestock breeding could reduce European livestock GHG emissions by up to 53.5MtCO_2e by 2029, representing an 8% reduction in emissions intensity. In order to achieve this reduction barriers to the uptake of improved genetics need to be overcome. In particular, genetic improvement in the beef sector has been slower and unlocking the untapped genetic potential in the beef cattle population may be aided by schemes that improve the recording of animal performance data or provide greater clarity and certainty regarding the financial benefits of investing in genetic improvement. Research could support this by improving understanding of the impact of improved genetics on farm profit, and identifying ways of internalising the external benefits of breeding (such as reduced methane excretion).

1 Introduction

1.1 Background

There are many possible technical mitigation options for livestock systems. These could be delivered through improved livestock and livestock system efficiency - converting more energy into product output, thereby reducing GHG emissions per unit product. One of the tools available to farmers is genetic selection. Genetic improvement of livestock is a particularly cost-effective technology, producing permanent and cumulative changes in performance. Mechanisms by which genetic tools could be used to reduce emissions per kg product include: (a) improving productivity and efficiency; (b) reducing wastage at the herd or flock level; and (c) reducing emissions by direct selection, if or when individual animal emissions are measurable.

1.2 Aims

The aim of this report is to review the existing evidence regarding the current and potential use of animal breeding to reduce GHG emissions. It also comments on the likely impact of breeding on farm economics, identifies barriers to achieving GHG reductions via breeding and highlights some future research needs.

1.3 Scope

The project focuses on the following livestock commodities within the EU-28:

- Beef
- Cow's milk
- Pigmeat
- Chicken meat
- Hens' eggs

Small ruminants (i.e. sheep and goats, SG) are not included because, while they are important in some member states, overall they represent a small percentage of emissions (Table 1).

Table 1. Total GHG emissions in the EU 27 by commodity (including land use and land use change, quantified assuming a mixture of grassland and forest is converted to farmland, i.e. scenario 2). (Source Leip et al. 2010). SG: sheep and goats diam.

	Beef	**Cow's milk**	**Pork**	**SG meat**	**SG milk**	**Eggs**	**Poultry meat**	**Total**
ktCO$_2$e	191,000	193,418	164,780	24,425	12,103	20,574	54,360	660,659
% of total	29%	29%	25%	4%	2%	3%	8%	100%

1.4 Methodology

The study reviews published studies on the costs and GHG mitigation potential of livestock breeding (including academic papers and technical reports, such as DEFRA (2008a), MacLeod et al. (2017)). In order to contextualise the potential reduction in GHG emissions that may be achieved via breeding, trends in key parameters (such as cow milk yield, and pig and broiler growth rates) are examined, using industry data (e.g. Aviagen (2014a, b), AHDB (2018)) and other data sources such as Eurostat and FAOstat. The study also draws on unpublished results of project team members are involved in (e.g. GENTORE, https://www.gentore.eu/).

2 Greenhouse gas emissions from European livestock production

Previous studies have quantified the GHG emissions arising from livestock production within the EU (Leip et al (2010), Lesschen et al. (2011)). More recent estimates for Europe have been produced by the FAO using GLEAM, the Global Livestock Environmental Assessment Model (FAO 2017). These estimates are for 2015 and include the EU and a small number of non-EU states (i.e. Belarus, Moldova, Ukraine, Albania, Bosnia and Herzegovina, Montenegro, Serbia, Republic of North Macedonia, Switzerland, Norway, Iceland and the Faroe Islands). These studies highlight the importance of cattle, pigs and poultry as sources of GHG emissions within Europe (Figure 1). They also highlight the main sources of GHG: feed production, enteric methane excretion and manure management (Figure 2).

Figure 1. Production and GHG emission in Europe in 2015 (based on FAO 2017)

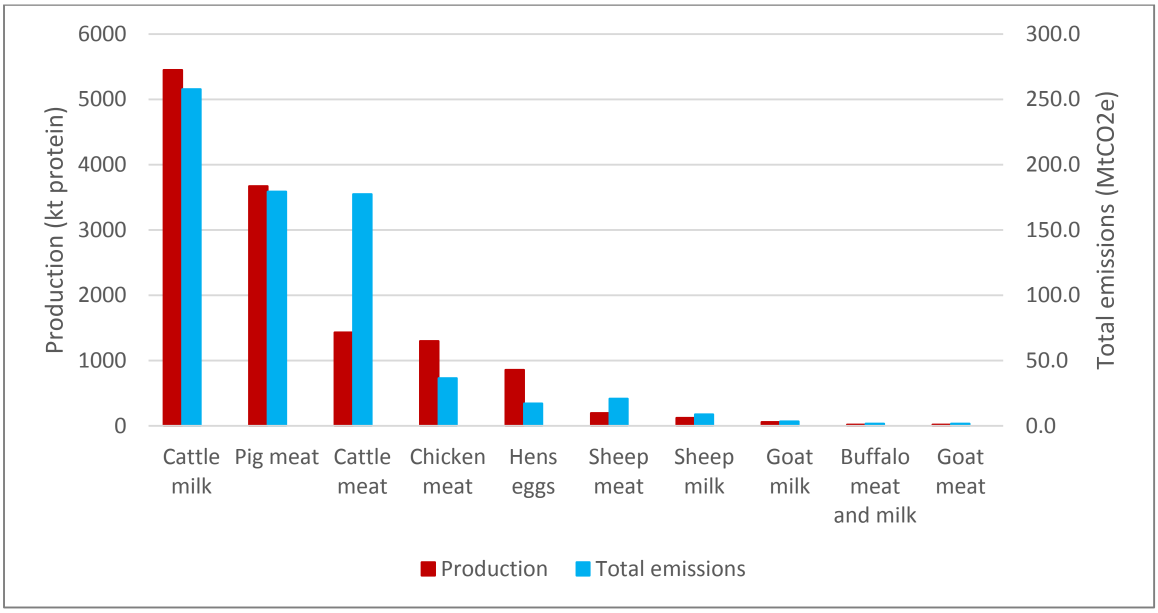


Figure 2. GHG emissions by commodity and category, Europe 2015 (based on FAO 2017)

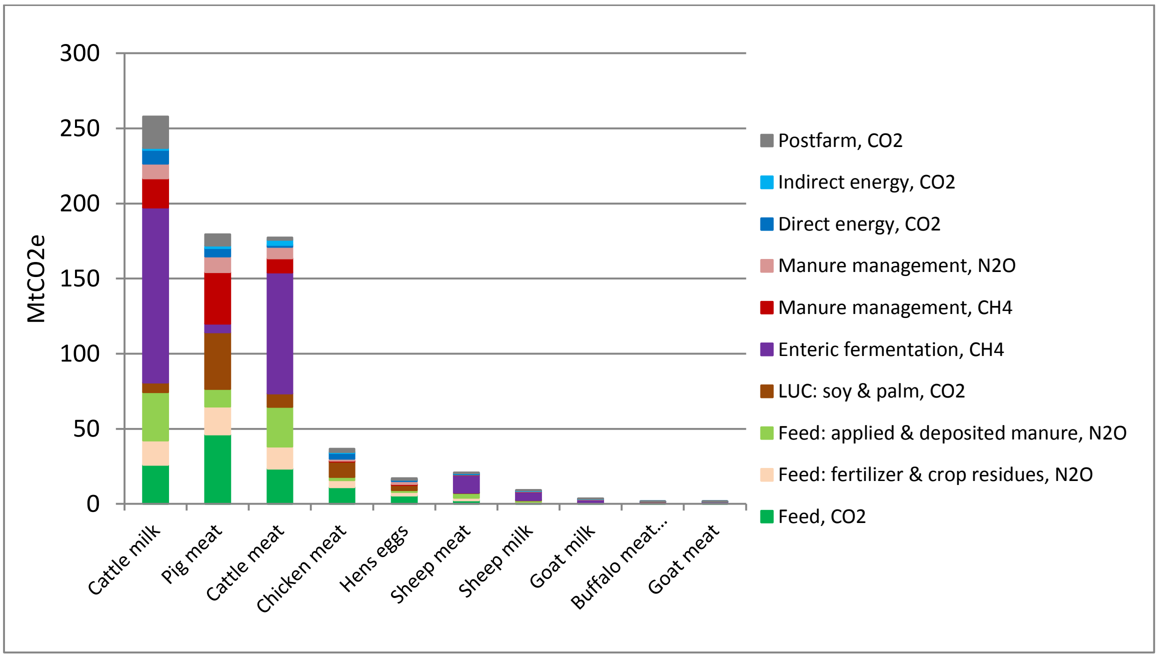
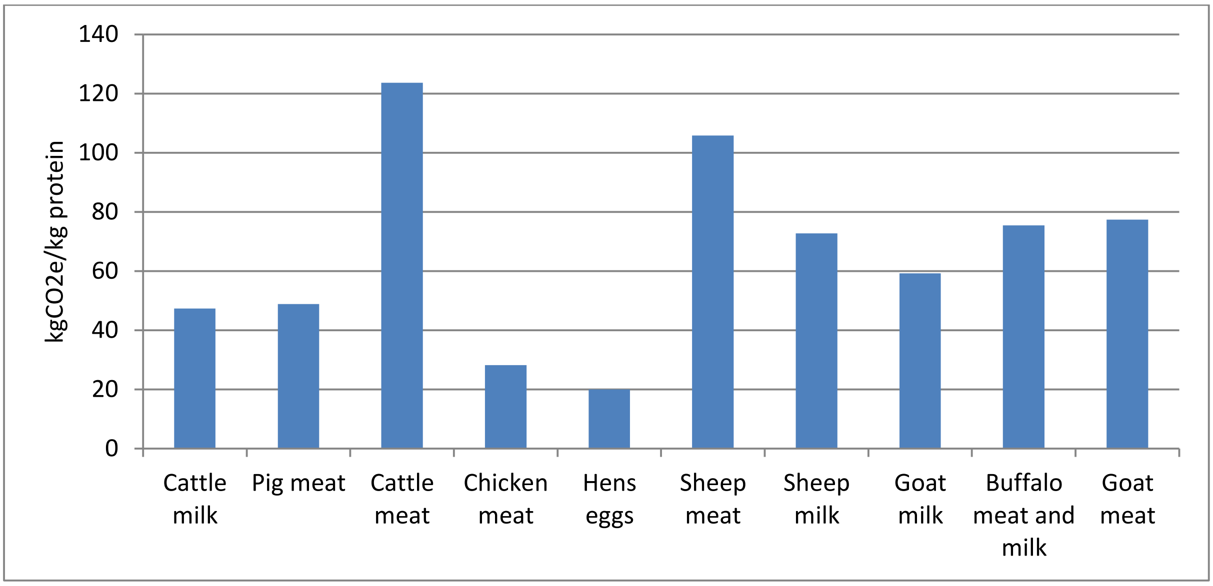


Figure 3. Emissions intensity by commodity, Europe 2015 (based on FAO 2017)



The emission intensities (EI, i.e. the kg of GHG per unit of output) of the main commodities are shown in Figure 3. In the previous 40 to 50 years there have been major gains in the productivity of livestock, which have led to "significant reductions in the greenhouse gas emissions and global warming potential per tonne of animal product…achieved either through genetic improvement alone or in combination with better husbandry, nutrition and disease control." Hume et al. (2011). In the following sections, key changes in productivity are examined and the extent to which further reductions in EI may be achieved via genetic improvement analysed.

3 Cattle

3.1 Background

The main sources of GHG emissions from European beef and dairy cattle production are enteric methane excreted directly by the animals and nitrous oxide and carbon dioxide arising from feed production (Figure 2). Enteric methane is a function of the amount of feed intake per unit of output and the rate at which the methanogenesis takes place during digestion. Feed emissions are a function of (a) the emissions intensity (EI) of the feed and (b) the efficiency with which feed is converted into live weight gain, i.e. the feed conversion ratio (FCR). While feed EI is unaffected by animal genetics, FCR is a function of a range of parameters, some of which can be strongly influenced by genetics, notably: cow fertility and milk yield, calf growth rates and the health status of both breeding and growing animals. Rates of methanogenesis depend on the gut microbiome, which can be influenced by genetics. Finally, the herd structure (the relative proportions of each animal type within the herd) influences the total amount of emissions and meat/milk produced, and the parameters that determine the herd structure (such as cow replacement rates or calf death rates) can also be influenced by genetics.

Many cattle production and fitness traits have been shown to have a genetic component and have scope to be improved via genetic selection. GHG reductions can be achieved simply through selection on production traits, e.g. milk yield and growth rates, e.g.:

- Reducing the number of animals required to produce a fixed level of output, e.g. the dairy sectors in the UK, Canada and the USA have maintained milk production while reducing the number of dairy cows (DEFRA 2001, Désilets, 2006, Capper 2009).
- Reducing the finishing period for beef animals, thereby reducing emissions per unit output. Hyslop (2003) showed that there was also a significant breed difference suggesting that bigger continental breeds of cattle produced less emissions/unit output than the smaller British type breeds.

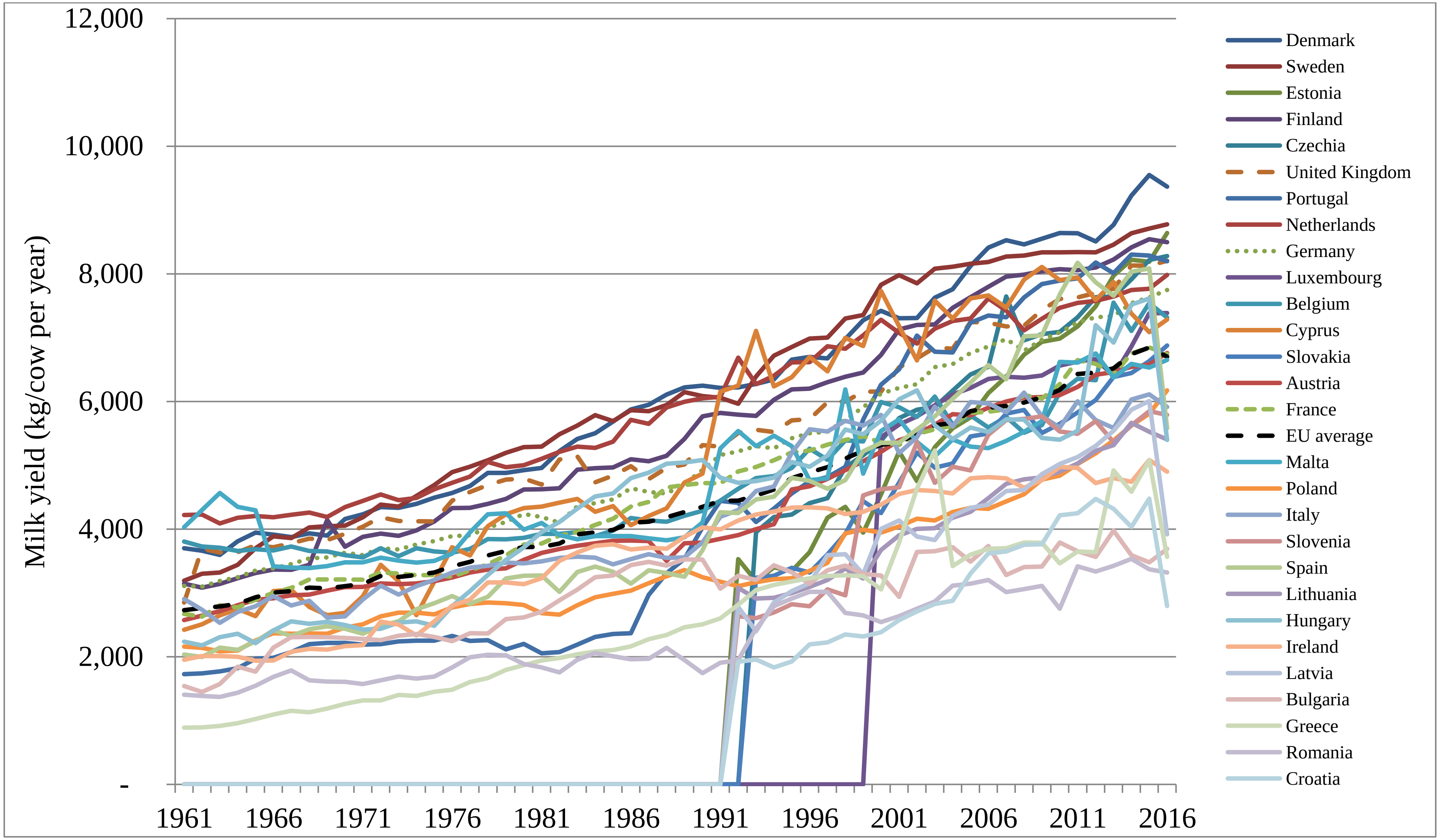
Selection for fitness traits (lifespan, health, fertility) will help to reduce emissions by reducing wastage of animals. For example, lengthening the lifespan of breeding females will reduce wastage by reducing the number of followers. Improving health and fertility will reduce involuntary culling rates thereby reducing the numbers of followers required. Improving fertility will reduce calving intervals and inseminations resulting in shorter dry/unproductive periods. This reduces management costs as well as emissions. Improving health reduces incidence of health problems/diseases, thereby improving animal welfare and reducing treatment costs (and lower antibiotic use) and reducing emissions by maintaining the productivity level of the animal (which is reduced during periods of poor health). Improving calving and maternal traits will reduce emissions by improving survival of offspring during the peri-, neo- and post- natal periods. This will reduce wastage in a farming system, thereby decreasing overall emissions as well as improving calf and maternal welfare and survival.

3.2 Trends in key parameters influencing emissions intensity (EI)

Milk yields within the EU vary considerably between member states (Figure 4). There have been steady increases in milk yield across all member states over time, with little sign of the rate of increase reducing. Over the period 1961-2016 the EU annual rate of increase in milk yield was 2.6%.

Increasing milk yield can lead to significant reductions in EI, by diluting the "maintenance overhead", i.e. the baseline GHG emitted by the cow (the emissions arising from the maintenance requirements of the cow, rather than the emissions associated with lactation). For example Capper et al. 2009 estimated that the EI of milk in the USA had decreased by 37% between 1944 and 2007.

Figure 4. Cow milk yield over time in EU member states. Country list sorted by 2016 milk yield (highest to lowest). Data downloaded from FAOstat, 16/10/18



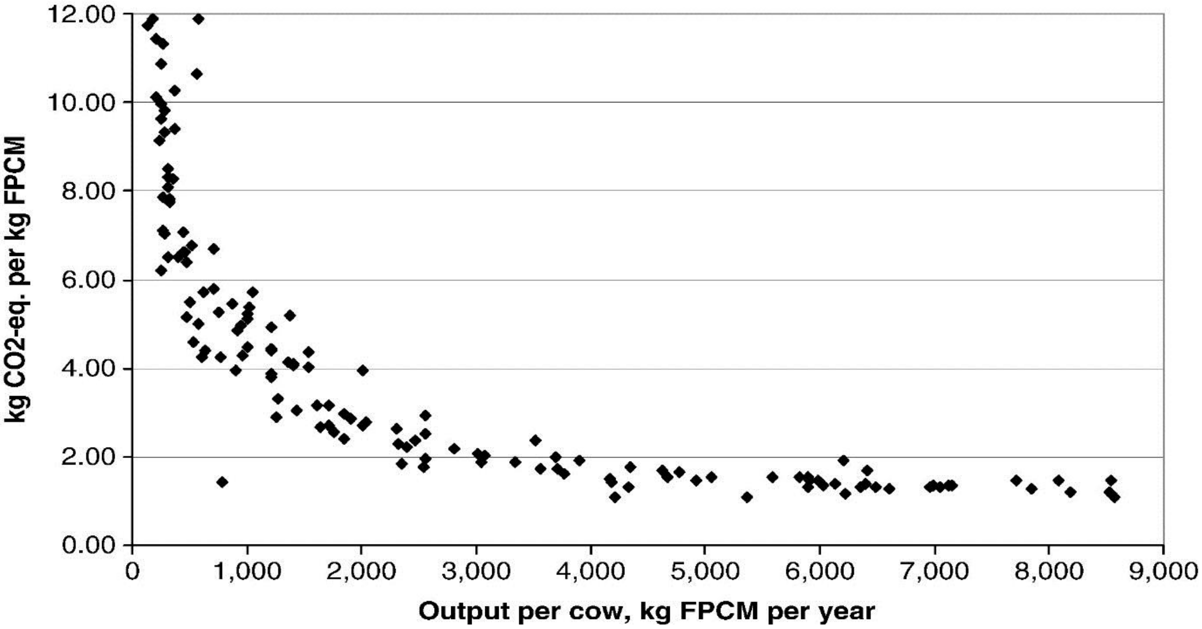
For beef cattle, increasing growth rates dilutes the "maintenance overhead" in a way analogous to increasing milk yield in dairy cattle. In the USA significant increases in growth rates has been achieved via breeding, feeding and the use of growth-promoting hormones. Beef cattle in the EU generally have lower growth rates and are finished significantly older, suggesting that significant reductions in EI could be achieved by using breeding to increase growth rate and reduce age at slaughter.

3.3 Scope for further reductions in emissions intensity via breeding

Dairy cattle

The trends in Figure 4 imply that there is scope to significantly increase milk yield in the future (EU average in 2016 was 6,702 kg milk per milk cow per year compared to 10,330 in the USA). Furthermore, experimental herds in the UK have achieved yields of over 13,000kg milk per milk cow per year (Dewhurst pers comm 2019). DEFRA (2008a, p13) estimated that the "Impressive rates of genetic improvement have been achieved over the last few years for dairy cattle." had resulted in a 0.8% per year reduction in milk EI over the period 1988-2008, and predicted that "the high rates of annual reduction in emissions achieved to date would still be expected to be achieved over the next 15 years if current selection practices were to continue." Lamb et al. (2016b) predicted that it should be possible to sustain the rates of improvement in dairy cow FCR achieved over the last few decades, and predicted an annual decrease in FCR of between 0% and 1%. However, even if such improvements in milk yield and FCR are realised, it is unlikely to result in a proportionate reduction in EI, as there is a diminishing marginal reduction in EI from increasing milk yield (Figure 5). This means that future reductions in EI from increasing milk yield in the EU are likely to be modest, i.e. in the range 0% to 0.5% per annum.

Figure 5. Relationship between total greenhouse gas emissions and output per cow. Each dot represents a country (Gerber et al. 2011)



Beef cattle

In the UK, DEFRA (2008a) noted that "the overall effect of past genetic improvement in beef cattle (on EI) was positive but small when considered across the whole industry, being less than 0.5% over 20 years…The relatively low effect of genetic improvement in beef and sheep on emission is largely due to the lack of uptake of recording and partly due to a lack of focus within some recording flocks and herds, which has resulted in a lower than possible rate of genetic improvement."

They estimated that if these barriers to genetic improvement could be overcome, then reductions in EI of around 2% to 5% could be achieved for the beef industry within 15 years, i.e. annual reductions of 0.1% to 0.3%.

Lamb et al. (2016b, p21) argued that the slow rate of genetic improvement in beef cattle meant that there is "significant untapped genetic potential in the beef cattle population". Based on results from recent breeding programmes, which reported improvements in beef cattle FCR of 7% to 25% within one generation, they concluded that a combination of genetic selection and improved nutrition could lead to an annual reduction in FCR of between 0% and 1%. Assuming half of this gain is due to genetic improvement, this would translate into a reduction in EI from genetic improvement of between 0% and 0.25%.

New traits for cattle

The reductions discussed above are based on traits that are routinely included in selection objectives. New traits that may help further reduce emissions are outlined below.

Feed utilisation efficiency has been considered in the selection programmes for pig and poultry species. Due to the nature of many cattle production systems, with less opportunity for intensive feed recording, the use of such traits in selection has been limited but there have been some examples. Herd et al. (2002) showed that there is a decreased enteric methane production per day in animals selected for reduced residual feed intake. Reduced residual feed intake is akin to selection for high feed efficiency as an animal is eating less but maintaining a similar growth rate (high net feed efficiency) and therefore less feed is required to produce a unit of output. Lines were divergently selected for high and low residual feed intake and showed no significant differences for most production traits. This shows the possibilities for selection of reduced GHG emissions through the selection of animals which use less feed and produce less methane than average to achieve a given level of performance.

Feed intake has a large influence on the amount of CH_4 produced during enteric fermentation. Basarab et al. (2013) describe three hypotheses explaining how this influence takes place. i) Animals with a higher feed efficiency take in lower amounts of food, while maintaining the same levels of production and body maintenance. Less feed intake leads to less CH_4 production, while production and body processes are maintained at the same level as for cows with a lower feed efficiency. ii) Level of feed intake influences the time the feed stays in the rumen, as well as rumen volume. When rumen retention time goes down, the amount of CH_4 produced will be lower. iii) High feed efficiency has underlying differences in behaviour and digestion, causing a change in response in the microbial communities. This causes a shift from acetate into propionate, which will decrease the amount of hydrogen available for the formation of methane (Basarab et al., 2013). Oliveira et al. (2018) assessed the relationship between feed efficiency (residual feed intake) and CH_4 production but could not confirm that higher feed efficiency leads to lower CH4 production. Other studies have shown that improving feed efficiency will lower CH_4 production in cattle (Alford et al., 2006; Hegarty and McCorkell, 2007; Basarab et al., 2013).

Traits related to the efficiency of absorption of dietary nutrients. Direct selection for efficiency of utilisation of the different components of the diet is difficult to achieve as many animal and feed parameters need to be collected. Work on these types of traits has mainly been at an experimental level. Ferris et al. (1999) showed that medium genetic merit (for production) Holstein-Friesian cows have higher nitrogen and methane emissions per unit of N and gross energy intake respectively than high genetic merit cows. This suggests that high genetic merit cows convert the energy and protein components of the feed more effectively than medium genetic merit cows. Hegarty (2004) reviewed the evidence for a genetic difference in gut function in ruminants covering genetic components of things such as diet selection and eating rate, digestive kinetics and methane production. There were data to suggest that there are genetic differences in the amount of methane produced/unit feed intake. Further examination of the metabolic turnover of nutrients in animals may be required to understand the underlying biological differences between high producing animals in their feed utilisation and lower genetic merit animals. Other metabolic traits that require further examination due to their impact on emissions include water dynamics (manure consistency), gut function (nutrient and mineral absorption) and litter quality.

Breeding for reduced methane emissions. Some literature suggests that the genetics of mammals have an influence on the micro-organisms present in the gut (Hegarty and McEwan, 2010). Goopy et al. (2014) showed it was possible to select sheep for high or low CH_4 yield and found selection for low CH_4 yield caused changes in the animal's nutritional physiology. In their recent review, Dewhurst and Miller (forthcoming) found that while several studies (e.g. Roehe et al. (2016), Difford et al. (2018)) had identified in-breed variation in methanogenesis related to rumen microbiome, the limited evidence available suggests that selecting for reduced methane emissions may have negative effects on other aspects of productivity that offsets any reductions in methane production.

3.4 Cost of breeding programmes and impact on farm economics

Broader breeding goals have become the norm in many livestock species, usually incorporating production and "fitness" (health, fertility, longevity) traits. Breeding goals can be built in a number of ways including the popular method of weighting traits by their relative economic value (REV). These REV's tend to be calculated by estimating the economic dis/benefit to the system of a unit change in the traits being examined. A lot of the example traits given earlier have been incorporated into indices for particular livestock sectors. However, livestock industries have more recently needed to consider societal views of aspects of farming systems, including issues such as welfare, biodiversity, food safety, health properties and environment.

There is evidence that cattle breeding provides a substantial cumulative economic benefit. Taking the UK as an example, the annualised rate of return for genetic improvement of beef cattle is estimated at up to £4.9m for the period 2001-2013 (Amer et al., 2015); for dairy, the annualised rate of return for genetic improvement of dairy cattle is estimated to average £7.4m for the period 2004-2009 (Amer et al.,2011). In addressing just one barrier, for example the uptake of genomic selection tools in UK beef production, the annualised rate of return is projected to increase by £0.7m (Amer et al., 2015). However, benefits of genetic progress should not only be measured in monetary terms, with reductions in overall emissions and emissions intensity known not only by improvements in traits associated with production, but also fitness and functional traits including disease, lameness and longevity (Bell et al., 2014; Grandl et al., 2018).

Eory et al. (forthcoming) quantified the GHG mitigation cost-effectiveness of four different approaches to genetic improvement in cattle: (a) traditional selective breeding, (b) selective breeding with genomics, (c) breeding for rumen microbiome with reduced methanogenesis, and (d) genetic engineering. They found that for all four cases, the financial benefits were greater than the costs, i.e. GHG emissions were reduced and farm profits increased.

3.5 Barriers to achieving reductions

The general goal of animal breeding is to produce a new generation of animals that will yield the desired products more efficiently under future farm economic, social and environmental circumstances, and be more resilient to perturbations than the present generation of animals (Groen, 1989). Improving the rate of genetic gain relies on identifying and mating cattle with reliable estimates of high genetic merit. The rate of gain will be greater where there is large variation in a population, and when supported with tools such as AI and sexed semen. And the sooner reliable data is available on a particular animal, the sooner that animal can be used to breed the next generation, thus is the importance of genomics to the achievable rate of genetic progress. Animal breeding delivers substantial cumulative and permanent gains to cattle industries, and new opportunities offer the potential to enhance the rates of improvement. However, barriers exist to the use of genetic improvement tools, which slow the rate of improvement, with resultant missed opportunities in terms of economic gains and GHG mitigation.

A recent survey, conducted as part of the H2020 GenTORE project, asked cattle system stakeholders across Europe what they perceive to be the most substantial barriers to genetic progress (GenTORE 2019 pers. comm.). In the context of both dairy and beef production, four of the top five perceived barriers were the same for both systems (although the order differed), they were: (i) performance recording (phenotyping), (ii) uncertainty of future production circumstances, (iii) disagreement with breed society priorities, and (iv) cost for farmer.

Taking phenotyping and cost for farmer as examples, the continued use and proliferation of schemes such as Scotland's Beef Efficiency Schemes (BES) and Ireland's Beef Environmental Efficiency Scheme (BEES) incentivise farmers to provide animal performance data by offering financial and advisory benefits. Schemes such as these address multiple barriers at once, in relieving pressure on farmers who otherwise may see limited immediate benefit from recording performance data and, for breeding organisations who require participation of farmers to provide the large datasets necessary for breeding technologies such as genomic predictions. Additionally, further structural changes in the way performance data is collected may involve actors from further down the supply chain; for example, supermarkets in providing consumer-focussed meat quality attributes, and abattoirs in providing more specific data on disease traits.

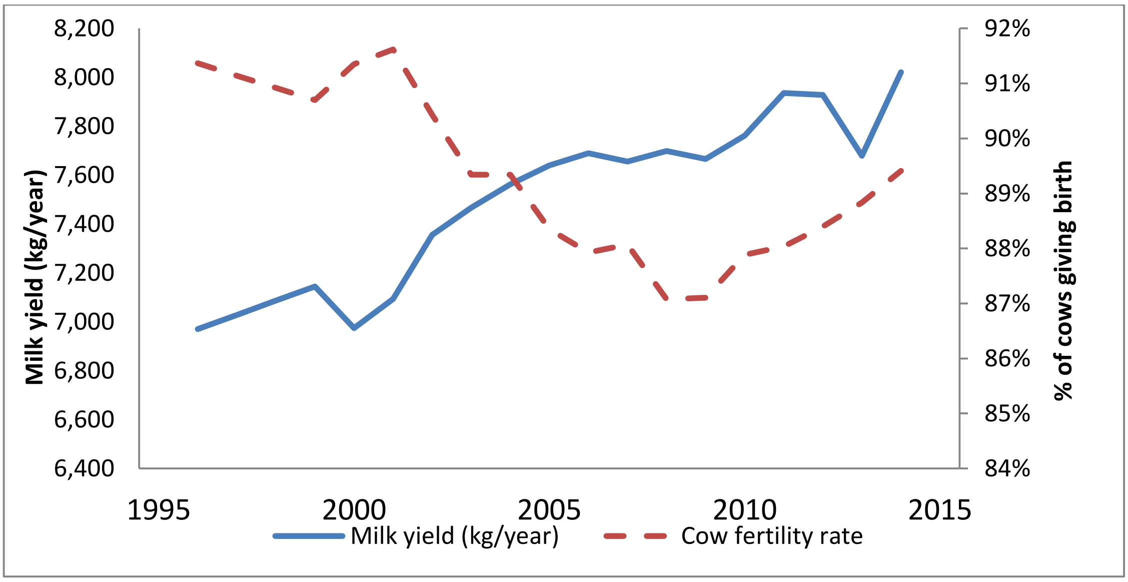
Additionally, there are barriers to specific aspects of genetic improvement, for example the use of AI technologies, which have been explored by Telford et al. (2003) in the context of UK suckler beef producers. The authors found the main barriers to be: insufficient labour 60% (particularly in larger herds and in non-LFA herds), believing AI is too expensive 40% (particularly in larger herds and in LFA herds), expecting poor *conception rates 40% (particularly in larger herds and in non-LFA herds), lack of access to handling facilities 32% (particularly in non-LFA herds), believing AI bulls are not superior to existing stock bulls 17%.*

Improved genetics may require increased use of concentrates to the detriment of fibre utilisation. Ruminants fill the niche of utilising fibre and non-protein nitrogen sources to produce food (meat and milk) for human consumption. Increased grain use will conflict with pig, poultry and human food resources (and biofuel production) and may not be acceptable to consumers.

There is the risk that some genetic improvements may not be permanent. Rumen microbes very easily adapt to dietary changes to restore the status quo so prolonged effects may be difficult to achieve.

Moving towards higher producing animals may have knock-on effects on essential fitness traits. Any reduction in EI via breeding for increased milk yield may be negated if it impacts on other aspects of physical performance. For example in Scotland, selecting for a single trait (milk yield) led to a reduction in cow fertility which was reversed when multiple trait selection was adopted around 2008 (Figure 6).

Figure 6. Trends in Scottish dairy cow milk yield and fertility (based on data in CDI 2016).



Beef produced from the European dairy herd has an EI of about half that of beef from suckler systems (Opio et al. 2013, p30), and is one of the main reasons that European beef has a lower EI than beef from other regions of the world. Improving dairy cow milk yield means that fewer cows are required to produce the same amount of milk. While this reduces the breeding overhead in the dairy herd (assuming cow replacement rates do not increase) it also reduces the amount of beef produced by the dairy herd, thereby increasing the average EI of all European beef.

Taking account of societal views in the economic framework of selection indices can be difficult as there may be no clear and direct monetary return from such considerations. Using restricted or desired gains approaches to selection indices allow the weightings to be derived that will see the desired response in traits of interest. For example, Wall et al. (2007) showed how restricted index methodology could be used to halt the expected genetic decline in fitness traits in dairy cattle if selection were to continue on the available economic index. The difficulty in restricted/desired gains index methodology is developing a robust way of deciding on the desired outcomes of the selection index. As selection considers the longer term changes in a system the desired outcomes of selection cannot change year on year.

The environment in which cattle are managed will change (e.g., temperature changes, grass growth seasons, drought and flood prevalence, and duration of housing periods). Genetic improvement can be used as a tool to help livestock species adapt to the new environment as well as help to mitigate emissions. Examples include selection for heat tolerance (US work), selection for hardiness traits (could be introduced for other breeds through crossing or by breed substitution) and selection for efficiency/sustainability of production levels in future systems (change in dietary regimes). Genotype by environment interaction will also become important in adaptation to climate change so that animals will be suitable for the new production systems that will result from climate change (e.g., disease challenges, shorter/longer housing periods, feed quality). The GenTORE project ("GENomic management Tools to Optimise Resilience and Efficiency", https://www.gentore.eu) *seeks to develop innovative, genome-enabled selection and management tools to optimise cattle resilience and efficiency in widely varying environments across the EU (Friggens et al. 2017).*

3.6 Future research needs

Further research is required to quantify the changes in EI that are likely to arise from the forecast changes in performance (e.g. in terms of milk yield and growth rates) once the wider system level effects are included. Realising the full expression of genetic potential may require changes to the production system, i.e. changes to the ration and housing, which may enhance or reduce the GHG effect of the genetic improvement. Life-cycle analysis is a useful tool for capturing these systemic effects.

Given the relatively slow uptake of improved genetics in beef farming, work is required to identify the barriers to uptake in order to develop policies for overcoming these. This may be aided through the identification of examples of best practice of reducing EI via beef genetic improvement within the EU. Addressing barriers may be assisted by an improved understanding of:

- Variation in the impact of improved cattle genetics on farm profit.
- The main cost barriers and how they might be overcome.
- How farmers might be encouraged to better record animal performance data.
- How farmers might be rewarded for selecting genetics with external benefits, e.g. lower rates of methane production.

It would also be useful to clarify the extent to which new traits could reduce EI and be integrated into breeding goals, i.e.:

- Traits related to the efficiency of absorption of dietary nutrients
- Breeding for reduced methane emissions
- Feed utilisation efficiency

Genetic engineering presents an opportunity to speed up the process of reducing EI via genetic improvement. The extent to which this potential may be will realised depends to a large extent on consumer attitudes. A better understanding of the social acceptability of different technologies (e.g. transgenic modification versus gene editing) and the likely timescales for regulatory approval would help predict the future rates of commercial deployment.

As noted in the previous section, breeding for lower emission in cattle can lead unintended consequences. Further analysis is required to improve understanding of the (a) potential trade-offs between breeding for reduced EI and for resilience in the face of climate change and (b) the effects of breeding for increased dairy cow milk yield on the EI of European beef as a whole.

4 Pigs

4.1 Background

The physical performance of pigs can vary depending on a wide range of factors, such as genetics, diet, housing and management. These factors produce marked differences in growth rates, fertility rates and death rates which, in turn, produce significant variation in both individual animal performance and the overall herd structure. These variations can affect emissions intensity by:

- changing the proportion of the growing pig's energy intake that is devoted to growth, rather than unproductive activities such as maintenance;
- changing the relative proportions of each animal type within the herd. For example, increasing the sow fertility rate (or reducing piglet mortality) will lead to a reduction in the ratio of breeding: growing animals;
- changing losses through mortality.

The main sources of emissions from European pig production are N_2O and CO_2 arising from feed production and N_2O and CH_4 from manure management (Figure 2).

Feed emissions are a function of (a) the emissions intensity (EI) of the feed and (b) the efficiency with which feed is converted into live weight gain, i.e. the feed conversion ratio (FCR). While feed EI is unaffected by genetics, FCR is a function of a range of parameters, some of which can be strongly influenced by genetics (Table 2).

Table 2. Parameters influencing FCR

Parameter	Genetic influence	Other influences
Growth rate	Yes	Age at slaughter, body composition, health status
Body composition	Yes	Age at slaughter, ration composition, health status
Activity level	Limited	Housing and management (e.g. free range or housed)
Health status	Yes, e.g. see PRRSV and ASFV (Tait-Burkard *et al*. 2018)	Wide range of factors, e.g. housing, biosecurity, vaccination, nutrition etc.

In theory the volatile solid and N excretion rates (and therefore manure emissions) could be influenced by changing genetics; there is a genetic basis of variation in N excretion that raises the possibility of breeding for reduced N excretion. Transgenics have also been used to improve N (and P) digestion, thereby reducing the subsequent conversion of excreted N into N_2O (Zhang et al. 2018).

4.2 Trends in key parameters influencing emissions intensity (EI)

Figures 7 to 10 show trends in the physical performance of UK and EU pigs over the last 20 years or so. Perhaps surprisingly, given the importance of FCR to financial performance, the FCR of finishing has not decreased over this period. However, liveweight at slaughter has increased over this period. Although between trial comparisons are confounded with a number of aspects, similar observations arose from comparing a series of pig trials at SRUC over the last 10 years or so (Houdijk, 2018). As FCR increases as the pig grows, the older and heavier a pig is slaughtered, the higher the lifetime average FCR. Therefore maintaining FCR while increasing LW at slaughter represents an improvement in physical performance. This is reflected in the increases in the growth rates of the finishing pig. Figure 8 shows that there has been a significant increase in the meat produced per sow. This is due to the increased growth rates combined with significant increases in sow fertility; between 2005 and 2017 the number of piglets born per sow per year increased by 26% in the UK and 20% in the EU (although some of this improvement has been offset by an increase in the sow *replacement rate). Increasing the CW output per sow (while keeping the finishing pig FCR constant) should lead to reduced feed costs and emissions per unit of output.*

Figure 7. Trends in the physical performance of finishing pigs in UK indoor systems. 2005=1. Based on Interpig data reported in the AHDB Pig Cost of Production in Selected Countries reports (e.g. AHDB 2018; AHDB 2019).

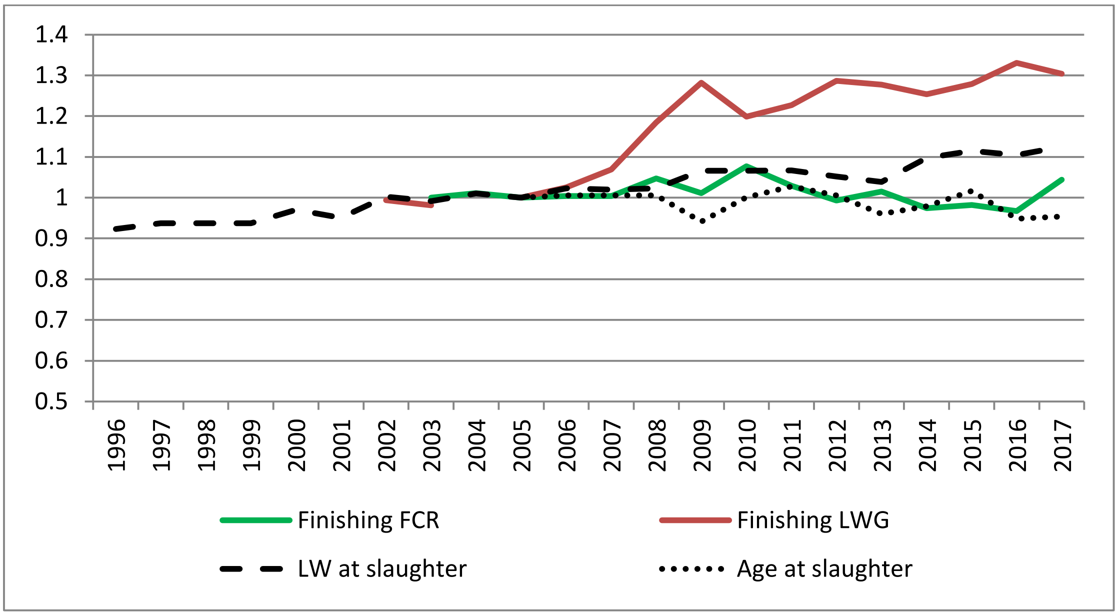


Figure 8. Trends in the physical performance of sows in UK indoor systems. 2005=1. Based on Interpig data reported in the AHDB Pig Cost of Production in Selected Countries reports (e.g. AHDB 2018; AHDB 2019).

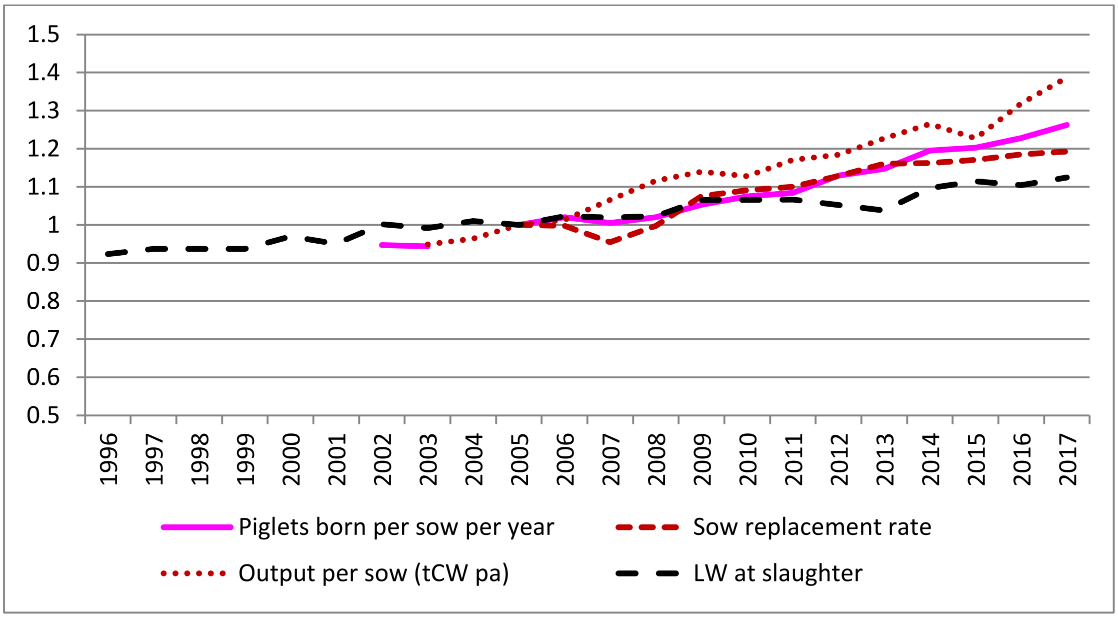


Figure 9. Trends in the physical performance of finishing pigs in the EU (EU average). 2005=1. Based on Interpig data reported in the AHDB Pig Cost of Production in Selected Countries reports (e.g. AHDB 2018; AHDB 2019).

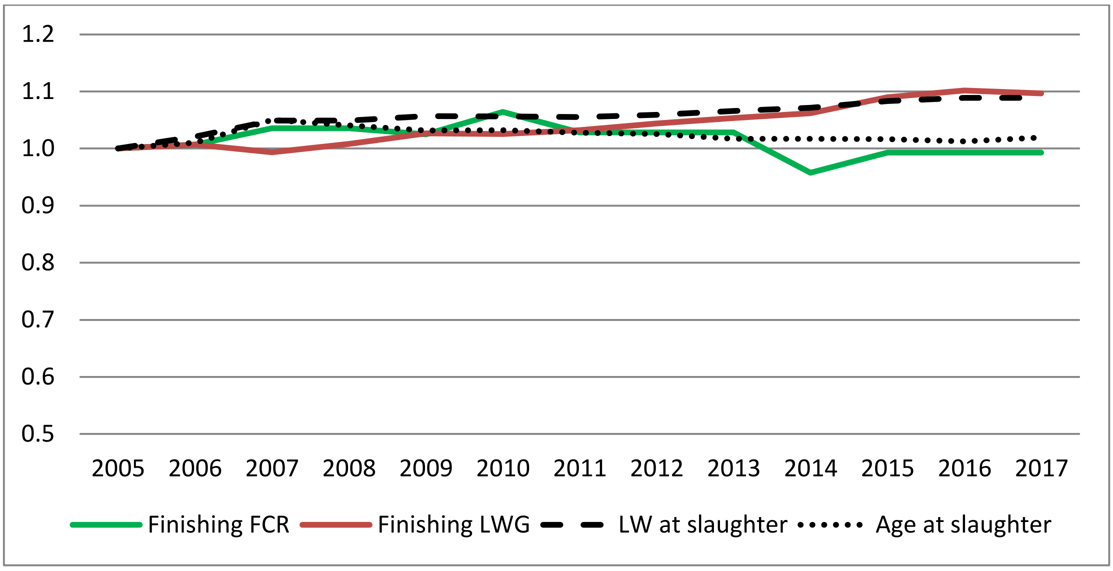
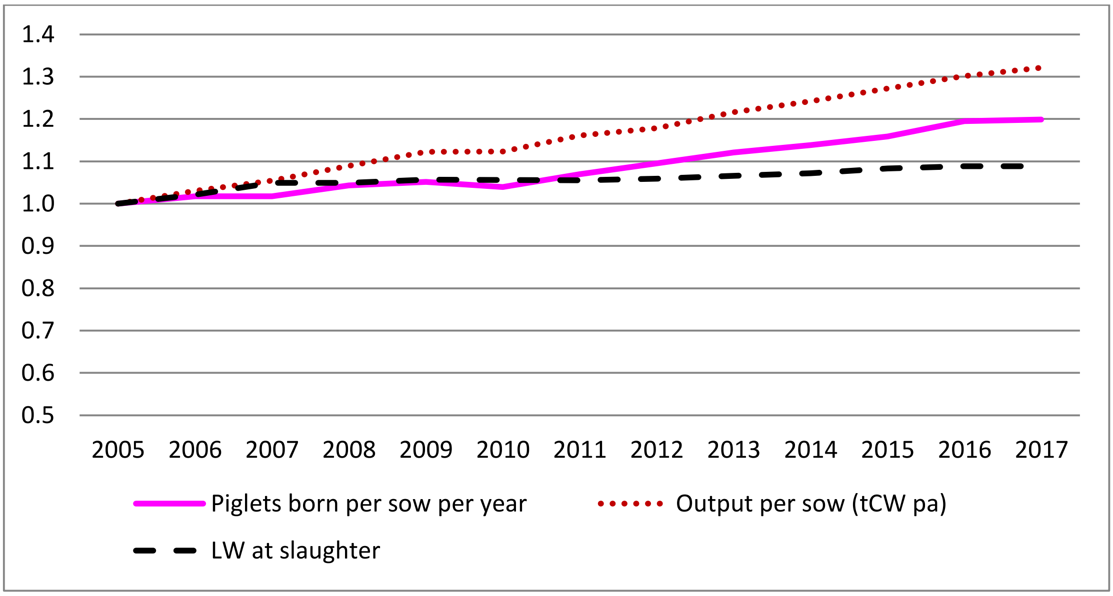


Figure 10. Trends in the physical performance of sows the EU (EU average). 2005=1. Based on Interpig data reported in the AHDB Pig Cost of Production in Selected Countries reports (e.g. AHDB 2018; AHDB 2019).



4.3 Scope for further reductions in emissions intensity via breeding

Lamb et al (2016b) have predicted that for pigs (and poultry) "FCR improvements are projected to arise through genetic improvement rather than changes in diet" Lamb et al. (2016b).

DEFRA (2008) reviewed trends in pig growth rates, FCR and fertility and used them to predict future performance. Actual performance (as reported by Interpig) has differed in some ways from the predictions; the rate of improvement in FCR has been slower but the rate of improvement in sow fertility faster (Table 3). The slower than predicted improvement in FCR represents a rebound effect – improved genetics have reduced FCR at a given weight but this has also led to increases in weights at slaughter, offsetting the reductions in FCR.

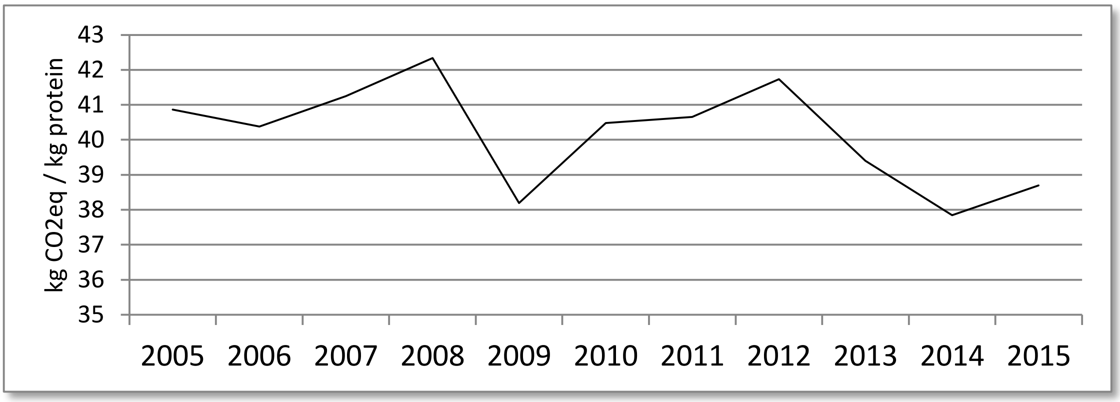
Table 3. Predicted and reported changes in pig physical performance

Year and location	*Lifetime daily gain (g)*	*FCR (kg/kg)*	*Numbers born alive per litter*	*Source*
UK 1988-2007 and 2008-2022 (projected)	6.4	-0.020	0.12	DEFRA (2008b, p11)
UK 2005 - 2017	8.0	0.010	0.16	Interpig data in AHDB (2019) etc.
EU 2007-2017	4.2	-0.012	0.21	

Based on a literature review and expert opinion, Lamb et al. (2016) defined the upper and lower rates of improvement in pig FCR over the period 2010 to 2050 as 0% and 1.0% per annum, while noting that "these gains might be untenable in practice on economic, animal welfare or technical grounds and we note that other studies (Wirsenius et al 2010, IIASA 2013) predicted much lower future livestock productivity growth in Europe".

Figure 11 shows a decrease in EI of pigmeat in Scotland of 0.5% per annum from 2005-2015, driven by increases in sow fertility and pig growth rates. DEFRA (2008a, p14) reported an annual decrease in the EI of pigmeat of 0.8% for the period 1998-2008, achieved via improvements in FCR and growth rates. They also predicted that these "high rates of annual reduction in emissions achieved to date would still be expected to be achieved over the next 15 years if current selection practices were to continue". However, lower rates of reduction in EI have occurred due to lower than predicted improvements in FCR.

Figure 11. Emissions intensity of pigmeat from pigs in Scottish indoor systems. Calculated by author, using SAEM (MacLeod et al. 2017)



The sensitivities of pigmeat EI to changes in key parameters are given in Table 4. These imply that (if rebound effects are avoided) sustaining the recent increases in growth rates and sow fertility should lead to a reduction in the EI of pigmeat via genetic improvement of around 0.3% per annum.

Table 4. % change in the EI of pigmeat in Scottish systems when parameters are increased by 10% (MacLeod et al 2017)

Parameter	EF1	Growth rate	Fertility
Change in EI	1.0	-3.4	-0.9

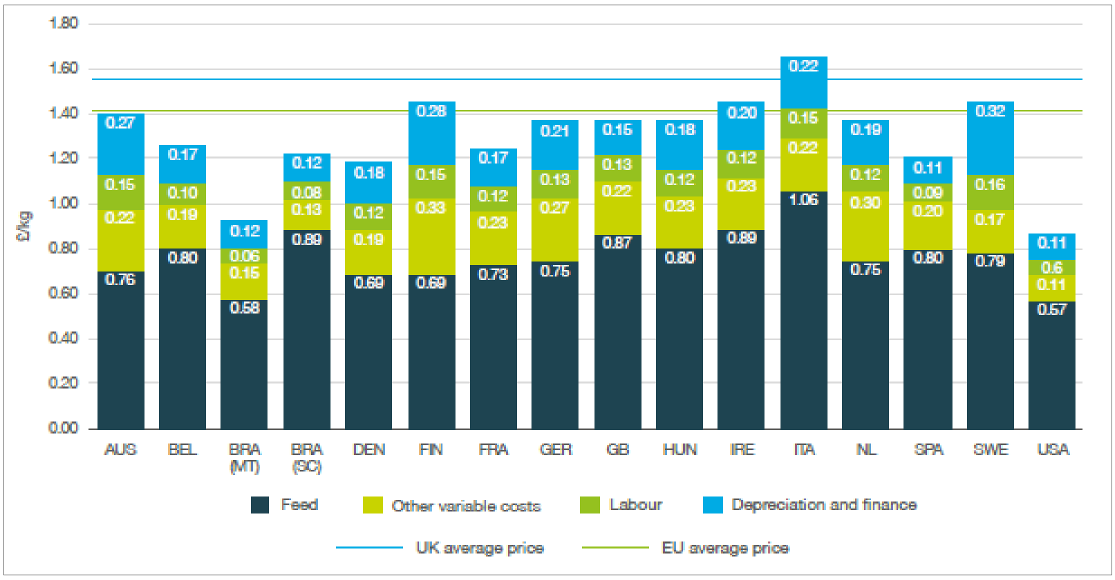
4.4 Cost of breeding programmes and impact on farm economics

Private costs and benefits

Feed is the single biggest cost in pig production (Figure 12). AHDB (2018) reported that the EU average feed cost for pig producers was £0.80 per kg of deadweight, or 58% of the total costs. Feed production accounted for 64% of the GHG emissions from European pig production in 2015 (FAO 2017). Therefore, it follows that improvements in the FCR of the growing pigs, or of the herd as a whole (including breeding animals), will reduce production costs. Lopez et al. (2016) reported that "as much as 8% extra income was possible when implementing genomic selection", while Bianca Samorè and Fontanesi (2016) found that:

> *"in pigs no great economic changes are expected with the introduction of genomic selection and the advantages should cover the extra financial costs associated to its implementation in pig breeding programmes (Tribout et al. 2013). The primary expected benefit from incorporating genomic information into pig breeding value estimation is the improved accuracy and this increase should be large enough to recover the genotyping costs (Abell et al. 2014)"*

Figure 12. Cost of pig production in selected countries (£ per kg of deadweight), 2017 (AHDB 2018)



Social costs and benefits

Increased growth rates can lead to reduced feed consumption per unit of output and a reduction in the impacts associated with feed production (GHG emissions, impacts on water and air quality, biodiversity, non-renewable resource depletion etc.) (Table 5).

Breeding has also led to reductions in nutrient excretion, and the impacts arising from manure management: "35 years of lean growth rate improvement in pigs has reduced nitrogen excretion by 25% per animal and by 31% per kilogram of protein produced (Knap, 2011). In line with this, feed conversion ratio, a simple trait that has been under selection for decades, is very strongly correlated (r > 0.9) to nitrogen excretion in growing pigs (Shirali et al., 2011)." Neeteson-van Nieuwenhoven et al. (2013)

Breeding for improved physical performance can have negative effects on animal welfare. For example, it has been suggested that breeding for increased fertility can lead to increased sow lameness and risk of prolapse (Greenaway 2018). However breeding can also be used to improve animal welfare, for example by selecting for disease resistance or reduced boar taint

Table 5. Summary of costs and benefits

Change	**Costs**		**Benefits**	
	Private	**Social**	**Private**	**Social**
Increased growth rates	Cost of testing	Animal welfare?	Reduced FCR and feed costs	-Reduced GHG -Reduced impact of feed production -Reduced Nx and Px
Increased sow fertility	Increased sow replacement rate	Animal welfare, e.g. increased lameness	Increased number of finished animals	Modest reduction in GHG

4.5 Barriers to achieving reductions

The full genetic potential may not be achieved in practice, due to the limitations of the production environment, e.g. the commercial unit may have lower biosecurity than the breeding unit. Neeteson-van Nieuwenhoven et al. (2013) outline selection techniques that can be used to make better predictions of pig performance in commercial conditions. They also argue that (for pigs and poultry) we are some way from reaching selection limits as "there will be plenty of genetic variation available to exploit for future animal breeding."

For transgenic animals, the time taken to get legal approval for sale (GM salmon took 25 years to get to market). However, it has been argued that "precise, accurate genome-editing techniques are very different in nature to transgenesis" and consequently may be approved more rapidly (Tait-Burkard et al. 2018).

The social barriers to some types of genetic modification were illustrated in the Enviropig project, where pigs were modified to express salivary phytase (Golovan et al 2001), which consequently resulted in low P manure, with the expected reduction in eutrophication potential. The economic benefits of such approaches have been demonstrated (Novoselova et al 2013) though societal barriers are acknowledged as well (Mulhern, 2011). It can only but be expected that similar GM methodologies will assist creating animals with reduced EI (Krens, 2018), leaving society to decide whether such technologies are acceptable.

4.6 Future research needs

The observations that the predicted improvement in FCR through genetic selection has not (yet) materialized may indicate that there is a biological upper limit to the extent that FCR can continue to improve (reduce) through selection on performance traits in order to reduce EI. This view would be consistent with earlier observations that energetic efficiency of lipid and protein deposition is independent of pig weight and genotype for modelling purposes (e.g. Whittemore 2006).

Tolkamp et al (2010) concluded that there is no convincing evidence from whole animal studies for useful differences between breeds or genetic lines in the efficiencies of energy and protein utilisation proper (i.e. the efficiency with which animals convert feed energy and protein in the specific functions of generating animal growth and production). There is, however, some recent research that suggests differences between genotypes in the functioning of specific mitochondrial respiration chains, especially when genotypes with high or low residual feed intake are compared. This could in principle result in genotype effects on energetic (or protein) efficiency at the level of the animal as a whole. However, more evidence of the existence of such physiological variation is required before exploitation can be considered (Tolkamp et al 2010).

There is evidence from pigs studies that variation in metabolisable energy requirements for maintenance does exist, which may be related to differences between genotypes in maintenance related processes such as activity and thermal regulation (Tolkamp et al., 2010 and references therein). This would suggest that there is opportunity to select for pigs with reduced levels of nutrient requirements for maintenance, which ultimately will reduce (improve) FCR and thus reduce EI. There will likely be limited scope for this, since maintenance functions would traditionally be considered to also include nutrient requirements for immunocompetence. Thus, careful selection to target the correct components in such breeding goals would be required. Almost in *contrast, there is great interest to select for improved disease resistance, which would increase energy and protein costs for maintenance. However, the possible energy and nutrient costs of increased disease resistance have not been systematically investigated in pigs. This forms, therefore, a major gap in our knowledge of factors that affect nutrient efficiency of different pig genotypes in a variety of (disease) environments (Tolkamp et al., 2010).*

Breeding for disease resistance therefore may provide a trade-off on effects on EI. On the one hand, increased disease resistance may increase nutrient requirements for non-productive functions (increasing EI) while on the other hand, if the outcome of challenge in the presence of increased disease resistance is reduced impact of challenge on productivity, then that may reduce EI. These would include breeding for improved disease resistance, as exposure to challenge typically result in anorexia (reduced intake) and whilst animals generally overcome anorexia over time, provided they do not succumb to the challenge, the resulting overall FCR will have increased, and thus EI will have increased.

Comparisons of contrasting genotypes (e.g. Meishan and Large White x Landrace crosses or Landrace versus Pietrain) have concluded that a limiting protein supply is utilised with the same efficiency for protein retention (Kyriazakis et al., 1994; 1995; Susenbeth et al., 1999) and that, therefore, no major genotype effects on this efficiency can be expected for pigs. Oddy (1999) agreed that there is little evidence for genotype effects on efficiency of protein utilisation at the whole body level but also suggest that methodological issues might be a problem here. However, whilst there is some evidence for genetic (breed) differences in digestive efficiency for energy as well as amino acids in pigs (e.g. Carre et al. 2008), this may arise largely from the ability to digest fibre (Tolkamp et al 2010). This would suggest that genetic selection for modified microbiome regarding fibre "digestibility" may be a useful route to consider. The gap in knowledge here is on the quantification of factors governing microbiome composition and activity.

Overall, useful future studies include modelling studies where difference scenarios of variation in nutrient requirement for immunocompetence are contrasted with that arising from disease challenge. Furthermore, given that there the potential upper limit on nutrient and energy efficiency proper may have already been reached through conventional breeding strategies, breeding for non-production traits that improve FCR per se may be a sustainable route forward.

In summary, future research priorities include investigating: (a) the trade-offs between improved nutrient use efficiency and disease resistance to identify the optimal combinations that can reduce EI while improving financial performance (b) non-production traits that can reduce EI by improving FCR (c) the extent to which practical barriers (such as the limitations of the production environment) and rebound effects may constrain the GHG reduction potential.

5 Broilers

5.1 Background

The greenhouse gas emissions arising from broiler meat and egg production are largely associated to two sources, namely 1) feed production, processing and transport, and 2) manure emissions from housing and manure management (Figure 2.2). According to an analysis of typical UK broiler and egg production systems, the contribution of these sources is about 85-90% of the total GHG emissions arising from these systems (Leinonen et al. 2012a,b). The main additional source of emissions is direct farm energy, including gas or oil use for heating and electricity for ventilation, lighting and feeding. Since the farm energy consumption is mainly dependent on the type of the production system, not so much on the genetics of the birds, it is clear that the traits associated with the feed efficiency of the bird are the key factors determining the changes in emissions intensity and how they can be affected trough animal breeding. Improving the feed efficiency would reduce both the intake of feed (per unit output) and also the nutrient excretion of the birds (per unit output), thus affecting the emissions associated with both feed production and housing/manure management. Obviously the feed efficiency has been a major target of breeding because improvement in this trait is an efficient way to improve the profitability of both broiler and egg production.

5.2 Trends in key parameters influencing emissions intensity (EI)

The process of modern broiler breeding can be summarised as follows (Tallentire et al. 2016). At the highest level of the production chain, the pure-breeding lines are owned and controlled by the breeding companies. These lines are subjected to full scale selection programs, and all of a company's broiler products descend from these lines. The great-grandparent stocks, which are produced from the pure-bred lines, are subjected to mass selection for certain traits. Specific grandparent lines are then cross-bred to produce the parent stock, and these birds are then distributed to specialist traders and integrated producers. The final step of the selection process is the crossbreeding of these hybrids (parent stock) to give rise to the production broilers grown for meat (Tallentire et al. 2016).

Since the beginning of the industrial broiler breeding programmes of the early 1950s, global trends have been mainly focusing on growth rate, meat quality and feed efficiency (Arthur and Albers 2003). The growth rate has been the main selection trait, for both practical reason (ease of selection, high heritability) and economic reasons (effect on the cost of meat production). The selection for meat quality has resulted in increased production of breast meat, due to consumers' preferences. The feed efficiency is also an obvious target for selection as it has a strong impact on the cost efficiency of the broiler meat production (Arthur and Albers 2003). During the last decades, the breeding programmes have focused on the whole production chain, including the breeder (parent) birds. As a result, the target of the selection can be seen to be the improving of meat production per one breeder bird, thus taking into account the improvement in both the growth of the broiler birds and the rate of reproduction of the parent birds (e.g. Pollock 1999, Decuypere et al. 2003).

The success of the broiler breeding programmes since 1950s has been quite spectacular, and improvements in the main traits such as growth rate and feed efficiency probably exceed the achievements in any other production animal. Comparison of the old and more recent genotypes show that growth rate of broiler chickens increased by over 400 % between the years of 1950 and 2005 (Zuidhof et al. 2014, Tallentire et al.2016), and the increasing trend has continued until present day (Aviagen, 2014a).

In broiler breeding, high growth rate and high feed efficiency (and resulting improvements in GHG emissions intensity) are actually very closely connected with each other. This connection becomes obvious when examining the past trends in broiler breeding. As mentioned above, probably the most notable genetic trend during the last decades has been an increase in growth rate and therefore reduction of the time required to reach the slaughter weight (Laughlin 2007). As discussed by Leinonen 2016) an automatic outcome of the shortening of the production cycle is that a smaller proportion of the metabolizable energy obtained by the animal from feed is released as heat (generated by metabolic activity), simply because the birds have less time to produce heat before the slaughter. Consequently, increasingly higher proportion of the energy intake is retained in the body (as protein and lipid). In practical farming, this trend has been observed as a smaller feed consumption by the birds during the entire production cycle (de Beer et al. 2011, Laughlin 2007, Mussini 2012).

In addition to the increasing growth rate, another trait potentially affecting the feed efficiency is changing body composition, or more specifically the ratio between protein and fat in the body. It has been suggested that the selection for increased body weight initially promoted fat accretion (Decuypere et al. 2003). This *seems logical because increasing fat content is an easy way to increase the total body weight. However, during the recent decades, leaner body composition has become one of the targets of the selection, and therefore it is likely that current trend in body composition is decrease rather than increase of the body fat content (Whitehead 1990, Havenstein et al. 2003, Fleming et al. 2007, Tallentire et al. 2016). Due to high energy content of fat, producing leaner birds would need less energy compared to fatter birds, and therefore reducing the body fat content has probably resulted in further improvements in the feed efficiency of the broiler birds.*

A common misconception is that the increased feed efficiency of broiler chicken is due to more "efficient" metabolism, which would in practice mean slower metabolic activity and therefore slower rate of metabolic heat production. In order to better understand the past trends and their mechanisms in the improvements of the energy efficiency of broilers, a quantitative analysis was carried out by Tallentire et al. (2016) using mechanistic energy balance modelling. Their results show that the energy intake per bird per day has not decreased but instead increased considerably in the recent decades as a result of broiler breeding. The metabolic heat production (or metabolic activity) has also increased, probably because of the higher energy demand of the higher growth rate. However, the efficiency of utilising energy for growth has increased; this is due to an increased growth rate, so that broilers reach slaughter weight more quickly and therefore need to allocate overall less energy to metabolic processes, with the exception of growth. A consequence of this is that the daily rate of feed intake must increase to facilitate the faster growth resulting from the selection process. Interestingly, the higher daily feed intake will lead to shorter production cycle and therefore also to reduced cumulative feed intake and higher feed efficiency. This is demonstrated in Figure 13 and 14. However, it is obvious that there will be biological limits in the daily feed intake. This is an important constraint when considering the future potential to improve the feed efficiency and reduce the GHG emission intensity in broiler chicken.

Figure 13. The total feed metabolisable energy (ME) intake needed to reach a body weight of 2 kg for broiler bird genotypes originating from certain years. Adapted from Tallentire et al. (2016); original data from Havenstein et al. (2003), Zuidhof et al. (2014) and Aviagen (2007a,b, 2014a,b).

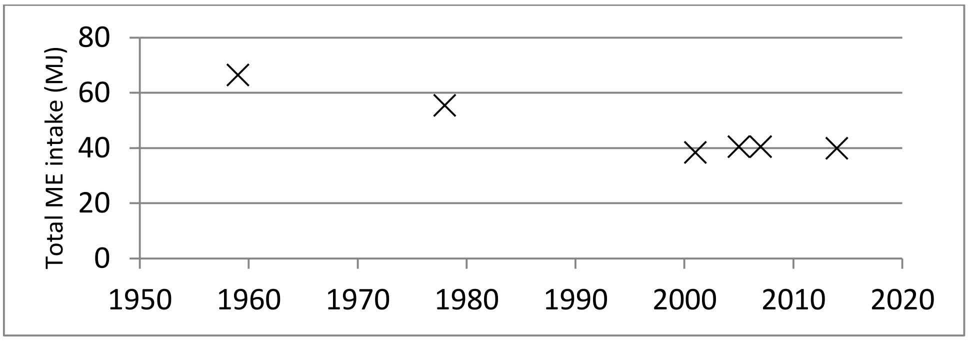
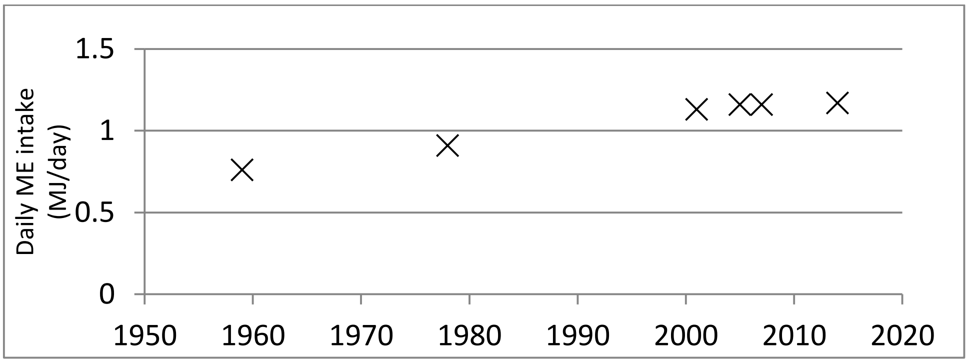


Figure 14. The daily ME intake needed to facilitate the growth. Adapted from Tallentire et al. (2016); original data from Havenstein et al. (2003), Zuidhof et al. (2014) and Aviagen (2007a,b, 2014a,b).



5.3 Scope for further reductions in emissions intensity via breeding

Leinonen et al. (2016) identified traits that could potentially further improve the environmental performance of broiler chicken as a result of breeding in the future. In their modelling analysis based on the energy balance of the bird, they examined traits that were targets of breeding industry, and the scenarios analysed in that study were based on the industry expectations for the genetic improvement during coming decades. The analysed traits were increasing growth rate, increasing carcass yield (largely associated with breast meat yield), reduction of broiler mortality, increase of fertility (i.e. the number of chicks produced by one parent bird), and change of body composition. All these traits were associated (directly or indirectly) to improved feed efficiency.

As mentioned above, the increasing growth rate has been the key factor in reducing the GHG emission intensity of broiler chicken. Furthermore, as improvements in this trait will bring economic benefits to poultry farmers, it is obvious that in order to achieve both environmental and economic improvements in broiler chicken production, growth rate remains a key target of broiler breeding. As could be expected, the analysis by Leinonen et al. (2016) showed that amongst all potential traits, further improved growth rate has by far the highest potential to reduce the GHG emissions of broiler production. Amongst the other traits, increasing carcass yield could reduce the emission intensity per unit of carcass weight (or per unit of protein output), but would have no effect if the emission were considered per live weight of the bird. Changing the body composition, i.e. further reducing the fat content of body, could also slightly reduce emission intensity, as a result of improving feed efficiency.

Reduction of mortality would have only a minor effect on the reduction of emission intensity (Leinonen et al. 2016). This is because the rate of mortality is already very low in commercial intensive broiler production (an industry estimate of 3.5% was used as a baseline in the analysis). However, this conclusion is not valid if the mortality would go to opposite direction in the future; highly increased mortality would lead to reduced output of broiler meat per unit of resources used, and therefore could considerable increase the emission intensity.

According to the industry, some improvements are still expected in the fertility of the parent birds (Leinonen et al. 2016). However, improvement in this trait could lead only to minor reductions in the emission intensity. In practice, higher fertility would mean that fever parent birds (and therefore less feed and other resources) would be needed to produce a certain amount of broiler meat. However, it should be noted that the overall contribution of the parent flock to the total GHG emissions of broiler production is relatively low (about 8%, according to Leinonen et al. 2012a). Therefore, even relatively big improvement in these birds would have a relatively low effect on the GHG emissions when the whole broiler production chain is considered.

In order to determine the biological limits of future improvements in the broiler feed efficiency and GHG emission intensity, another energy balance modelling analysis was carried out by Tallentire et al. (2018). In their analysis, the ultimate limits for increasing growth rate (and resulting improvement in feed efficiency) were considered to be determined by the maximum potential feed intake that could facilitate such growth. Similarly, for the body composition, a biological limit of leanness (i.e. zero fat reserves) was determined, resulting in highest possible energy efficiency of broiler growth. The analysis showed that the opportunities for further improvements of the feed efficiency of the broilers are rather limited. Further increase in the growth rate would require increasing daily feed intake. However, already in the current broiler birds, the feed intake is very high and it is enhanced to its upper limits by management practices such as maintaining 23 hours light period in broiler houses. Similarly, in the case of body composition, the current broiler birds are already very lean, so further reduction in the body fat content is also rather limited. As a result, it was found that only about 8% reduction in the total feed energy intake of the bird upon reaching slaughter weight could be achieved within the ultimate biological limits.

According to Tallentire et al. (2018), reaching the biological limits in the feed intake and body composition (and resulting limits in the growth rate and feed efficiency) would reduce the nitrogen excretion of the broiler birds by 23%. This reduction is due to the fact that shorter growth cycle would increase the proportion of nutrient intake that is retained in the bird body instead of excreted. Assuming that the manure emissions from housing and manure management would be proportional to the nitrogen excretion, and considering the relative contributions of broiler manure and feed emissions to the total GHG emissions of broiler production chain based on the industry data obtained by Leinonen et al. (2012a), it can be concluded that the further potential to reduce the overall GHG emissions arising from broiler meat production, achieved through breeding, would be less than 10%.

5.4 Cost of breeding programmes and impact on farm economics

According to an EU-level comparison of production costs of broiler meat, it was found that feed is by far the biggest single cost in primary production (van Horne 2017). When comparing the costs in nine European countries, van Horne (2017) found that the contribution of feed cost to the total primary production cost (including labour) varied from 58% to 67%. The second biggest cost component was the purchase of day-old chicks. The contribution of this cost varied from 15% to 21% of the total costs between countries. Consequently, these two components, both of which can be strongly affected by breeding, contribute up to 83% to the overall costs of broiler primary production.

As demonstrated above, feed efficiency has been one of the main targets of broiler breeding, and improvement in this trait has clearly high direct impact on the farm costs. Increase in the growth rate can improve the feed efficiency and therefore also reduce feed costs. Meat yield is also an important trait, as its improvements are expected to reduce all variable costs (including feed and day-old chicks) per unit of output. Further improvements in mortality would have direct reduction on the costs arising from feed and day-old chicks, because the already consumed feed and the purchased chick would be wasted in the case of every dead bird. On the other hand, if the mortality would increase from its current low level, it would considerably increase the production costs. In general, it is obvious that the animal health is important for reduction of the production costs (similarly as in reduction GHG emissions). Therefore, further breeding programmes should have improved health as one of the selection targets and avoid adverse health effects associated with fast growth and efficient production.

As a result of animal welfare concerns, it is very likely that less feed efficient, slowly growing broiler birds will be preferred by European consumers in the future. It is very clear that production of such birds will considerably increase the primary production costs, mainly due to higher consumption of broiler feed.

Concerning the social costs and benefits, improved feed efficiency would reduce not only the GHG emissions but also many other environmental burdens, such as impacts on water and air quality, biodiversity and non-renewable resource depletion. As explained above, breeding for higher feed efficiency has also reduced nutrient excretion and the impacts arising from manure management. Based on the analysis by Tallentire et al. (2018), improving the feed efficiency up to its biological limits would result in further reduction in nitrogen excretion by 23% and phosphorus excretion by 15%. Such reductions would have considerable effects of eutrophication and acidification arising from manure management. On the other hand, reducing the growth rate to meet certain welfare standard would have an opposite effects on nutrient excretion. For example, extending the slaughter age to 56 days would increase the nitrogen excretion even more that 60% and phosphorus excretion about 50%.

5.5 Barriers to achieving reductions

It is not very likely that all the biological potential for reducing the GHG emissions outlined above will be fully achieved through breeding. It was speculated already a couple of decades ago that the rapid genetic progress cannot continue much longer (Albers 1998, Arthur and Albers 2003). In addition to the biological limits in growth rate and body composition discussed above, there can be other traits that may limit the improved environmental efficiency of chicken. It has been suggested that many instances of bird ill-health are associated with fast growth rate, including musculoskeletal disorders, myopathies and organ failures (Tallentire et al. 2018). If such health problems reduce the meat yield or increase mortality of the birds, that will automatically reduce the resource efficiency of broiler production and therefore limit the achievement the full environmental benefits. On the other hand, modern breeding programmes include the bird health in their targets, and also aim to further reduce the bird mortality (Leinonen et al. 2016).

Another important constraint to achieving even higher resource efficiency in broiler breeding is the changing consumer preferences. While fast growing feed efficient broilers will likely remain a source of affordable meat in large parts of the world, there is an increasing market for speciality birds and in their production other properties than fast growth are more preferred. For example, consumer concerns about the welfare of fast-growing chickens and their meat quality have shifted selection pressures towards traits such as robustness, reproduction and adaptability (Tallentire et al. 2018).

During recent years, there has been a growing market demand for slow-growing broilers, which have perceived higher welfare, as an alternative to the fast-growing, energy efficient broilers. For example, there are 'welfare-friendly' policies adopted by some businesses across Europe. Such policies stipulate that chickens must have a reduced growth rate and live a minimum of 56 days. Growing such slow-growing lines would result in a substantial increase of GHG emissions and other environmental burdens due to increased feed *consumption of the birds over the longer production cycle (Tallentire et al. 2018.). Therefore, the consumer preferences of slow growing birds are likely to partly reverse the efficiency of broiler production achieved until present day through breeding. It is also possible that further development towards higher efficiency will be restricted through legislation at least in many European countries.*

5.6 Future research needs

The research related to broiler breeding has very much concentrated on the genetics and biological properties of the broiler birds. However, the results discussed above demonstrate the importance of the use of mechanistic energy and mass balance models in estimating the environmental impacts of past, current and future broiler genotypes. The use of this kind of modelling can produce exact estimates on the theoretical limits of breeding, since it is based on real, physical constraints. Therefore, it provides clear benefits over other approaches such as empirical correlation of certain traits, or trends of the past changes in traits of interests (and assumptions that such trends will continue also in the future). However, more detailed understanding on the mechanisms behind the altered bird performance (including possible changes in heat production, body composition, nutrient utilization and so on) and their consequences on feeding and husbandry would be required in order to evaluate and further develop such modelling framework and to produce reliable predictions on the environmental performance of the broiler chicken in the future. In order to make further progress and better respond to consumers' preferences, it is important for the breeding industry to understand the physical mechanisms of the improvements in energy use efficiency and growth rate in the past and be aware of their potential limitations in the future.

6 Laying hens

6.1 Background

The European egg production industry has gone through major changes during the last decade. From 1 January 2012 keeping hens in conventional (battery) cages was prohibited in the EU, and egg producers had to change to either enriched cages or to one of the cage-free production systems. According to the EU directive (EU 1999), the area of the enriched cage must be 750 cm2 per hen, of which 600 cm2 is 45 cm high, it should have at least 15 cm of perch per hen and at least 12 cm of food trough per hen. Additional required features include a nest, a claw shortening device and a littered area for scratching and pecking. Several birds are housed in a single cage. The alternative, cage-free production systems include barn, aviary and free range (either organic or non-organic) production. It is obvious that these changes have increased in the cost of producing eggs in Europe (van Horne 2012). The diversity of new production systems also brings challenge to the layer breeding industry. However, throughout the history this industry has had "a remarkable record of coping with new challenges" and has successfully adapted to consumer preferences (Preisinger 2018).

Concerning the greenhouse gas emissions arising from egg production, similarly as in broiler production, these emissions are largely associated with feed production, processing and transport, and manure emissions from housing and manure management. According to an analysis by Leinonen et al. (2012b) in the old cage egg system in the UK, the contribution of feed to the total GHG emissions was 72% and the contribution of manure 17%. In the new enriched cage system, the relative contribution of feed and manure was even higher, due to a reduction of the farm energy use (mainly electricity used for ventilation), compared to the old system. Therefore, as in broiler production, changes in the traits associated with feed efficiency largely determine the changes in emissions intensity, and they are also a central target of breeding. In both broiler and egg production systems, improved feed efficiency would reduce both the emissions arising both from feed production and manure management.

When considering the whole egg production chain, the contribution of the breeder (parent) birds to the total GHG emissions is even lower than in broiler production, being less than 2% according to the data provided by the UK egg production industry (Leinonen et al 2012b). The reason for this is that the life cycle of breeder birds is comparable to the life cycle of the production birds (unlike in broiler production), and the rate of producing offspring is very high. The egg production stage itself can be divided to two periods, that may occur separately from each other, e.g. on different farms. These periods are 1) raising pullets (young hens), and 2) the actual period of egg laying. According to Leinonen et al. (2012b), these periods contribute 17% and 81% of the total GHG emissions of the egg production chain respectively.

6.2 Trends in key parameters influencing emissions intensity (EI)

Lorem For decades, the most important general breeding goals have been number of eggs produced, feed efficiency, various egg quality traits, low mortality and adaptability to different environments (Thiruvenkadan et al. 2010, Preisinger 2018). Continuous improvement in egg production per housed hen has been the most important selection criterion in layer breeding (Preisinger 2018). The increase in egg production during the last three-quarters of the 20th century was exceptional: according to Decuypere et al. (2003) the typical production increased from 176 eggs per hen per year in 1925 to 309 eggs per hen per year in 1998. This improvement is comparable to the development that has occurred in chicken meat production. During the same period, the time to reach a 1500 g live weight of a broiler chicken decreased from 120 days in 1925 to 33 days in 1998 (Decuypere et al. 2003). The improvement in the egg production has further increased after 1990s until the present day. Based on field data, Preisinger (2018) reported that from 2010 to 2015, the egg production has increased from 313 to 325 eggs per her per year, indicating that the annual rate of improvement has been about two eggs per hen per year.

The increase in the productivity of the hens has had direct consequences on the feed efficiency. According to (Arthur and Albers 2003), the conversion of feed into eggs is primarily a function of egg numbers, and also influenced by egg size and body weight. The data shown by Preisinger (2018) indicates that feed conversion ratio (kg feed consumed per kg eggs produced) has decreased globally from 2.45 to 2.00 between the years of 1995 and 2015. This over 20% reduction can be expected to provide a similar magnitude of reduction in the feed-related GHG emissions, and also reductions in emissions arising from manure management.

ipsum Many single traits that are targeted in layer breeding have direct or indirect connection with feed efficiency, and therefor they can contribute to the reduction of the GHG emissions intensity of egg production.

According to Arthur and Albers (2003), the specific traits that are selected for include the age at sexual maturity, rate of lay before and after moult, low mortality in the growing and laying house, egg weight, body weight, feed conversion, shell colour, shell strength, albumen height, egg inclusions (blood and meat spots), temperament, and traits affecting the productivity of the parent birds. As mentioned above, egg production per hen has been the single most important trait under selection. However, the emphasis has been gradually shifting from peak rate of lay to persistency of lay (Preisinger and Flock 1998, Arthur and Albers 2003). When the birds maintain high rates of lay for longer periods, it is possible to keep the flocks longer, and constant rate of egg production can be maintained without pauses caused by moulting (Arthur and Albers 2003).

Continuous egg production has clear benefits when the improved feed efficiency and related reductions in GHG emissions are considered. Similarly, high egg output (number of eggs and their mass) improves the GHG emission intensity. This is also affected by traits such as shell strength and resulting reduction in losses of the eggs. Reducing mortality is an important trait, but its role in reduction of the emission intensity is not as big as in broiler production; if a laying hen dies, it may have already produced a considerable amount of eggs, while dead broilers will produce no meat but they have still consumed feed and other resources.

6.3 Scope for further reductions in emissions intensity via breeding

Increasing the number of saleable eggs per hen is expected to remain as one of the main selection goals of layer breeding in the future. This goal is associated with targets to extend the productive laying period of hens. Further goals include improving shell quality, reducing hen mortality and maintaining consistent feather cover until the end of lay (Preisinger 2018). The feather cover is important because losses of feather would result in increased heat loss from the bird, and therefore reduce feed efficiency, especially in alternative production systems where low temperatures may occur (e.g. Leeson and Morrison 1978). It is also suggested that production of stronger shells and maintaining longer production cycles without moulting (temporary loss of feathers connected with a pause in egg laying) should be combined with stronger bone structure. Bone strength and possible bone breakages are likely to be a major issue in new cage-free environments where the hens are more susceptible to physical damage. Environmental enrichment for example using perches in poultry houses can be a potential cause of skeletal injuries and bone breakages, and therefore brings new challenges for future breeding programmes.

As discussed above, feed efficiency is likely to be the main trait in breeding that can further reduce the GHG emissions of egg production. In theory, feed efficiency can be affected not only by the number of eggs produced per hen, but also by the body weight, body composition and growth rate of the hen. In the past, body weight of the laying hens has actually decreased as a result of breeding for higher feed efficiency. However, according to Preisinger (2018), the optimum body weight for white and brown layers has been already achieved, and the improvement in feed efficiency is now mainly driven by a "stable maintenance requirement and constant daily feed intake". For this reason, improved egg mass output would be the major driver for a further improvement in feed efficiency (Preisinger 2018). Furthermore, the biological maximum for laying hens can be physiologically determined to be one egg per day (Decuypere et al. 2003). Based on these assumptions, the biological limit for the reduction of greenhouse gases as a result of breeding in the future can be calculated.

In our calculations, the year 2015 egg production number given by Preisinger (2018), namely 325 eggs per hen per year, was used as a baseline. When assuming a constant feed intake, increasing the number of eggs to its biological maximum (365 eggs per year) would reduce the feed consumption by 11% per unit of egg mass, and the reductions in the GHG emissions related to feed production, processing and transport would be of similar magnitude (when assuming no change in feed composition). In addition to emissions related feed production, improved feed efficiency would also reduce the manure emissions. Considering a typical protein content of layer feed (Leinonen et al. 2012b) and the protein content of eggs, the changes in nitrogen excretion as a result of increased egg production can be calculated. Similarly as in the case of the broiler analysis above, the GHG emissions arising from layer manure management were assumed to be proportional to the amount of excreted nitrogen. Based on these calculations, increase of the egg production to its biological limit would result in a further reduction by 7% of the manure GHG emissions. As a result, when only the laying period is considered, this improved feed efficiency would reduce the total GHG emissions by 9%. However, it should be note that the period of raising the pullets (young birds) was not included in these calculations. It can be assumed that there will be no major changes in the feed efficiency of pullets, because pullet traits such as growth rate are not amongst the primary targets of breeding. Therefore, assuming that the emissions from puller rearing would remain constant, the overall potential reduction of the GHG emissions arising from the entire egg production chain as a result future breeding would be only about 7%.

One of the challenges for future hen breeding is that although the focus is likely to remain on the high production rate at competitive cost, there will be additional requirements that are affected by changing consumer habits and public opinion (Preisinger 2018). Following new legislation and public demand, the egg production industry has gone through major changes during the last decade in the EU, and such changes are expected to continue in the future. It is likely that the proportion of alternative production systems will continue to increase and this development needs to be taken into account also in breeding. The environment the hens are exposed to in alternative systems such as free range is very different compared to the previously dominant cage system, due to very large flock sizes and potentially stressful conditions. To maintain the high productivity also in the new systems, potential changes in hen behaviour may need to be focused in breeding. For example, reducing pecking behaviour and cannibalism may become important traits in selection, as may avoid egg losses, which is affected by nesting behaviour of the hens. Therefore, robustness and stress tolerance may be important traits in future breeding of the birds for alternative conditions.

6.4 Cost of breeding programmes and impact on farm economics

As a result of the new EU legislation that banned the conventional cage system in egg production from 1 January 2012, a research was carried that compared the production costs for eggs and egg products in several EU and non-EU countries (van Horne 2012). According to that study, similarly as in broiler production, feed was the biggest single cost in primary production before banning the cage production (van Horne 2017). When comparing the costs in seven European countries, it was found that the contribution of feed cost to the total primary production cost (including labour) varied from 48% to 64%. The second biggest cost component was pullets (young birds), the contribution of which varied from 20% to 25% of the total costs between countries. The combined costs of these two components varied between 73% and 85% of the overall costs of the primary production, depending on the country. These figures are comparable to the contribution of feed and young birds to the total costs of broiler production, indicating that there is an opportunity to considerably reduce the farm costs related egg production through breeding, in order to achieve even higher feed efficiency of the birds.

Following the new legislation, increased space allowance per bird has evidently lowered the bird density per m2 in a poultry house. As a result, the investment for housing and equipment has increased. It has also been suggested that for the enriched cage and for alternative housing systems such as aviary, the labour needs and investments for house and equipment per hen have increased. (van Horne 2012). However, the move from battery cages to enriched cages has had no negative effects on bird performance (Leinonen et al. 2014). So the efficiency has remained high and the costs related to feed have likely remained constant or even decreased. However, in alternative systems (barn, aviary, free range), where the bird activity is likely to be higher, environmental conditions less stable and the loss of eggs probably higher (Leinonen et al. 2012b), the feed costs are expected to be slightly increased.

When considering these changes, van Horne (2012) made some calculations on the differences of production costs between the old battery cage system and new, alternative systems. According to those calculations, there would be a 7% increase in the total cost per kg of eggs when moving from the conventional cage system to enriched cages, and a 22% increase when moving from conventional cages to an aviary system. Furthermore, van Horne (2012) stated that in general, due to environment and welfare regulations, the costs of egg production are higher in the EU than in many other large egg producing countries. For this reason, it is obvious that breeding for higher feed efficiency will remain an important goal for reducing the total costs of egg production.

In addition to the direct farm costs, new environmental and welfare regulations and changing consumer preferences are expected to increase the costs of the breeding programmes themselves. Preisinger (2018) stated that due to the diversification of the systems and the demand for certain types of layers, "maintaining and developing new lines, testing, selection and reproduction of primary stocks involve high fixed costs in the operation and require superior skills in quantitative genetics as well as internal organization to keep track of the availability of different sub-lines for niche markets".

Concerning the social costs and benefits, similarly as in broiler production, improved feed efficiency would reduce many other environmental burdens, in addition to the GHG emissions. Achieving the full egg production potential and at the same time improving the feed efficiency to its biological limits would result in reduction in nitrogen excretion by 7%, which would reduce eutrophication, acidification and direct and indirect global warming arising from manure management.

6.5 Barriers to achieving reductions

One of the limitations of achieving the full reduction in the GHG emissions of egg production is related to the diversity of the production systems in the future. However, some of such system changes can be seen as opportunities rather than barriers. For example, it was shown that the new system with enriched cages and highly modernized new poultry houses has actually improved the efficiency of production compared to the old battery cage system (Leinonen et al. 2014). However, it is very likely that when using the alternative systems such as barn, aviary, free range and organic, it is not possible to achieve the same level of efficiency that has been observed in the enriched cage system. The high feed efficiency is limited in alternative systems by higher activity of the birds, which will result in higher energy loss in form of heat, and that would reduce the efficiency of feed conversion. Furthermore, it would be more difficult to control the environmental conditions especially in the free range system, and for example the temperature may not be optimal ("thermally neutral") for the chicken. This could result in further reductions in feed efficiency.

Earlier studies have shown that although the environmental conditions may not be optimal for the birds, relative high production rates can also be achieved in alternative egg production systems (Leinonen et al. 2012b). However, a bigger threat to the efficient production may come from higher unpredictability of the alternative systems. The changing conditions in the free range and organic systems may be stressful to hens (Leenstra and Sambeek 2014). Furthermore, it has been suggested that with organic production, the dietary requirements can make it difficult to formulate adequate diets, and that may also imply stress. In free range conditions, preventing of various diseases will be much more difficult than in highly controlled cage housing systems. In such conditions, the robustness of the bird may become an important property and an important target of breeding (Leenstra and Sambeek 2014).

6.6 Future research needs

In order to improve the efficiency of layers within the biological limits of egg laying capacity, it will be necessary to extend the period during which the maximum rate of laying (i.e. one egg per day) is possible. To achieve this, better understanding on the physiology of age-related changes in laying and the elements that trigger these events would be necessary (Arthur and Albers 2003). Understanding of these processes is needed for more effective selection, and it is connected to genetic research that would need to identify specific genes that influence the egg laying capacity related to ageing (Arthur and Albers 2003).

The diversity of future production systems brings new complications to predictions of the GHG emissions arising from poultry production, and new modelling studies are needed to fully understand the GHG emission intensities and other environmental indicators in the new systems. The bird performance is a key factor in such systems, and the environmental impact assessment models should be able to predict possible changes and variation in performance in different conditions. Modelling of the variation in feed efficiency in layers has for a long time been based on an empirical relationships between the expected feed intake and "metabolic" body weight, body weight gain and egg mass production (Thiruvenkadan et al. 2010), and focus of those analyses has been in the error term of such equations, called "residual feed consumption". Although the approach is practical, it does not provide much mechanistic understanding on the bird energy requirements and energy flows. For this reason, more process-based energy balance models are needed, similarly as in broiler research (Leinonen et al. 2016, Tallentire et al. 2016, 2018). Such modelling work would help to better understand the biological limits of the energy efficiency of layer birds, and to better predict how the efficiency could be maintained or improved in alternative egg production systems through breeding programmes specializing for producing birds for a wide range of alternative production systems.

7 The abatement potential from livestock breeding in Europe

7.1 Quantifying the abatement potential

In order to provide a preliminary estimate of the abatement potential that could arise from breeding in Europe, the maximum likely percentage reduction in each emissions category was multiplied by the 2015 emissions (based on FAO 2017, see Figure 2). The reductions in emissions (i.e. abatement potentials) are given in Table 6. The abatement potentials are the amount by which the annual emissions would be reduced after 20 years of continuous genetic improvement, with constant output. It was assumed that the minimum change in emissions would be zero, i.e. the abatement potential ranges from 0 to 53.5MtCO$_2$e/year. This is the abatement potential for conventional breeding goals; it is possible that further reduction could be achieved by targeting new traits, i.e. a further abatement potential of 5MtCO$_2$e/year may be achievable by specifically breeding for reduced methane emissions in cattle.

Table 6. Estimated reduction in emissions that could be achieved via livestock breeding in Europe*

	Total GHG in 2015	**Abatement potential by 2029**	
	MtCO$_2$e/year	MtCO$_2$e/year	% reduction
Cattle milk	257.9	22.7	8.8%
Cattle meat	177.3	10.3	5.8%
Pig meat	179.4	16.5	9.2%
Chicken meat	36.6	3.0	8.2%
Hens eggs	17.2	1.1	6.2%
Total	**668.3**	**53.5**	**8.0%**

*Defined as the EU plus a small number of non-EU states, i.e. Belarus, Moldova, Ukraine, Albania, Bosnia and Herzegovina, Montenegro, Serbia, Republic of North Macedonia, Switzerland, Norway, Iceland and the Faroe Islands

7.2 Achieving the abatement

In order to fully realise the abatement potential in Table 6, barriers to the uptake of improved genetics need to be overcome. Within the dairy cattle sector, there have been impressive rates of genetic improvement and uptake of allied technologies (artificial insemination and sexed semen). Genetic improvement in the beef sector has been slower and unlocking the untapped genetic potential in the beef cattle population may be aided by schemes that improve the recording of animal performance data or provide greater clarity and certainty regarding the financial benefits of investing in genetic improvement. Research could support his by improving understanding of the impact of improved genetics on farm profit, and identifying ways of internalising the external benefits of breeding (such as reduced methane excretion).

Breeding has contributed to significant increases in pig growth rates and sow fertility in recent years, significantly increasing sow productivity. However rebound effects may have offset the improvements in FCR (and associated reductions in GHG emissions). The evidence suggests that scope remains for reducing GHG emissions from pig production via breeding, though these may not be fully realised in practice, due to the limitations of the production environment. Future research priorities include investigating: (a) the trade-offs between improved nutrient use efficiency and disease resistance to identify the optimal combinations that can reduce EI while improving financial performance (b) non-production traits that can reduce EI by improving FCR (c) the extent to which practical barriers (such as the limitations of the production environment) and rebound effects may constrain the GHG reduction potential.

In chicken production changes in the traits associated with feed efficiency largely determine the changes in emissions intensity, and they are also a central target of breeding. The success of the broiler breeding programmes since 1950s has been quite spectacular, and improvements in the main traits such as growth rate and feed efficiency (which are associated with reduced GHG emissions intensity) probably exceed the achievements in any other production animal. The evidence suggests that that the opportunities for further improvements in the feed efficiency of the broilers are rather limited. Genetic improvements in feed efficiency are possible for laying hens, however in order to maintain the high productivity in the new housing systems, breeding may need to focus on hen behaviour, limiting the scope for reductions in GHG emissions intensity.

8 Conclusions

The evidence suggests that there is, in theory at least, significant potential to reduce EU livestock GHG emissions via genetic improvement. Perhaps unsurprisingly, given their contribution to EU emissions, the largest predicted reductions are from cattle and pigs. Smaller reductions are also possible for chickens, however these may be difficult to realise while meeting consumer demand for more welfare-friendly and less intensive rearing systems.

While there is scope to significantly increase dairy cow milk yield via breeding, the consequent reductions in EI are likely to be modest, i.e. in the range 0% to 0.5% per annum. It is estimated that a reduction in EI from genetic improvement of beef cattle of between 0% and 0.25% per annum could be achieved in the future. For both beef and dairy cattle, further reductions in EI may be achieved by targeting new traits, e.g. feed utilisation efficiency and rumen ecology. Recent evidence indicates that the genetic improvement of cattle can reduce emissions while providing financial benefits.

For pigs, sustaining the recent increases in growth rates and sow fertility should lead to a reduction in the emissions intensity of pigmeat of around 0.3% per annum. This reduction should be achievable at low/no cost as the financial benefits of improved physical performance should outweigh the costs.

The potential for reducing broiler emissions through breeding is relatively low, likely no more than 10% compared to the level of the current intensive broiler production. The GHG reductions for laying hens are likely to be modest.

Research priorities: cattle

Future research priorities include: (a) quantifying the changes in EI once wider system level effects are included (b) identifying best practice of reducing EI via beef genetic improvement within the EU (c) investigating the extent to which new traits could reduce EI and be integrated into breeding goals (d) investigating the social acceptability of nascent technologies and (e) quantifying the effects of increased dairy cow milk yield on the EI of European beef as a whole.

Research priorities: pigs

Future research priorities include investigating: (a) the trade-offs between improved nutrient use efficiency and disease resistance (b) non-production traits that can reduce EI by improving FCR (c) the extent to which practical barriers (such as the limitations of the production environment) and rebound effects may constrain the GHG reduction potential.

Research priorities: chickens

Reducing chicken emissions may be facilitated by the development of mechanistic models that link the environmental performance of different broiler/layer genotypes to physical energy and mass balance calculations. Research is also required to better understand the limits of the laying capacity of the hen, in particular the duration of the period of maximum rate of lay.

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List of abbreviations

AHDB: Agriculture and Horticulture Development Board (UK)

AI: Artificial insemination

AP: Abatement potential

AR: Abatement rate

ASFV: African swine fever virus

CE: Cost-effectiveness

CEA: Cost-effectiveness analysis

CW: Carcass weight

DEFRA: Department for the Environment, Food and Rural Affairs (UK)

EI: Emissions intensity (i.e. the kg of GHG per kg of output)

FAO: The Food and Agriculture Organization of the United Nations

FAOstat: FAO Statistics

FCR: Feed conversion ratio (i.e. the kg of feed input per kg of liveweight gain)

GHG: Greenhouse gas

GLEAM: the Global Livestock Environmental Assessment Model

IPCC: Intergovernmental Panel on Climate Change

LUC: Land use change

LW: Liveweight

LWG: Liveweight gain

Nx: Nitrogen excretion

PRRSV: Porcine reproductive and respiratory syndrome virus

Px: Phosphorous excretion

SCC: Social cost of carbon

UNFCCC: United Nations Framework Convention on Climate Change

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