# Sustainability assessment of chicken meat production

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# Abstract

As the global appetite for chicken meat grows, the competition for scarce land, water and other natural resources intensifies, whilst virtually all aspects of the environment are adversely affected. There is also increasing public concern over the standards of farm animal welfare. Hence, the aim of this thesis was to assess the sustainability of the poultry industry, identify its future challenges and evaluate potential solutions.

Artificial selection of chickens for commercial objectives has been employed at an unprecedented magnitude over recent decades. In terms of sustainability, feed provision represents the poultry industry's biggest challenge. Thus, understanding the interactions between genetic change and energy use efficiency was necessary to quantifying the industry’s future impacts. Modern chickens reach slaughter weight more quickly than in the past and therefore less energy overall is used in metabolic processes. However, continuing artificial selection for efficiency will be subject to both biological limits and animal welfare concerns. Using an analytical energy flow modelling approach, the potential genetic improvement in energy use efficiency was shown to be small relative to past progress.

To understand fully the environmental impacts of the poultry industry, a holistic diet formulation methodology was developed, which employed both Life Cycle Assessment (LCA) and linear programming to account for environmental burdens and bird nutritional requirements. Europe presented much opportunity to reduce the environmental impacts associated with the poultry industry via changing the formulation of the feed. Both conventional and novel ingredients were considered; the latter presented enormous potential for use as alternatives to conventional feed protein sources, mitigating the increased environmental burdens inherent in transitioning towards a high welfare chicken meat production system in the future.

Finally, an innovative methodology that can account for bird welfare within a social LCA framework was developed. By applying this methodology, an association was found between the number of birds reared together in a building and the negative welfare impacts related to chicken meat production in Europe.

The methodologies developed in this thesis facilitate the development of sustainable feeding strategies and animal management choices for future livestock production systems.

# Declaration

This thesis has been composed by me and has not been submitted as part of any previous application for a degree. All sources of information have been specifically acknowledged by means of referencing.

C. W. Tallentire

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# Publications and conference presentations

The following publications have been produced from the research in this thesis and appear in peer reviewed journals:

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- Tallentire, C. W., Mackenzie, S. G. & Kyriazakis, I. 2017. Environmental impact trade-offs in diet formulation for broiler production systems in the UK and USA. *Agricultural Systems,* 154, 145-156.
- Tallentire, C. W., Leinonen, I. & Kyriazakis, I. 2018a. Artificial selection for improved energy efficiency is reaching its limits in broiler chickens. *Scientific Reports,* 8, 1168.
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The following work has been presented at conferences:

- Tallentire, C. W., Mackenzie, S. G. & Kyriazakis, I. How important is the region in determining the nutritional strategy applied to broiler systems in order to reduce environmental impact? *In:* Proceedings of the 10th International conference on Life Cycle Assessment of Food, October 2016, Dublin, Ireland.
- Tallentire, C. W., Mackenzie, S. G. & Kyriazakis, I. Determining broiler system nutritional strategies to reduce environmental impact in two regions. *In:* Proceedings of the 21st European Symposium on Poultry Nutrition, May 2017, Salou/Vila-Seca, Spain.
- Tallentire, C. W., Mackenzie, S. G. & Kyriazakis, I. Novel feeds for future chicken lines to enhance sustainability. *In*: Proceedings of the 11th International Conference on Life Cycle Assessment of Food, October 2018, Bangkok, Thailand.

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# List of Abbreviations

| | |
|---|---|
| ALU | Agricultural Land Use |
| AP | Acidification Potential |
| BPM | Bacterial Protein Meal |
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| d | Days |
| Defra | Department of Environment, Food and Rural Affairs |
| $D_{efficiency}$ | Coefficient of Digestive Efficiency |
| DDGS | Dried Distillers Grains with Solubles |
| DOA | Dead On Arrival |
| EFSA | European Food Safety Authority |
| ELCA | Environmental Life Cycle Assessment |
| EP | Eutrophication Potential |
| Equiv | Equivalent |
| EU | European Union |
| FAO | Food and Agriculture Organisation |
| FCR | Feed Conversion Ratio |
| FWEP | Fresh Water Eutrophication Potential |
| g | Gram |
| GEI | Gross Energy Intake |
| GER | Gross Energy intake Rate |
| GHG | Greenhouse Gas |
| GWP | Global Warming Potential |
| IPCC | International Panel on Climate Change |
| K | Potassium |
| Kg | Kilogram |
| kWh | Kilowatt-hour |
| LCA | Life Cycle Assessment |

| | |
|---|---|
| LEAP | Livestock Environmental Assessment and Performance partnership |
| LPC | Leaf Protein Concentrate |
| LW | Live Weight |
| ME | Metabolizable Energy |
| MEP | Marine Eutrophication |
| MER | Metabolizable Energy intake Rate |
| MHR | Metabolic Heat production Rate |
| MJ | Megajoules |
| mrh | Medium risk hours |
| N | Nitrogen |
| $NH_3$ | Ammonia |
| $NO_x$ | Nitrogen oxides |
| $NO_3$ | Nitrate |
| $N_2O$ | Nitrous oxide |
| NREU | Non-Renewable Energy Use |
| P | Phosphorus |
| $PO_4$ | Phosphate |
| RSPCA | Royal Society for the Prevention of Cruelty to Animals |
| SHDB | Social Hotspot Database |
| SHI | Social Hotspot Index |
| SLCA | Social Life Cycle Assessment |
| $SO_2$ | Sulphur dioxide |
| TAP | Terrestrial Acidification Potential |
| UK | United Kingdom |
| USA | United States of America |
| USDA | United States' Department of Agriculture |
| YPC | Yeast Protein Concentrate |

# Chapter 1. General introduction

## 1.1 Overview

The chicken (*Gallus gallus domesticus*) has been a reliable food source since its domestication in Asia in the late Neolithic period (Wood-Gush, 1959, West and Zhou, 1988, Liu et al., 2006, Siegel, 2014); however, it was not until recently that chicken meat achieved the cultural and culinary dominance it has today. In the last century, the chicken has inspired countless contributions to science and become a ubiquitous staple food, thanks to a lack of societal boundaries and advancements in the knowledge of genetics and animal husbandry (Siegel et al., 2006, Schmidt et al., 2009, Siegel, 2014).

The increased importance placed on the sustainability of food production in recent times has been reported to be broadly reconcilable with the progress that has been made within the poultry industry. For instance, chicken meat production has relatively low environmental impacts compared with meat produced by other livestock sectors (Williams et al., 2006, 2007). This can be attributed, in part, to decades of intensive artificial selection and improvements made in bird nutrition. However, due to the widespread consumption and increasing popularity of chicken meat, further improvements in sustainability are sought after (Leinonen et al., 2013, MacLeod et al., 2013, Nastasijevic et al., 2015).

In seeking further progress towards sustainable agri-food systems, the research presented in this thesis explores the potential implications for sustainability of alternative chicken diets and future artificial selection outcomes. The potential increase in growth rate via artificial selection, given the birds' biological limits of energy intake and energy partitioning, was predicted. Thus, future chicken nutritional requirements could be estimated. Increased growth rates have been associated with reduced animal welfare (Bessei, 2006, EFSA Panel on Animal Health and Welfare, 2010, Rodenburg and Turner, 2012, Meseret, 2016), hence the growing market demand for slow-growing birds has also been considered. Finally, a novel methodology for assessing animal welfare on chicken farms was developed. In this first chapter the challenges associated with modern chicken meat production, and how they have been addressed throughout this thesis, have been outlined.

## 1.2 Research context

### *1.2.1 The origin of the broiler chicken industry*

As was first speculated by Darwin (1868), most research indicates the Red junglefowl (*Gallus gallus*) was the main progenitor from which all modern commercially reared chickens descended (Fumihito et al., 1994, Hillel et al., 2003), with other research strongly suggesting various degrees of hybridization having occurred with other species (*Gallus spp.*) (Nishibori et al., 2005, Liu et al., 2006, Eriksson et al., 2008, Eltanany and Distl, 2010, Storey et al., 2012). The bird naturally displayed group social structure, high fecundity, limited agility and a large natural range; traits that made it predisposed to domestication and widespread dispersal. Thus, the chicken eventually spread across the globe where, due to a combination of genetic drift in geographical isolation and artificial selection for desired characteristics based on specific cultural requirements, they developed into hundreds of breeds (Tixier-Boichard et al., 2011). These characteristics include but are not limited to: size, musculature, colour, egg yield, egg colour, plumage and the appearance of the comb and other appendages (Albers et al., 2006).

Standards of excellence were first established in the 19th century as a way of classifying breeds (The Poultry Club, 1865), as breeding chickens continued to become a more sophisticated endeavour (Felch, 1888). However, it was not until the last century that scientifically based selection methods were applied to breeding programmes (Derry, 2015). During this time chicken breeding went through profound changes due to the emergence of new science, changes in the organization of the agri-food sector and, importantly, communication channels opening between scientists and breeders.

The age of modern genetics was ushered in by the rediscovery and verification of the laws of Mendelian inheritance at the turn of the 20th century (Simunek et al., 2011). Much research followed, and the poultry industry was subsequently split into two sectors: one dedicated to rearing meat-producing birds and the other to egg production (Siegel et al., 2007). Although it would take several decades before the influence of modern genetics were thoroughly adopted by the poultry industry (Hunton, 2006, Derry, 2015), the interest in the bird genetics was intensified by this market shift which led to the emergence of the broiler industry (Albers et al., 2006). No longer was meat production a by-product of the egg-laying industry and so selection pressures were able to move from improving egg production to improving meat production (Siegel et al., 2007). Long-term selection experiments involving numerous types of poultry were initiated; commercial breeding companies emerged, taking these experimental procedures into the arena of industrial application (Hunton, 2006).

Eventually mathematical-statistical approaches to genetic selection were established as the norm within the industry (Henderson, 1953). Superior breeding candidates were identified through the use of pedigree-based estimated breeding values (Rishell, 1997, Muir and Aggrey, 2003). This technique resulted in the magnitude of genetic change witnessed in meat-producing chickens (hereinafter also referred to as “broilers”) over the recent decades discussed in Chapter 2 (Faraday, 2007, Laughlin, 2007, Zuidhof et al., 2014, Tallentire et al., 2016).

Natural selection ensures the alleles, which produce the most successful phenotype, are propagated in a natural population and artificial selection ensures the alleles, which produce a phenotype with traits desirable to humans, are propagated within the pedigree lines (Dawkins, 1976). Likewise, competitive forces have assured that only breeding programmes (and the breeding companies that employ them) that effectively devoted emphasis to the traits demanded by the market have survived until today. The world market is now dominated by only a handful of companies: Aviagen, Cobb-Vantress and Hubbard. Each of these companies are active in both conventional and slow-growing chicken parent stock production, although each company focuses on one of these markets specifically. For instance, in the UK the two largest companies, Aviagen and Cobb-Vantress, produce between 70-80% and between 20-30% of the parent stock of meat-producing chickens respectively (Defra, 2006, CMA, 2018). Consequently, there has likely been substantial losses in genetic resources, as lines were either lost as companies failed, or lines were combined as companies merged. Furthermore, as gene flow does not occur between pedigree and non-commercial birds, some degree of inbreeding is inevitable (Muir et al., 2008). This may result in homozygosity, increasing the chances of birds being affected by deleterious traits or reduced immunity to future diseases (Decuypere et al., 2010). Thus, questions arise as to whether sufficient genetic diversity remains within industry stocks to address future needs.

It is understood that many instances of bird ill-health are the result of intensive selection for growth rate (Gonzales et al., 1998, Gonzales et al., 1999, Bessei, 2006, Fanatico et al., 2008, EFSA Panel on Animal Health and Welfare, 2010, Rodenburg and Turner, 2012, Meseret, 2016). In addition, it has been shown that high occurrences of meat quality-reducing myopathies correlate with faster growth and increased breast muscle yield (Kuttappan et al., 2013); these are determined by a combination of differences in growth patterns and diet. Whilst reducing instances of such myopathies in fast-growing birds has been shown to be possible (Alnahhas et al., 2016, Kuttappan et al., 2016, Beauclercq et al., 2017), the appearance of the reduced quality meat has been shown to negatively impact upon customer acceptance in the meantime (Kuttappan et al., 2012). This will potentially harm the product's reputation, impact the industry's bottom line and exacerbate the market shift towards meat from birds that grow more slowly. Information on past trends, combined with the issues discussed in this section and the apparent limits of genetic change determined by underlying bird biology (discussed in Chapter 4), ultimately defined the future chicken production scenarios that have been presented later in this thesis.

### *1.2.2 Meat production and its "long shadow"*

The human population has grown exponentially since the end of the 19th century. As of 2017, the world population stood at an estimated 7.6 billion and is expected to reach 9.8 billion by the year 2050 (United Nations, 2017). Humans, their livestock and pets have been estimated to account for around 98% of the terrestrial vertebrate biomass (Dennett, 2017, Bar-On et al., 2018). This has had global scale environmental and social implications for which we need to take responsibility as a species, as MacCready (1998) explained:

> *"Over billions of years, on a unique sphere, chance has painted a thin covering of life - complex, improbable, wonderful, and fragile. Suddenly we humans… have grown in population, technology, and intelligence to a position of terrible power: we now wield the paintbrush."*

Resources are finite; thus, livestock farming is under increasing pressure to become more efficient to meet the demands of a growing global population within Earth's carrying capacity. Agricultural activities account for 38% of the planet's total land area, which is further divided between pasture (≈68%), plantations and orchids (≈3%) and arable land used for annual crops (≈29%) (FAO, 2014b, The World Bank, 2014); a third of this arable land is used to produce feed for livestock (Steinfeld et al., 2006, Mottet et al., 2017).

Not only does the livestock sector require a considerable amount of land, it also accounts for a large portion of global freshwater use, greenhouse gas emissions, water and land pollution, land-use change and is a threat to biodiversity (Steinfeld et al., 2006, FAO, 2012, Mekonnen and Hoekstra, 2012, Vermeulen et al., 2012, Herrero et al., 2013, Springmann et al., 2016, Sell-Kubiak et al., 2017). Expansion of the livestock sector has been a major contributor to deforestation, especially in South America. Deforestation is the second largest anthropogenic source of carbon dioxide ($CO_2$) released to the atmosphere, after fossil fuel combustion (van der Werf et al., 2009). Furthermore, in the pursuit of increasing short-term crop production via modern agriculture practices, long-term losses in ecosystem services due to the degradation of soil and water quality can be expected (Foley et al., 2005).

As the wealth of developing countries grows, so does their appetite for meat products (Boland et al., 2013). Paired with population growth, the collective production of meat is expected to reach 455 million tonnes by 2050, an increase of 100% since the turn of the millennium (Steinfeld et al., 2006, Alexandratos and Bruinsma, 2012). The global demand for poultry meat, in particular, is rapidly increasing (Windhorst, 2006, 2011). It is estimated that, at any one time, domestic chickens now outnumber humans 3:1 (FAO, 2016b). The poultry meat industry is the only land-based meat sector predicted to increase its market share over the next decade (European Commission, 2017b).

To meet the increasing demand for chicken meat, farming has become (and continues to become) more intensive in Europe; that is, the number of birds that are reared together and the size of the farms on which they are reared have increased (Wasley et al., 2017). Traditionally, chickens were reared in what nowadays may be referred to as “backyard production systems” (Pathak and Nath, 2013). Birds would have been able to scavenge for food whilst their owners would have provided grain and food scraps to supplement their diets. In return, owners ate or sold locally the birds and their eggs (Hamilton-West et al., 2012). These low input, low output systems were how birds were typically kept since their domestication up until the 20th century and, whilst this production system is still important for the poorest of communities (Dolberg, 2007, Sonaiya, 2008), the research that has been presented in this thesis focuses on broilers reared in what is now considered the “conventional system”. Birds reared in this way are done so on an industrial scale, in large flocks, indoors in climate-controlled, often artificially lit facilities.

### *1.2.3 Breeding of broilers*

Modern poultry production systems grew out of the purebred chicken industry and were established by applying modern breeding strategies to various breeds that had evolved over the centuries; notable breeds include the White Leghorn, Rhode Island, Cornish Game and Plymouth Rock (Albers et al., 2006). Highly efficient selection programmes have resulted in a few highly specialized lines that dominate today's world market (Emmerson, 1997). This genetic material is held by: Aviagen Broiler Breeders, Cobb-Vantress and Hubbard. These chickens have been subjected to intensive selection pressure, primarily directed at economic traits, which has increased energy efficiency and increased growth rate, reducing costs of production. Hence, the trend over recent decades has been that these broiler chickens have been reared and then slaughtered, en masse, at an increasingly younger age (Emmans and Kyriazakis, 2000).

Modern commercially produced broilers are typically a cross of three or four lines, each intensively selected based on a set of breeding goals dictated by the market requirements of the meat-producing birds (Pollock, 1999, Hiemstra and Napel, 2013). The pedigree birds are reared in flocks at multiple, geographically spread and bio-secure breeding facilities where they are subjected to intensive artificial selection. At this level, the lineage of each bird is closely monitored, so that information on the performance of the birds' relatives can be used to identify which birds should be selected (Katanbaf and Hardiman, 2010). Inbreeding is minimised by keeping the average genetic relationship within the group as low as possible, whilst the average value for the selection index is kept high (Bijma et al., 2001).

The second stage (great-grandparent stock) involves pure-bred multiplication, with the objective of producing sufficient birds from each pedigree line without having to increase the size of the pedigree flocks. To facilitate this, many more birds are produced from the maternal lines. Although artificial selection still takes place at this stage by rejecting visibly low performing birds, no genetic material flows back into the pedigree flock. At the next stage, the four lines (grandparent stock) are crossbred to produce two crossbred lines which form the parent stock. These two crossbred lines are then crossed to produce the broilers which will be reared for the meat market (Hiemstra and Napel, 2013). The crossbreeding process is carefully implemented so that all birds of any given marketed broiler line display consistent performance potentials.

Combined with the high reproductive rates and short generation intervals of the chickens, the vertically integrated structure of commercial poultry production has permitted the widespread and rapid application of new technologies to large numbers of birds (FAO, 2009). The number of pedigree birds in the genetic selection programme is relatively small compared with the number of crossbred broilers that are eventually produced after four stages of multiplication. The genetic time lag from the pedigree birds to the meat-producing birds is around 4 years (Pollock, 1999). The market requirements that determine the weight that is given to each individual trait in the selection process are ultimately dictated by the customers and have changed over time; the societal and economical aspects accounted for by the breeding programmes have been discussed throughout this thesis.

### *1.2.4 Sustainability of livestock systems*

Sustainability is the end-point whereby everybody achieves at least a socially acceptable quality of life while living within the natural limits of the planet. Progress towards this goal can be referred to as sustainable development. This has been described in many different ways (Blowfield and Murray, 2014). However, the most widely used working definition of sustainable development was put forward by the United Nation’s Brundtland Commission (Brundtland et al., 1987), which is based on the principle of intergenerational equality:

> *“Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”*

Sustainability, as it is defined above, is about ensuring an increasing global population is not malnourished by addressing its evolving food and energy demand, whilst decoupling socio-economic development from environmental impact. The dimensions that sustainability is comprised of (i.e. economy, society and environment) and their interactions are illustrated in Figure 1.1. Allocating all resources into only one dimension may optimise that dimension at the expense of others, highlighting the fact that sustainability is often a trade-off between the three (Figure 1.1a). The dimension that has by far received the most attention from most industries until now has been the economic dimension (Elkington, 1997). The livestock sector is no exception to this rule and this has driven the changes witnessed in chickens over in the last century (Zuidhof et al., 2014). Figure 1.1a has been criticised, however, for not accurately presenting the economy as subsidiary to nature (Senge, 2008, Young and Dhanda, 2012). Another example of how sustainability can be visualised is the "fried egg" model (Figure 1.1b). This model better reflects the emphases of this thesis, where more attention was given to the environmental impacts of chicken meat production than the social impacts, which in turn received more attention than the economic impacts. Albeit the model is less well-known than the basic Venn diagram (Figure 1.1a), Figure 1.1b shows that the economy operates within the limits set on it by society (e.g. equality, justice, liberty etc.), which in turn must operate within the hard ecological limits placed on it by the environment (Kane, 2011).

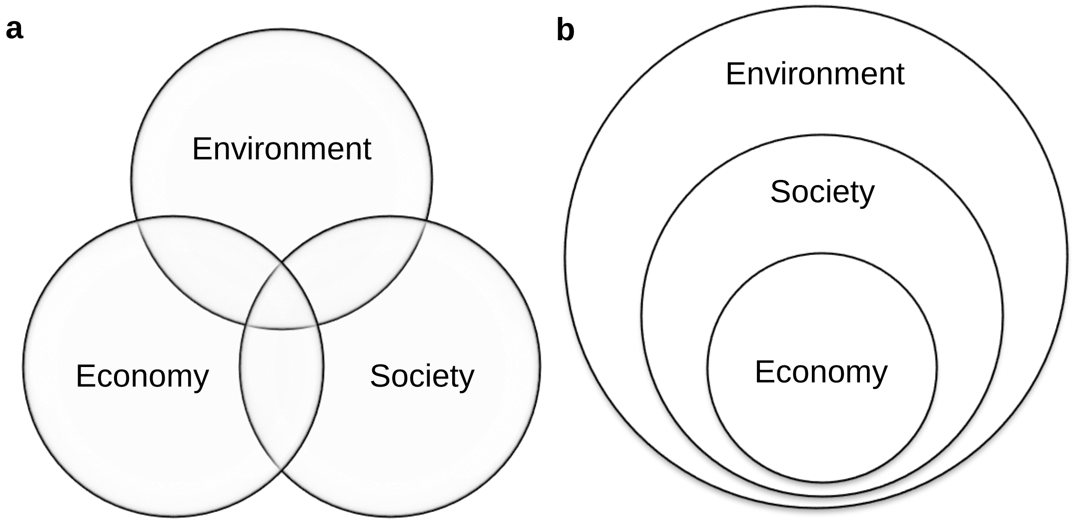

**Figure 1.1**: Diagrams illustrating the relationship between the three dimensions of sustainability, i.e. the economy, society and the environment: a) the "Venn diagram" model of sustainability and b) the "fried egg" model of sustainability.

The advent of agriculture led to the formation of villages, cities, societies, government – the birth of civilization. This human investment into the planet was made possible by the relatively stable environmental conditions presented by the Holocene, the interglacial period that began over 10000 years ago. Where reliable seasons allowed an increasing population to feed themselves, and where knowledge accumulated, and science began. However, we have now entered a new epoch known as the "Anthropocene", characterised by human activity being the dominant influence on the climate and the environment (Crutzen, 2006). In order to minimise the disruption to the environmental conditions that allowed us to flourish - the climate that our food systems and infrastructure have been built upon - we must become an active steward of all planetary boundaries, of which Rockström et al. (2009) described nine. Three of these identified boundaries (climate change, biodiversity loss and the rate of interference with the nitrogen cycle) have likely already been transgressed. The transgression of one boundary may jeopardise our ability to stay within other planetary boundaries, e.g. ocean acidification. However, many boundaries are simply not known and so the precautionary principle must be applied. Much work is still needed in identifying Earth system thresholds such as these in order to fully assess the sustainability of the agri-food sector.

In the face of the threats posed by the livestock sector, such as runaway climate change and land degradation, and the increasing food demand from an increasing world population, greater scrutiny has been placed on the industry regarding its environmental impacts. In addition, issues related to poverty, inequality and food security remain concentrated in rural areas (FAO, 2017). The progress that is made towards the United Nations (2015) sustainable development goals for 2030 will depend on the extent to which sustainable agriculture is promoted moving forward. Such challenges have led to an increased interest in using models to quantify impacts as a means of finding ways to increase the sustainability of livestock production (Leinonen et al., 2012, de Boer et al., 2014, de Visser et al., 2014, Kebreab et al., 2016, Mackenzie et al., 2016a). Modelling impacts can involve a large array of approaches, from quantifying the emissions of a particular compound at one point during the production cycle, to more complex approaches which cover the inputs and outputs of more or less the whole production chain such as what was applied throughout this thesis.

## 1.3 Sustainability assessment methodologies

### *1.3.1 Life cycle assessment: framework and applications*

Life Cycle Assessment (LCA) is a technique used to quantify the impacts of a product or service holistically over its lifetime (Benoît-Norris et al., 2012). This means that the whole system is considered within predefined boundaries; thus, raw material extraction, manufacture and waste streams are all included. Product distribution and the use phase may also be considered. The methodology may be used to aggregate inputs and outputs of resources and the release of chemicals to air, water and soil into several environmental impact categories. The methodology can also be used to identify socio-economic risks in the supply chain, in order to carry out a sustainability assessment of a system. As an effective tool for identifying hotspots within systems, direct applications of LCA include but are not limited to: product development and improvement, enhancing production efficiency, strategic planning, public policy making and marketing. Thus, LCA has been applied by governmental organizations, nongovernmental organizations and industry in a wide variety of sectors (Rebitzer et al., 2004). Through the application of LCA methodology within the research presented in this thesis, it was possible to derive strategies that promote the shift towards sustainable agriculture and food production systems.

In the studies reported in this thesis, the focus of the research was on reducing impacts of chicken meat production, thereby increasing the relative sustainability of the poultry industry. Thus, using an LCA methodology was appropriate. Whilst LCA is the most widely used and accepted approach of measuring and documenting the degree of eco-efficiency of a product or service, it is worth mentioning that it is not the only methodology that can be used to assess sustainability. For instance, a cradle-to-cradle methodology could have been applied; this approach challenges the LCA methodology by envisioning an absolute sustainability (Bjørn and Hauschild, 2013). Such an approach would be of some interest in relation to the topic of this thesis, as it is worthwhile considering whether the outlook for chicken meat production could ever be sustainable (discussed further in Chapter 7, section 7.3.3). However, cradle-to-cradle methodology, and the products conceived by its approach, are not guaranteed to perform well with respect to the system characteristics considered by LCA. Meanwhile, the perception that human interaction with nature can be beneficial to all aspects of a system, and the assumptions used to arrive at such a view, are also debatable. Hence, the cradle-to-cradle methodology is regarded with some scepticism by researchers and can only be considered as a complementary tool that may be employed alongside LCA (Bakker et al., 2010).

LCA has several fundamental stages to which a practitioner must adhere when modelling a system (Figure 1.2), these are: 1) the identification and interpretation of the goal and scope of the study; 2) the compiling of an inventory of the system inputs and outputs and; 3) the impact assessment. Defining the goal and scope of a study is arguably the most important step of the LCA process and should be clearly defined at the outset, since all key design decisions should relate to it (Curran, 2017). Crucially, this involves outlining the functional unit. The functional unit of the product system is a quantified description of the performance requirements that the product system fulfils. By defining the functional unit, similar or alternative systems can be compared based on having comparable outputs that fulfil the same needs. As is very common in LCA studies of livestock systems, the functional units used in the studies in this thesis were based on live weight (LW) or the weight of the meat (Mackenzie, 2016). Compiling the inventory can be the most time-consuming stage of carrying out LCAs although it is often considered a straightforward procedure (Suh and Huppes, 2009). Quantifying of inputs and outputs for a given product system relies on careful interpretation of literature, national inventory reports and databases. Scientifically defined characterisation factors can then be applied to different emissions, social indicators and resource inputs associated with the system in order to quantify its overall impacts.

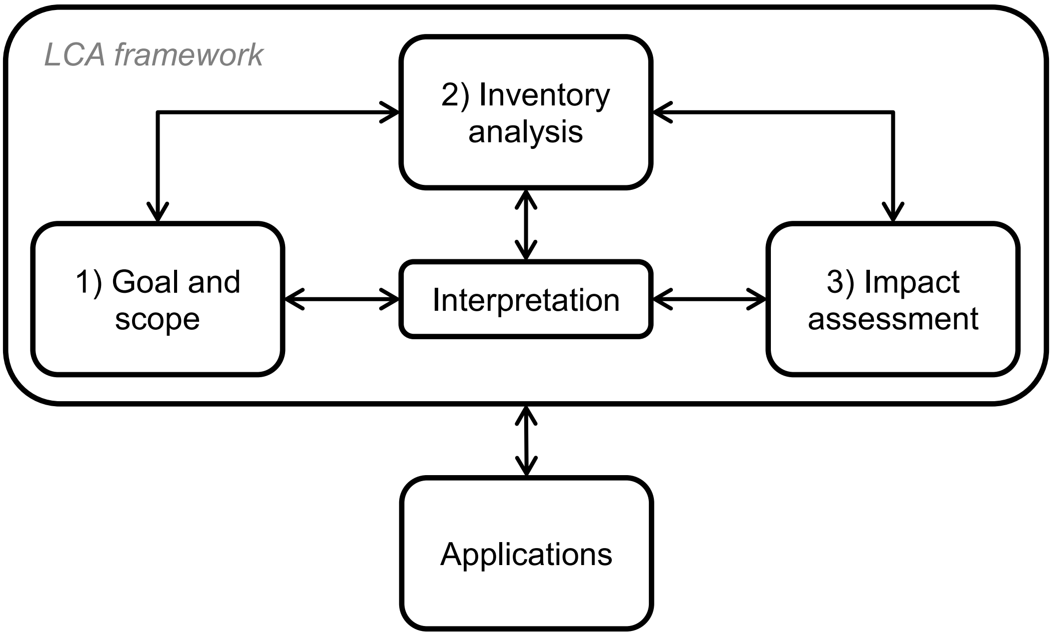

**Figure 1.2**: The fundamental stages of a Life Cycle Assessment (LCA) according to ISO 14040 (adapted from International Organisation for Standardisation, 2006).

A plethora of LCA methods have emerged in recent years (Guinée et al., 2018). This is understandable, as different challenges need different models and approaches to resolve them. As the questions practitioners ask become more complex, it is necessary that a suite of applicable models and approaches are developed to deal with this complexity.

An attributional LCA methodology was applied in the studies discussed in this thesis, as such models describe the pollution and resource flows within a chosen system attributed to the delivery of a specified functional unit. Attribution LCA is synonymous with co-product allocation (discussed in section 1.3.4). Alternatively, consequential LCA could have been applied. Consequential LCA estimates how pollution and resource flows within a system change in response to altering the output of the functional unit. Consequential LCA avoid co-product allocation, and the issues associated with it, by applying system expansion or substitution. But consequential LCA is more sensitive to uncertainties compared with attributional LCA, due to the inclusion of (often not known) market prospects. In addition, consequential LCA can be impractical; the adoption of system expansion or separation throughout entire LCA models can require large amounts of extra data, whilst increasing model complexity can reduce transparency and increase the risk of using inaccurate assumptions (Curran, 2007). For these reasons, the majority of existing meat production system LCA studies adopt an attributional approach to modelling the feed supply chain. In the relatively few studies where consequential LCA has been used to model meat production (e.g. Nguyen et al., 2011), none have applied LCA as part of a feed decision process as was the purpose of Chapters 3 and 5.

Defining LCAs as being either attributional or consequential overlooks studies that do not fit squarely into either definition and hinders constructive dialog when LCA models are seldom wholly attributional or consequential anyway (Suh and Yang, 2014). For instance, system expansion was implemented in the manure model in Chapter 3. The models presented here may be more accurately defined as "Integrated LCA", due to the LCAs being combined with other modelling approaches, i.e. linear programming (e.g. Chapters 3 and 5) and modelling future bird growth (e.g. Chapters 4 and 5). The LCAs in Chapters 4 and 5 may also be described as "Prospective LCA", due to the fact future impacts were estimated using scenarios and novel, not yet marketed product systems were considered (Guinée et al., 2018).

### *1.3.2 Environmental life cycle assessment*

An Environmental LCA (ELCA) can be defined as a systematic evaluation of the environmental aspects of a product or service system through all stages of its life, including production, its use and disposal phases (Guinée et al., 2002). The standardized methodology is described in ISO 14040/44 (International Organisation for Standardisation, 2006). The impact categories considered for the ELCAs reported in this thesis are discussed in this section; these were selected based on the recommendations made by LEAP (FAO, 2016a) and reflect some of the agri-food sector's biggest environmental challenges. The impact categories relate to several of the relevant parameters identified by Rockström et al. (2009), such as climate change, land use change, acidification and the nitrogen (N) and phosphorus (P) cycles. However, the assessment of water consumption and biodiversity loss is not currently recommended by the LEAP guidelines and so, although they are extremely important to sustainability, these impact categories were not considered in this thesis.

N and P excretion were considered in each ELCA study. These nutrients are classed as environmental burdens (Elser et al., 2007). Such environmental burdens can be aggregated into potentials, or other indicators, for causing environmental impacts. For instance, N or P is usually the limiting nutrient of aquatic biomass yield, e.g. algae and duckweed. Excess nutrients applied to agricultural systems (manure, synthetic fertiliser etc.) leach into soil and enter water bodies (Carpenter et al., 1998). Hence, the influx of the nutrient that is limiting in a water body will lead to an increased biomass load in a process known as eutrophication.

Food production accounts for ≈79% of global eutrophication (Poore and Nemecek, 2018), which results in reduced biodiversity and ecological resilience (Smith et al., 1999, Smith, 2003). This is because algal blooms or increased duckweed on the surface of the water blocks out sunlight, making the water body inhospitable for other autotrophs, whilst the increased decomposition of the biomass depletes oxygen. Freshwaters are typically limited by P (Schindler, 1977, Sharpley and Rekolainen, 1997, Correll, 1998), whereas N usually limits production of algal biomass in marine waters (Howarth, 1988, Howarth et al., 1996, Nixon et al., 1996). Hence, the eutrophication potential (EP) of a system can be split into fresh water (FWEP) and marine (MEP) categories, the values of which can be calculated using different fate factors to direct emissions to water. Where these impact categories have been applied, the framework used was consistent with the ReCiPe methodology, outlined by Goedkoop et al. (2008). The ReCiPe methodology is a recently developed and harmonised indicator approach, offering the broadest set of midpoint impact categories, including those recommended by LEAP (FAO, 2016a).

The agri-food sector also accounts for a considerable portion of global terrestrial acidification (Dentener et al., 2006, Lucas et al., 2011, Poore and Nemecek, 2018). Caused by the atmospheric deposition of acidifying compounds, such as nitrogen oxides ($NO_x$), ammonia ($NH_3$) and sulphur dioxide ($SO_2$), increased soil acidity can reduce plant productivity and thus disrupt ecological services (Azevedo et al., 2013, Huijbregts et al., 2017). The terrestrial acidification potential (TAP) of broiler production systems was also assessed using the ReCiPe methodology in Chapter 3.

In each ELCA study reported in this thesis, the global warming potential (GWP) was considered. The indicators of the GWP of a system are the emitted greenhouse gases (GHG), which insulate Earth by absorbing energy and then emitting it back towards the surface of the planet, instead of allowing it to escape the atmosphere into space. GHGs differ in longevity and in their ability to absorb this energy. It is these characteristics that determine the global warming capabilities of a gas. For instance, although much shorter lived, methane ($CH_4$) has a much greater GWP than $CO_2$ due to its greater ability to absorb energy (IPCC, 2006). $CO_2$ is used as the reference, which is given a GWP of 1 for a specified timescale, to which the equivalent GWP of other GHG emissions are calculated. GHGs, specifically, have received the most attention in environmental impact studies and this is often referred to as the “carbon footprint” of a production system (Wiedmann and Minx, 2008). This terminology has become popular due to the attention climate change has been afforded on the global environmental agenda, however being the exclusive indicator of the environmental impact of meat can generate conflicts with the other impact categories considered in this thesis (Röös et al., 2013).

The non-renewable energy use (NREU) environmental impact category was also considered in Chapter 3. NREU is an important consideration because the burning of fossil-fuels releases GHGs into the environment that were extracted from the atmosphere billions of years ago; this leads to climate change (Pittock, 2017). The combustion of fossil fuel also releases other pollutants, such as $SO_2$. Characterisation factors for NREU, in terms of the total primary energy extracted (MJ), were calculated based on the upper heating value (Jolliet et al., 2003).

The agricultural land use (ALU) associated with rearing livestock, as previously discussed, is an important consideration with regards to sustainability because the arable land requirement of each crop is a determining factor for how much food can be produced. In this thesis two indicators were considered: 1) the total occupation of an area of land during a certain timescale associated with the functional unit and 2) the total area of land which was transformed (e.g. from forest into arable land) for the functional unit. The characterisation of this impact factor followed the ReCiPe methodology (Huijbregts et al., 2017). The GHG released due to land transformation was also calculated (BSI, 2012).

Following the recommendations made by LEAP (FAO, 2016a), each of the environmental impact categories discussed above were included where ELCA was applied in the first instance (Chapter 3): i.e. GWP, FWEP, MEP, TAP, NREU and ALU. However, in Chapters 4 and 5 FWEP, MEP, TAP and NREU were not included. This was because these ELCA studies predicted future impacts using scenarios; it is difficult to foresee the condition of future soils and water bodies, future manure management strategies and the future reliance on non-renewable energy sources, hence any assumptions regarding these system aspects were avoided. Instead, the feed-related environmental indicators of broiler production that were quantified in Chapters 4 and 5 were limited to GWP, ALU, N excretion and P excretion. For instance, the future excretion of N and P may be used to quantify the potential EP of future broiler chicken production but, for the purpose of the research presenting in this thesis, such inferences were not necessary.

### *1.3.3 Social life cycle assessment*

Consumers are becoming more likely to demand transparency in the products they buy or the services they use, such as the associated environmental implications or social injustices in the supply chain; in economic theory this implies providing key information to help stakeholders make decisions, which in turn creates incentives for businesses to align their practices with what is socially acceptable (Goleman, 2010, Benoît-Norris et al., 2012). The aspects of social acceptability that are most often discussed within the literature are: 1) poverty and inequality, i.e. addressing basic human needs, the creation of social capital, justice etc.; 2) the interactions between changing behaviour and the environment; and 3) the preservation of socio-cultural patterns (Vallance et al., 2011). With the exception of the impact category of human health, which considers the harmful chemicals released during the product's production, use and disposal phases, social wellbeing is not assessed in ELCA (Benoît-Norris et al., 2012). However, the social dimension of a system may be assessed holistically via Social LCA (SLCA), which incorporates critical indicators of wellbeing that are influenced by processes or companies in the supply chain, such as: worker's rights, community development, consumer protections, and societal benefits. With the complexity of globalized production and consumption, a great deal of transparency can be lost, resulting in unintended and/or overlooked social and environmental impacts. Comprehensive and systematic assessment methodologies, such as is provided by the LCA framework, provides a solution to this challenge.

SLCA, however, is still in its infancy and therefore it is experiencing similar difficulties to ELCA in the beginning (Traverso, 2018). For instance, there is not a standard method for carrying out a SLCA as there is for ELCA. Where SLCA was applied in this thesis, e.g. in Chapter 3, the study was conducted using the same four stages as in ELCA: identification of goal and scope, inventory analysis, impact assessment and interpretation (International Organisation for Standardisation, 2006). The studies adhered to the guidelines most practitioners follow (Wu et al., 2014), which were put forward by UNEP-SETAC (2009), by applying the interpretation of the methodology outlined by Benoît-Norris et al. (2011, 2015) in the Social Hotspots Database (SHDB). The SHDB, built by New Earth in conjunction with a global input/output economic model derived from the Global Trade Analysis Project, is an overarching framework designed to ease the data collection burden in SLCA studies (Benoît-Norris et al., 2012, 2014, Pelletier et al., 2018). Background data used in this study was compiled in an inventory following the SHDB framework.

Since their domestication, farm animals have been an integral part of human society. Not only are the livestock industries of economic interest, employing a considerable number of people; they are also seen as an important part of human culture and tradition (Lund et al., 2006). As for the farm animals themselves, their quality of life depends on human care. This has become a matter of increasing concern in society and is the focus of Chapter 6, where a case has been made for the inclusion of animals within a SLCA framework.

### *1.3.4 Methodological challenges of life cycle assessment*

Agricultural systems are complex and this can present issues when modelling their impacts within a LCA framework. Input data to LCA models is often highly variable (Groen et al., 2014). This is especially true of agricultural systems and is a cause of uncertainty. It is important to identify this uncertainty in order to produce credible results. Comparison of alternative systems, for example, can only be done so reliably if the uncertainty ranges of the results are calculated (Leinonen et al., 2013, Mackenzie et al., 2015). One way to address the issue of uncertainty is by implementing Monte Carlo simulations (Leinonen et al., 2012); this methodology has been described and applied to the LCA studies referred to later in this thesis (Chapters 3 and 5).

Many processes modelled in LCA have multiple outputs of function and value. Whilst allocating the environmental impact values of each output via system expansion is always preferable, it is often not possible to physically separate these outputs from the activities that yield them (FAO, 2014a, 2016a). When this is the case, practitioners must objectively assign the resource use, energy consumption and emissions of the process to each output based on the most appropriate allocation rule. Process outputs which are not the main product of a process are frequently characterised by having a lower economic value, although they are not necessarily the smallest output by mass. These outputs are referred to as co-products; hence this concept is referred to as co-product allocation. The methodological challenge of separating impacts between process outputs has been the focus of much debate in recent years (Ekvall and Finnveden, 2001, Guinée et al., 2011, Hanes et al., 2015, Mackenzie et al., 2016b). As such, whether allocation should be based on the shared physical properties of the co-products (i.e. biophysical allocation), or on their economic value continues to be a contentious issue amongst LCA practitioners.

The variation in the methodologies adopted for co-product allocation in LCAs of livestock systems has resulted in high levels of variation in the results presented in the literature (Mackenzie et al., 2016b). In many cases the choice between allocation methodology is arbitrary and, whilst this topic is of huge importance, it falls outside the scope of this thesis. Nevertheless, it is necessary to be transparent in which approach was applied in this research. Both biophysical allocation and economic allocation have pros and contras. Economic allocation has been by far the most common allocation methodology adopted in agricultural studies (Ardente and Cellura, 2012, Brankatschk and Finkbeiner, 2014, van der Werf and Nguyen, 2015, Mackenzie, 2016). Its critics argue that economic allocation is highly sensitive to price fluctuation and changes in the market; this, for example, often makes the methodology not relevant when comparing similar agricultural produce from different countries (Svanes et al., 2011, Gac et al., 2012). Biophysical allocation can avoid these issues by assigning impact values according to the causal relationships in the physical properties of the system, such as by mass or (more often) gross energy flow (Thoma et al., 2013, van der Werf and Nguyen, 2015, Wiedemann et al., 2015, Chen et al., 2017). Such causality, however, is often not clear (Finnveden et al., 2009, Mackenzie et al., 2016b). Furthermore, the economic value of system outputs can never be outright rejected, since it is necessary in determining whether an output is a co-product or a waste. Economic allocation, on the other hand, has been recommended by LEAP (FAO, 2016a) as the most appropriate methodology when looking at the feed supply chain of livestock. Since much of the allocation takes place in the feed supply chain in the research presented in this thesis, and to ensure methodological consistency across the models, economic allocation was applied here throughout.

SLCA also presents practitioners with unique challenges that are worth outlining from the outset. Whilst it is almost universally accepted that there is a causal link between system processes and environmental impact, in SLCA it is not so clear-cut. This is because most social impacts reflect the influence of a company's behaviour with respect to stakeholders as oppose to being proportional to physical energy or material flows (Jørgensen et al., 2008). The aforementioned lack of consensus on the SLCA framework has led to a multitude of different approaches with regards to each step of the LCA process (Figure 1.2). Linking the social impacts to the functional unit has been achieved by combining different quantitative and semi-quantitative social indicators which can be tenuous and subjective; this is often dependent on the researchers' own judgement or the expertise of others, especially when characterising animal welfare indicators (e.g. Scherer et al., 2017). The subjective nature of the characterisation procedure can be avoided by calculating social impacts based on quartiles, or other obvious transitions, within a dataset for a given social indicator. The SHDB methodology, which was applied in this thesis, used quartiles to define the level of risk of each social indicator compared to the performance of the sector (within a given country or region) for that indicator (Benoît-Norris et al., 2012). Each level of risk was given a weighting factor. The values of the weighting factors were arbitrary but can be used to identify social risk hotspots within a supply chain. Finally, there is no agreement on how animals may fit into SLCAs. Since the focus of this thesis was on broiler chicken production, animal welfare should be considered as important to the sustainability of the industry (Broom, 2010, Neugebauer et al., 2014). These issues have been discussed further in Chapter 6.

## 1.4 Thesis aims

The overarching aim of this thesis was to assess the environmental impact of genetic change in broiler chickens and how this may be mitigated via diet formulation. The thesis also aimed to consider (where possible) the social and economic dimensions of sustainability within the assessment of chicken production systems and develop a methodology for incorporating animal welfare within sustainability assessments. The specific objectives of the thesis were as follows:

- To assess the consequences of recent artificial selection on the energy use efficiency traits (i.e. traits which affect the energy retained in the body divided by the total energy intake: e.g. digestion efficiency, metabolic heat production rate and body composition) of broiler chickens (Chapter 2).
- To assess the sustainability of current broiler production (in both UK and USA chicken meat production systems), and to quantify the potential environmental

impact mitigation that can be achieved via diet formulation using conventional ingredients, using a novel methodology developed to formulate diets for minimal impact in specific environmental categories within defined economic constraints whilst not penalising bird growth (Chapter 3).

- To predict potential future genotypes of broilers based on current evidence and to assess the environmental implications of future production systems (Chapter 4).
- To assess the potential for mitigating the environmental impacts of future chicken meat production and Europe's reliance on imported protein via the incorporation of novel ingredients in broiler diets (Chapter 5).
- To develop a novel methodology for incorporating animal welfare as a social impact category in a SLCA framework and use it to assess the performance of European chicken meat production (Chapter 6).

# Chapter 2. Artificial selection of broiler chickens for efficiency

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## 2.1 Abstract

This review assesses the consequences of artificial selection on the following traits: digestive efficiency, body composition and utilization of metabolizable energy for growth and metabolic activity. The main findings were: 1) the digestive system has been subjected to much physical change due to selection in recent decades, but this has not led to any apparent change in digestion efficiency. 2) Both the energy intake per day and the rate of metabolic heat production (MHR) have increased in recent decades whilst 3) the efficiency of utilizing energy for growth has also increased; this is due to an increased growth rate, so that broilers reach slaughter weight more quickly and therefore need to allocate less energy overall to metabolic processes, with the exception of growth. 4) There may have been a reduction in the tendency to waste feed through spillage and carry out energetically expensive behaviours. There is a discrepancy in the literature with regards to the influence of selection on body composition and its contribution to feed efficiency. In this review two scenarios were demonstrated, whereby body composition either has or has not altered via artificial selection. Understanding the effects of artificial selection on the traits that relate to the feed efficiency of the broilers will contribute towards the reduction of the environmental impacts that arise from such systems.

## 2.2 Introduction

Modern chicken breeds are the result of billions of years of evolution by means of natural selection, on which artificial selection for commercial objectives has been applied. By far the greatest progress made in chicken genetics since their domestication has been witnessed in the latter half of the 20th century, since the advent of industrial scale agriculture (Schmidt et al., 2009). This can be attributed to developments made in quantitative genetics and the success of its commercial application (Siegel and Dunnington, 1997).

Broiler breeding methods were summarised in Chapter 1. At the highest level, the pure-breeding lines are owned and controlled by the breeding companies. These lines are subjected to full scale selection programmes; it is from these lines that all of a company's broiler products have descended (Muir and Aggrey, 2003). The great-grandparent stocks, which are produced from the pure-bred lines, are subjected to mass selection for selected traits. Growth rate has consistently been the prime selection trait since the 1950s, with more recent emphasis placed on the yield of breast meat, liveability and feed use efficiency (Emmerson, 1997, Muir and Aggrey, 2003, Laughlin, 2007, Renema et al., 2007). Specific grandparent lines are cross-bred to produce the parent stock, which are then distributed to specialist traders and integrated producers. The final step of the intensive artificial selection is the cross-breeding of these hybrids (parent stock) to give rise to the production broilers, which are raised for slaughter by production companies. Much progress has been made in artificial selection technologies over the last century: i.e. mass selection, the use of pedigree charts and hybridization, the introduction of selection indices, artificial insemination and (more recently) the development of modern breeding value estimation techniques that apply genomics (Rishell, 1997, Muir and Aggrey, 2003). Consequently, Zuidhof et al. (2014) showed chicken broiler growth rate to have increased by over 400% between the years of 1950 and 2005 (Figure 2.1), when genetically representative birds of those years were grown in identical environments. The consequences of these developments on the broiler traits, in order to increase growth rate and feed use efficiency, formed the focus of this chapter.

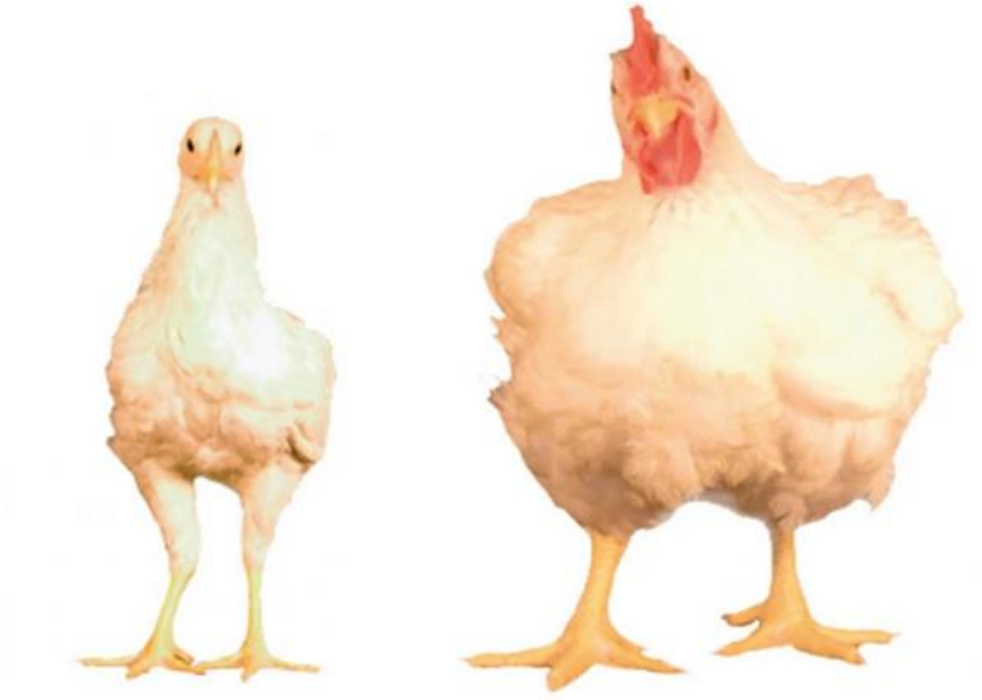

**Figure 2.1**: Photographs showing a commercial broiler genotype produced in the 1950s (left photograph) and a commercial broiler genotype produced in 2005 (right photograph). Both birds were the same age (56 days) and were fed on an identical modern diet; they weighed 905g and 4202g respectively (Zuidhof et al., 2014).

The change in the performance of broilers depicted by Figure 2.1 can all be attributed to the advancements made in their genetics (Havenstein et al., 2003a, Zuidhof et al., 2014) and this has environmental impact implications. For instance, feed provision represents the industry's greatest environmental hotspot (Pelletier, 2008, Leinonen et al., 2012, 2013, Prudêncio da Silva et al., 2014); as such, a bird that requires less feed to achieve the same slaughter weight will embody a lower environmental burden. This is a combined result of the reduction of environmental impacts related to 1) production of feed (e.g. greenhouse gas emissions from fossil fuels used in crop production and emissions related to land use change) and 2) reduced nutrient emissions form poultry manure, the amount of which is also reduced in more feed-efficient birds. Therefore, an investigation into the literature regarding the traits that can affect the feed use efficiency of the birds was justified.

The birds obtain the energy for growth and metabolic functions from their feed in the form of carbohydrates, proteins and fat. Since these components form a majority of the composition of the feed, they therefore strongly determine the total amount of feed consumed. With this in mind, placing selective pressure on increased feed use efficiency is indistinguishable from placing selective pressure on increased energy use efficiency, calculated by dividing the energy retained by the bird (mainly in the form of protein and lipid) by the total energy required to reach a defined LW. The growth rate, in turn, affects the energy use efficiency because a broiler chicken that reaches slaughter weight quicker needs to allocate less energy overall to the metabolic processes, with the exception of growth, during this shorter growth cycle (Emmans, 1994, 1997). Energy use efficiency and the growth rate are complex, highly aggregate “composite traits” which by definition are the result of many underlying biological traits (Pym, 1990). Thus, identifying these underlying biological traits forms the necessary starting point in quantifying the future environmental impact of the poultry sector. They include: behaviour, appetite, digestive efficiency, protein and lipid accretion and metabolic activity. The latter includes all life-sustaining biochemical transformations within the cells, such as those related to physical activity, protein turnover and the maintenance of energetically expensive systems, e.g. the digestive system (Emmerson, 1997). The objective of this review was to critically assess the direction and magnitude of the genetic change, which may or may not have taken place in each of these biological traits in recent decades, in order to understand the genetic potential for future improvements in broiler performance and environmental impact.

The first part of the review takes the form of a qualitative investigation into the literature in order to critically assess the potential consequences artificial selection has had on each biological trait and establish how much each of these traits has contributed, if at all, to the changes in energy use efficiency of modern broilers. Narrative summaries have been used to compare studies where experimental data exist but do not provide homogenous quantitative evidence. Studies that give evidence of potential genetic change were especially useful, such as by placing selective pressures on the individual traits of interest, and where data could be extracted from comparative studies of different broiler breeds. The second part of the review was quantitative, aiming to determine the metabolizable energy (ME) intake of different breeds of broiler and estimate how this energy was distributed between growth and metabolic heat production. This analysis, in part, focused on the grey literature, such as performance objective tables and nutritional specifications, produced by the breeding companies (Aviagen, 2007a, 2007b, 2014a, 2014b, 2014c, Cobb, 2014). These documents provided the information needed to derive typical energy intakes delivering a given performance. On top of genetics, feed formulation has played a crucial role in the improvement of the feed efficiency of production;

modern diets have a greater energy density than diets that were fed to broilers 30 years ago, plus they are balanced by an increased content of essential amino acids. It was important not to confound the effects of dietary differences with the potential effects of genetic change in the biological traits.

Much useful information exists in the literature that describes change in poultry genetics in relation to energy use efficiency, which is usually expressed as “feed conversion ratio” (FCR), i.e. the mass of the feed consumed divided by the body mass gain. Data in literature shows that feed efficiency has increased considerably since its adoption into breeding programmes in the 1970s (Emmerson, 1997, Faraday, 2007, Laughlin, 2007, Aggrey et al., 2010, de Beer et al., 2011). However, when used to evaluate the changes in the energy use efficiency of the birds, such data have no value unless the dietary energy content is known. For this reason, experiments which have compared different breeds on the same diet are of particular interest, from which biological traits such as digestive efficiency and body composition can be compared (Sherwood, 1977, Havenstein et al., 2003b, Mussini, 2012, Zuidhof et al., 2014). Until now the consequences of genetic selection on the biological traits aforementioned and ultimately the energy use efficiency of the birds have not been analytically reviewed in such a way as to show how artificial selection has led to an improvement in broiler performance. Therefore, the way in which the information is presented in this chapter is novel and of high interest to those concerned with poultry genetics.

## 2.3 Traits affected by artificial selection

### *2.3.1 Feed intake, digestion and absorption*

Intensive selection pressures placed on broiler performance traits, such as increased body weight and growth rate, have resulted in broilers with an increased appetite and therefore also increased voluntary feed intake per day (Siegel and Wisman, 1966, Pym and Nicholls, 1979, O’Sullivan et al., 1992b, Havenstein et al., 1994a, 2003a, Schmidt et al., 2009, Howie, 2010, 2011). As well as genetic selection, exogenous factors which influence many physiological and behavioural processes can be carefully controlled to increase feed intake and pre-ingestion efficiency. Light, for instance, is a critical environmental factor for manipulating the feed intake. By artificially increasing the length of time the bird is subjected to light, its feed intake can be increased; a technique employed in modern poultry systems to favour high growth rates (Olanrewaju et al., 2006, Karakaya et al., 2009). It is possible that improved housing conditions (ambient temperature and humidity, air flow etc.) have reduced the energy requirement of functions other than growth, from thermoregulation to immune responses. This modifies the energy requirements, but also the amino acid requirements of the birds, and could potentially affect feed intake, growth and body composition. However, within experiments discussed in this review, broiler breeds were compared in the same environmental conditions and on the same diet, therefore the differences in performance could only be attributed to genetics.

Years of advancement in feed distribution technologies and animal husbandry practices have undoubtedly reduced feed spillage to improve the feed use efficiency of the system (Svihus et al., 2004, Howie et al., 2011). Nevertheless, there is anecdotal evidence also to show the involvement of genetics in decreasing feed spillage. For instance, although it was not the aim of the experiment to examine differences in feed spillage between breeds, relatively high feed wastage was observed by Zuidhof et al. (2014) in less selected broiler breeds compared with modern breeds (i.e. birds which have a genotype similar to what could be expected to be grown commercially nowadays). Changing the consistency of the feed can make it less prone to being spilled by old-type breeds (i.e. broilers which are genetically representative of commercial broilers grown in the 1950s), whereas modern breeds show no observable difference in spillage between feeds with different consistencies (Zuidhof et al., 2014). The predisposition of an old-type breed to spill more feed than a modern breed was also observed by Havenstein et al. (1994a) and addressed in the design of later experiments (Havenstein et al., 2003a, 2003b). It can be speculated that breeding birds with increased feed use efficiency has applied selective pressures against temperaments which incur the worst feed handling behaviours; thus, feed spillage could contribute to the differences in the pre-ingestion efficiency between different breeds.

The gastrointestinal tract’s function is to supply the rest of the bird’s body, including the digestive organs themselves, with the energy and nutrients needed to survive, grow and reproduce (Jacob, 2015). Therefore, if limiting, growth and function of the organs that make up the digestive system could be enhanced by selection, better diet and improved husbandry practices in order to change the birds’ digestive efficiency and thus the efficiency with which feed is utilised (Nitsan et al., 1991). Since the nutrients that are not retained by the birds’ body are responsible for the eutrophication and acidifying emissions produced by the poultry system (Pelletier, 2008, Leinonen et al., 2012), improved digestive efficiency can influence the provision and the excretion of important nutrients, thus affecting the environmental impacts at both ends of the poultry production chain.

Differences in the digestive ability between laying hens and broilers are often reported, which indicates that, because both breeds were bred from a common ancestor, digestive efficiency has been altered via artificial selection (Spratt and Leeson, 1987, Jackson and Diamond, 1996). When young birds representing an egg-laying breed were compared with broilers at a common growth stage, Pishnamazi et al. (2005) showed that the former consistently metabolize a greater amount of energy from their feed. The reason for this may be that, in modern broiler breeds, digestive efficiency may have reduced from levels displayed by the egg-laying breed due to the intensified burden (i.e. increased digesta throughput) placed on the digestive system as a result of an increased growth rate and feed intake. However, when placed under selective pressures aiming to improve specific traits, digestive efficiency can actually be improved in broilers. For instance, birds selected for improved feed conversion have been shown to have higher digestive efficiency when compared with birds selected for high growth rate, when fed on the same feed (Ten Doeschate et al., 1993, Carré et al., 2008), whereas no evidence was found within the scope of this review for differences in digestive energy efficiency between divergent lines selected specifically to be lean and fat (Leclercq and Saadoun, 1982, Leenstra and Pit, 1987, Jorgensen et al., 1990). Furthermore, it is possible to select directly for high protein, lipid and starch digestive efficiency (Mignon-Grasteau et al., 2004, Lopez and Leeson, 2008). However, the results of experimental comparisons in digestive efficiency between birds are quite variable and are affected by their size and feeding regime (Zhang and Aggrey, 2003, García et al., 2007); for instance, some authors reported large genetic x feed interactions on the digestive efficiency trait (e.g. Mignon-Grasteau et al., 2010), making it unclear as to whether any improvement has been made to this trait in modern commercially grown broilers when compared with old-type breeds.

Selection for higher growth rate has led to a lower degree of maturity at slaughter and this affects the size of different organs at any given age with some organs, such as those that make up the digestive tract, being genetically predisposed to maturing sooner than others (Katanbaf et al., 1988, Mitchell and Smith, 1991, Nitsan et al., 1991, Nir et al., 1993). Despite the digestive system maturing more quickly in modern breeds when compared with old-type birds, the digestive system has reduced in size relative to body weight at a comparable age. This is reflected in the higher carcass yield (i.e. the proportion of the edible carcass of the total slaughter weight) of modern birds compared with old-type breeds (Havenstein et al., 1994b, 2003a). This might be expected, as maintaining the digestive system requires a high level of metabolic energy (see section 2.3.3). Reducing the size of this system relative to body weight therefore could increase the birds' overall energy use efficiency (Mitchell and Smith, 1991).

It has been suggested by Ravindran et al. (1999) that the inherently different nutrient utilisation seen between breeds could be due to differences in the structure of the gastrointestinal tract which relate to changes in digestive enzyme output, absorptive capacity and digesta transit time. Poultry rely on enzymatic digestion, more so than other livestock, as their colons are relatively short and largely lack the bacteria that aid other species in digestion. Nir et al. (1993) claimed digestive enzyme production to be the limiting factor in improving broiler digestion, particularly in young birds. Differences in enzyme production between high and low body weight lines have been reported in chickens at the same chronological age (Nir et al., 1987, O'Sullivan et al., 1992a). Elsewhere it has been found that birds selected for high body weight showed higher intestinal and pancreatic trypsin and amylase levels expressed relative to the intestinal contents (Nitsan et al., 1991, Dunnington and Siegel, 1995). Tolkamp et al. (2010) recently provided further evidence in support of the view that enzymatic production can also be altered via selection for growth rate and feed efficiency (Pym, 1985, Ten Doeschate et al., 1993), but not by selection for leanness (Leclercq and Saadoun, 1982). Investigations by Péron et al. (2007) showed evidence for variation in proventriculus pepsin activity between lines subjected to different selection pressures, which leads to differences in protein digestive efficiency.

A difference in the intestinal absorptive area and capacity between broiler lines subjected to different selection pressures was reported by Bedford (1996). High growth rate lines have a smaller intestine, which has a much greater proportion of muscle by mass than intestinal mucosa, than slow-growing lines relative to body weight when compared at the same age. Despite the actual number of villi decreasing concomitantly with the reduction in the length of the digestive tract, the surface area has increased due to greater intestinal villi size (Katanbaf et al., 1988, Mitchell and Smith, 1991, Mussini, 2012). Elsewhere it has been shown that more intestinal membrane transport proteins per unit area can be detected in high body weight genotype embryos when compared with a low body weight genotype, but no evidence has been presented to suggest this has translated into increased absorption post hatch (Mott et al., 2008).

One organ found in the digestive system that seems particularly susceptible to genetic change is the gizzard, which is responsible for grinding up feed. There is a selective tendency for the gizzard to increase in absolute size when the birds are selected for high digestive efficiency (Maisonnier et al., 2001). This adaptation becomes more pronounced if selection takes place on a diet where the physio-chemical properties of the grains make the feed tougher to mechanically breakdown (Péron et al., 2007). Furthermore, the gizzard can be stimulated into growing larger in low digestive efficiency lines when fed on coarse grains, thus improving bird digestive efficiency. This trigger has a much less pronounced reaction in the gizzard of broilers from lines selected for high digestive efficiency (Rougière et al., 2009). This suggests that the birds which have been specifically selected for high digestive efficiency are genetically predisposed to growing a large gizzard. The gizzard size may also play a vital role in improving digestive efficiencies by increasing the mean digesta retention time, described by some as the greatest influencing factor in the improvement of digestive efficiency (Pym, 1985, Maisonnier et al., 2001, Pishnamazi et al., 2005, González-Alvarado et al., 2008, Rougière and Carré, 2010). Therefore, should digestive efficiency have increased, the gizzard might be expected to be larger in modern broilers relative to body mass. However, neither the size of the gizzard relative to the body mass, nor the digestive efficiency of broilers, have been shown to have increased due to commercial breeding programmes (Mussini, 2012). It would seem that increasing the digestive efficiency of the bird is linked to size increases in the gizzard when digestive efficiency is selected for specifically; such an investment of energy, in contrast, is not placed in the growth of the gizzard when selection pressures are instead placed on energy use efficiency more generally.

The digestive efficiency of a modern commercial production breed was shown to be lower than that of a high digestive efficiency line (Carré et al., 2002, Péron et al., 2007, 2008), indicating that selection strategies have not led to the maximum potential digestive efficiency broilers are capable of. In both the experiments carried out by Carré et al. (2002) and Péron et al. (2007) broilers were placed on modern wheat-based diets. When placed on similarly soft wheat grain-based diets (Sideral and Sciphon wheat respectively), the commercial breed showed moderate digestive efficiencies of protein, starch and lipid when compared with the lines specifically selected for high and low digestion efficiencies. When placed on equally hard wheat grain-based diets (Bastille and Baltimor respectively), starch digestibility was high and lipid and protein digestibility were, again, moderate in a commercial breed when compared with high and low digestive efficiency lines. A comparative experiment to determine the digestibility of the same diet between a modern commercial production breed and the high digestibility line would be useful to determine the digestibility potential of broilers. However, these results tentatively suggest that it is unlikely that better overall energy use efficiency would be related to the highest potential digestive efficiency, especially in birds selected on feed with high digestibility. In a study by Mussini (2012) it was found that energy digestibility values show very little difference between modern broilers (78.86%) and birds produced commercially in the 1950s (79.05%) when placed on a modern corn-based diet. These examples suggest that breeding programmes, which aim to improve on overall efficiency, may not have led to significant changes in the overall digestive efficiency of broilers. Thus, most of the genetic gain in energy use efficiency might instead have come from improved metabolic efficiency in modern breeds selected on high quality feed.

Differences in resource allocation to digestive organs, observed between the broilers bred for high body weight (Katanbaf et al., 1988, Mitchell and Smith, 1991) and for high digestive efficiency specifically (Péron et al., 2006), suggests selecting for digestive efficiency may actually compromise other traits which are incorporated into modern breeding programmes and vice versa (Pym et al., 2004). Contrasting correlations in relative organ sizes have been discovered between lines selected for commercial objectives and high digestive efficiency (Carré et al., 2005, Péron et al., 2006, de Verdal et al., 2010, Rougière and Carré, 2010). For instance, Mussini (2012) showed that the gizzard is significantly smaller, and the pancreas similar, in modern commercial breeds when compared with old-type breeds fed on the same diet. On the other hand, Péron et al. (2006) found that the gizzard was much larger (correlation = +0.27, +0.82 and -0.05 with protein, starch and lipid digestibility respectively) and the pancreas much smaller (correlation = -0.22, -0.20 and -0.29 with protein, starch and lipid digestibility respectively) in the birds selected specifically for high digestive efficiency when compared with birds from a control line on the same diet. These observations in organ sizes between the lines indicate that selecting for the maximum energy digestive efficiency generally may not be compatible with selection for high performance traits.

On the other hand, experiments carried out by Zhang et al. (2005) showed that selecting for certain digestive efficiencies need not always adversely affect performance traits (e.g. when selecting for phytate P digestive efficiency). This suggests that it could be at least possible to target specific digestive traits in modern breeding programmes. To evaluate conclusively if selection for high energy digestive efficiency generally is compatible with high performance for effective incorporation into future breeding programmes, the following must be tested: 1) can performances of high digestive efficiency birds be altered compared with that of a control line consisting of a modern commercial breed? And 2) would a combined selection objective, which includes digestive efficiency instead of feed efficiency, generate similar responses to selection as observed in modern breeds? These experiments would fill a gap in the literature; the latter would define whether or not genetic correlations between the traits are as favourable with digestive efficiency as with feed efficiency.

Overall, the results found in literature indicate that increasing digestive efficiency is possible, however there is no clear evidence that breeding for commercial objectives has led to any change in this trait. The morphometries of the internal structures, in particular the organs that comprise the digestive system, are significantly different between high digestive efficiency lines and birds bred for high commercial performance (Carré et al., 2005, Péron et al., 2006, Rougière and Carré, 2010). Selecting for high digestive efficiency may conflict with performance traits and this probably goes part way to explaining why the genetic change witnessed in broilers does not appear to have delivered their full digestive efficiency potential, at least not to the extent it could have had digestive efficiency been the only trait of interest in breeding programmes. Artificial selection of broilers for high performance traits but not specifically for digestive efficiency, whilst fed on feed with high digestibility, has not placed high pressure on increasing digestive efficiency to the highest possible level. Further, selection for high carcass yield prevents the allocation of more resources into the digestive system as it has relatively low economic value. Instead it has been inadvertently reorganised in such a way as to improve its efficiency per unit of mass, and maintain digestive efficiency, whilst digesta daily throughput has augmented due to increased feed intake.

### *2.3.2 Growth and body composition*

As aforementioned, faster growth rate of modern broilers compared with older breeds has strongly contributed to the energy use efficiency of the birds, as they now reach their slaughter weight in a shorter time and therefore need relatively less energy for metabolic heat production, such as for protein turnover, physical activity etc. Furthermore, potential changes in body composition may have also affected the energy dynamics of the birds. The relationship between the amount of protein and lipid in the body can be influenced by diet composition, degree of maturity, sex and genotype (Leclercq, 1988). As broiler growth rate has improved, birds reach slaughter weight at decreasing degrees of maturity (Emmans and Kyriazakis, 2000). This in turn could lead to reduced carcass fatness, as relative lipid content of the gain increases with the degree of maturity of the animal (Leenstra, 1986, Katanbaf et al., 1988). Protein and lipid accretion differ in both energy values and the transfer efficiency of energy from feed to tissue. Fat contains much more combustible energy than does protein (Pym and Solvyns, 1979), therefore any change in the proportion of the retention of these two components will influence the ME content of the body and the efficiency of the weight gain.

A modern breed has been shown to be significantly heavier at every age with a significantly increased proportion of breast meat upon reaching slaughter than an old-type breed (Mussini, 2012); Schmidt et al. (2009) showed that the growth rate of breast meat has increased twice as fast as the overall body growth rate. Further, in an old-type breed, the breast muscle plateaued at 9% of the body mass at day 14. In contrast, by day 14, breast muscle constituted 14% of the body mass of the modern breed; this ratio continued to increase to 18% by day 35. Apparently, a major difference occurred at day 14, after which the old-type birds maintained a constant allocation of resources to breast muscle production, whereas the modern birds continued to incorporate additional resources into this tissue. Similarly, Fleming et al. (2007) reported that the proportion of breast meat by weight at slaughter has increased by 54% since the 1970s. The relative weight of wing and heart muscle has been shown to have reduced significantly in modern breeds, when compared with breeds grown commercially 50 years ago (Katanbaf et al., 1988, O’Sullivan et al., 1992a, Havenstein et al., 2003a). When compared on the same diet for example, wings were shown to have reduced by 2.2% and 2.0% relative to bodyweight at the ages of 43 and 57 days respectively due to genetics between the 1950s and 2001 (Havenstein et al., 2003a). Meanwhile the same experiment showed that, in the old-type breed, the heart grew to 0.57% and 0.50% of the body weight at 43 and 57 days of age respectively; at the same ages a 2001 breed was shown to have a heart that constituted only 0.50% and 0.44% of its total body weight respectively (Havenstein et al., 2003a). A lower relative heart weight through the starter period could be in part due to diversion in protein allocation from the heart to the breast tissues (Schmidt et al., 2009). In contrast, heart weight relative to body weight was shown to be similar in old-type and modern breeds in younger broilers by Mussini (2012), but by the age of 28 days the less selected old-type birds showed significantly larger hearts relative to their overall body mass. Similar disparity exists in scientific reports in the observed change in the relative mass and maturation rates of the liver due to selection (Nir et al., 1978, Katanbaf et al., 1988, O'Sullivan et al., 1992a, Schmidt et al., 2009, Mussini, 2012). Contrasting findings in organ growth may be due to differences in the response to selection for high body weight only and the multi-trait breeding programmes (i.e. selection for high efficiency and breast yield, as well as health and robustness) that have led to modern commercial breeds (Neeteson-van Nieuwenhoven et al., 2013).

Wang et al. (2004) suggested that the modern broiler is actually phenotypically fatter than broilers grown commercially in the 1970s due to their very inactive lifestyles and energy rich diets. This idea has been perpetuated since (e.g. Roeder, 2012) despite there being more evidence to suggest the birds have become leaner over this time (Pym and Solvyns, 1979, Remignon and Le Bihan-Duval, 2003). This is expected because high carcass fat is considered unfavourable by the customer and has been selected against in breeding programmes in order to improve the quality of the product (Muir and Aggrey, 2003, Laughlin, 2007). There has been more convincing evidence presented in literature to show that, although body fat increased up until the late 1970s in response to selection for greater LW at a specific age and rapid growth, modern breeds now have significantly reduced fat deposition due to commercial selection pressures (Leclercq, 1988, Zuidhof et al., 2014). Fleming et al. (2007) showed body fat content to have reduced from 26.9% in the 1970s to 15.3% in commercial breeds used in the last decade, when birds were compared after being reared on a modern diet. In that study, it was obvious that this fat reduction was due to an increased amount of energy being allocated to the growth of breast meat as discussed above.

In a 2x2 factorial design experiment it was found that, when fed on both a modern diet and a 1950s style diet, a modern broiler breed achieved a different body composition than an old-type breed, when raised to the same slaughter weight (Havenstein et al., 1994b, 2003a). When placed on the 1950s diet, modern broilers were much smaller but slightly leaner than those placed on the modern diet, nevertheless fatter than the old-type birds. When placed on the more balanced modern diet, which had a higher energy and protein content (Havenstein et al., 1994a, 2003a), the old-type birds became fatter at every age than they did when fed on the 1950s diet. It is likely that the less balanced 1950s diet did not contain enough nutrients required by the modern breed each day to reach its full genetic potential and so this led to a reduced growth rate. Furthermore, the modern breed had a higher body fat percentage when compared with the old-type breed when both breeds were fed on the old diet, probably because energy was overconsumed in order to increase intake of important nutrients (Leeson et al., 1996a, Wiseman and Lewis, 1998, Swennen et al., 2004, Leeson and Summers, 2005, Gous, 2007).

Conversely, in other studies the percentage body fat was similar between the modern and old-type broilers, at least until slaughter weight, when placed on a modern high protein diet (Mussini, 2012, Fancher, 2014). Contrary to the findings reported above, these data suggest that there has been little or no overall change in the body composition in commercial breeds due to artifical selection (Aletor et al., 2000). Elsewhere, there has been no difference in body composition found between breeds, when compared at an equivalent body protein weight, even where there has been heavy selection for the yield of specific parts and huge differences in growth rate and mature mass are displayed (Danisman and Gous, 2011, Danisman and Gous, 2013). As was already highlighted, modern diets are of higher quality than diets used in the past because they contain more energy, more protein and are more balanced. If the reduction in carcass fatness in commercial breeds is the result of considerable improvements made in the nutrition as opposed to genetics this could, in part, explain the possible peak in carcass fat in the 1970s. This is because 1970s diets contained relatively more energy to protein in an attempt to maximise growth and storing energy as fat is energetically more efficient.

Broilers can be specifically selected for fatness or leanness based on cholesterol levels in the blood plasma (Whitehead and Griffin, 1984), resulting in “genetically lean” and “genetically fat” divergent lines. These lean and fat lines were able to achieve the same body composition when the latter was fed on a higher protein diet (Whitehead and Parks, 1988, Whitehead, 1990). When fed in such a way that they reach the same body composition, Whitehead (1990) showed the “genetically lean” birds to have a better energy use efficiency and to retain a higher proportion of the protein that was taken in than the “genetically fat” line. This may be simply explained by the lower growth rate (and therefore longer time and higher metabolic heat production required to reach a certain body weight) achieved by the “genetically fat” birds when grown to a body composition comparable to the “genetically lean” birds. When fed on old diet formulations, growth rate was reduced, and the energy use efficiency suffered, in “genetically lean” lines as it does in modern commercial breeds. Therefore, the conclusion drawn by Whitehead (1990) is consistent with the trend presented by both Mussini (2012) and Havenstein et al. (2003a). Since selecting for leanness leads to birds which display greater performance traits (e.g. higher growth rate), selecting for greater performance traits will result in leaner broilers.

Modern commercial broiler body composition is the product of decades of bird and diet coevolution, as breeders and nutritionists have attempted to produce the most efficient birds with the most desirable characteristics, with concomitant advancements made in nutrition. From the data of the experiments discussed here, it would seem that this has led to commercially reared birds that are leaner now than they were half a century ago. However, body composition displays strong genotypic and environmental interactions; the absolute influence on body composition in commercial breeds that can be attributed to each of these factors remains uncertain due to conflicting literature. An interesting example of such interaction is the potential for genetic adaptation to high and low protein diets which has been demonstrated in poultry (Sorensen, 1985, Marks, 1993). When selection takes place on high protein diets, this results in birds that require such environments for maximum growth, whereas populations selected on low protein diets do not require high protein diets for full expression of their genetic potential for growth. Therefore, the body composition of modern broiler breeds can be seen as a culmination of 1) adaptation to a better diet via artificial selection for improved feed use efficiency and this has resulted in a bird which is genetically lean (Whitehead, 1990, Havenstein et al., 2003a, Mussini, 2012); and 2) genetic change in the body composition irrespective of the dietary changes due to selection pressures placed on reduced fatness (Fleming et al., 2007, Zuidhof et al., 2014).

### *2.3.3 Metabolic activity*

The ingested ME that is not stored in the body is released as heat to the environment, and by definition, a more energy efficient breed would release relatively less metabolic heat than an inefficient one. The effect of the reduced time to reach the slaughter weight on the energy use efficiency of the birds has already been discussed  in this chapter, but there has also been discussion on whether the basal metabolic rate (i.e. the metabolic heat produced per day) has changed as a result of genetic selection. There have been attempts to quantify the differences in the MHR between different broiler breeds (e.g. Pym et al., 1984) and it has been suggested that it is lower in breeds selected for high feed efficiency or high weight gain than birds selected for high feed intake. Pym and Farrell (1977) showed the fasting metabolic heat production, indicative of the basal metabolic rate (Noblet et al., 2013), to be 19% higher in lines selected for high feed consumption when compared with a control line by using respiration chambers to carry out feeding experiments; this led to an estimated 10% decrease in the feed use efficiency (Carré et al., 2008). This effect supports the view that the basal metabolic rate can be altered when subjected to selection in order to improve the energy use efficiency of broilers, as has been seen in laying hens (Luiting and Urff, 1991, Flock, 1998). Further evidence presented in literature that indicates that artificial selection can act on the variation in the traits on which the birds’ basal metabolic rate is dependant is discussed in this section.

There is a wide variety of theories in the literature concerning the physiological level (ranging from the cellular level to the locomotive activity of the bird) at which the changes in the bird metabolic rate have potentially occurred. As an extreme example, it has been proposed that genetic predisposition to possessing mitochondria that are more vulnerable to oxidative stress has the potential to lower efficiency due to magnified electron transport chain leak and production of reactive oxygen species (Bottje et al., 2002, 2006, Bottje and Carstens, 2009). However, it may seem unlikely, as an overarching factor on which energy use efficiency is dependant, that this would have remained suboptimal after natural selection. Elsewhere, protein turnover has been credited to account for anywhere up to 30% of broiler heat production, prompting some research into the genetic potential of reducing it (Millward et al., 1976, Pym et al., 1984, Muramatsu et al., 1987). There has been some indication that higher protein accretion rates are achievable through selection by lowering protein degradation rates (Tomas et al., 1988, 1991). However, despite there being some evidence for decreased protein breakdown being genetically predetermined, altered by asserting selection pressure on different traits such as growth rate and feed intake, net protein turnover (i.e. overall protein retention determined by the protein synthesising and degrading processes) does not appear to have been changed as a result of selection for commercial objectives (Pym and Farrell, 1977, Whitehead and Griffin, 1984, Jorgensen et al., 1990, Pym et al., 2004).

It is unclear how much the artificial selection has been able to change the efficiency of the basic metabolic processes at a cellular or molecular level. However, it is more obvious that selecting for energy use efficiency could lead to changes in the proportions of highly energy demanding tissues, such as in muscle and those found in the digestive system. This in turn can influence the basal metabolic rate. For instance, as mentioned previously (section 2.3.1), birds with the highest growth rate can be associated with a reduction in the relative amount of mucosa in the small intestine (Mitchell and Smith, 1991). It can be postulated that the reduction of this tissue, where cell turnover is high, could lead to a decrease in the energy requirement of the system. Elsewhere, Luiting et al. (1991) suggested the difference between efficient and inefficient laying birds in the unaccounted energy expenditure to be in small part attributed to plumage quality; evidence to suggest that the birds' basal metabolic rate is greatly affected by interactions between feathering and ambient temperature has been presented by Freeman (1971) and later by Carré et al. (2008). Observable delays in feathering are displayed in birds selected for high feed intake; Deeb and Cahaner (2001) showed that high heat loss is induced by low feathering in a temperate environment, which may lead to low feed efficiency. Conversely, in warmer climates delayed feathering can lead to a decrease in the heat-induced reduction in growth rate. The environments achieved by closed buildings with controlled systems, in which broilers are raised, are designed to alleviate the constraints that the natural environment might apply to the birds' traits, such as on metabolic processes. Adaptations, such as those described above, could result from selection pressures to increase energy use efficiency by means of reducing the overall metabolic energy requirement in such an environment.

As much as 54% of the difference between efficient and inefficient laying hens in the unaccounted energy expenditure has been attributed to differences in heat production related to physical activity (Luiting and Urff, 1991). Differences in the locomotive activity of young chicks is significantly influenced by genetics and has been shown to be reduced by 6% in fast-growing breeds when compared with slow-growing breeds (Bizeray et al., 2000, Bokkers and Koene, 2003). Fast-growing broilers also showed a lower physical activity level than slow-growing broilers when performing other behaviours such as preening, stretching and ground pecking (Lewis et al., 1997, Siegel et al., 1997, Bokkers and Koene, 2003). These behaviours were mostly performed on the spot in a sitting posture in the fast-growing breeds resulting in less energy expenditure. Artificial selection for higher growth rate and a more efficient rate of feed conversion has therefore probably favoured birds with reduced subsidiary energy expenditure and subsequently, and perhaps unintentionally, resulted in birds which show reduced physical activity (Weeks et al., 2000). It could also be proposed that reduced physical activity could have led to the reduced observed tendency to spill feed in modern commercial breeds, as was discussed in section 2.3.1. It makes sense to select for low physical activity, at least from an energy consumption perspective, if not for the associated animal welfare concerns (Thorp, 1994, Craig and Muir, 1998). It should be also noted that contrasting results were found in a study by Skinner-Noble et al. (2003), where it was shown that birds selected for better feed conversion efficiency actually showed a small but significant increase in time spent standing and a decrease in resting behaviour. In general, it can be suggested that at least in theory, broilers can be subjected to selection in order to bring down their basal metabolic rate, and by extension reduce their metabolic energy expenditure, by selecting for birds which express, above all else, low activity-related heat production (Tolkamp et al., 2010).

## 2.4 Quantitative assessment of genetic change in broiler energy use efficiency

In order to understand the effect artificial selection has had on the energetic efficiency of broilers, it is necessary to calculate and compare the energy intake of breeds that are representative of those used in industry in the past and present. This can be achieved by calculating the total ME that each breed requires to reach a defined LW, thus determining how efficiently energy is used. This energy requirement of the bird can also be defined as the difference between the combustible energy content of their feed intake and the combustion energy content of their excreta, and $CH_4$ from enteric fermentation (the latter being minimal in the case of non-ruminant species). This energy must then be distributed between growth (i.e. the combustion energy content of the protein and lipid retained in the bird’s body) and metabolic heat production (Figure 2.2). The energy retained in the body as protein and lipid can be quantified based on their heats of combustion, i.e. 23.8 and 39.6 MJ $kg^{-1}$ respectively (Boekholt et al., 1994, Emmans, 1994). These combustion heat values vary slightly throughout literature, probably due to differences in the proportions of the components on which the average properties are determined; however, it cannot be expected that the chemical structure of proteins and lipids (and therefore their combustion heat values) could be altered via conventional artificial selection (i.e. index selection, whereby several traits are selected simultaneously, using non-molecular techniques, and weighted depending on their importance) and so these values were kept constant in these calculations. The overall protein and lipid that is stored in the body, and their respective energy values, can be used to calculate the overall retained energy; the difference between this stored energy and the ME intake is that which is lost as heat. If the metabolic requirements of the birds are lowered, then less feed will need to be consumed in such a condition where energy storage as protein and lipids remains constant.

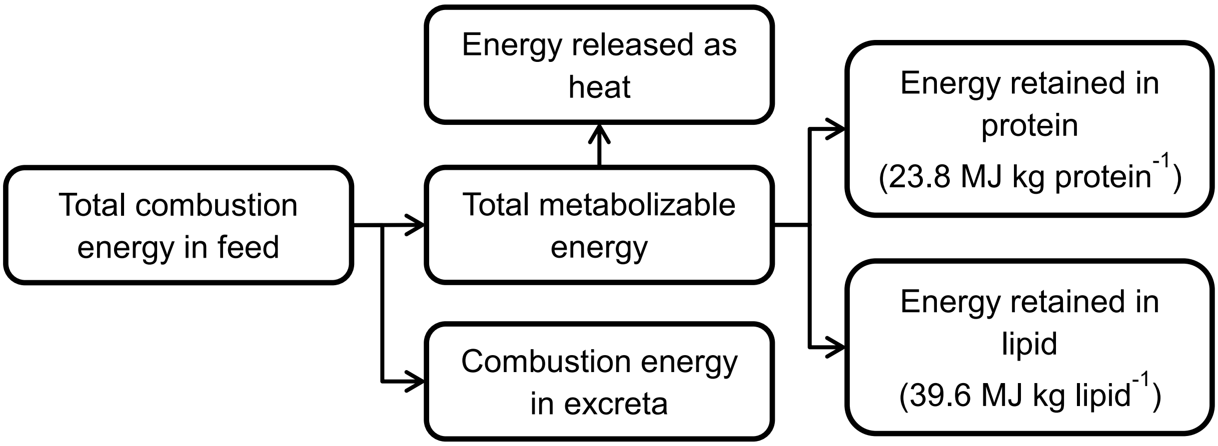

**Figure 2.2**: The main components of energy flow through a broiler chicken as applied in the quantitative data analysis of energy use efficiency. The energy contents of protein and lipid were kept constant in the analysis while other components (including the mass of protein and lipid within the bird) changed depending on the breed and the scenario.

The model, shown in Figure 2.2, was used to assess the genetic change in the broiler energy use efficiency and the partitioning of energy. The total ME intake of each bird to reach a defined weight can be calculated when the feed intake and the feed ME content are known. In this study, such information was obtained from the industry-provided performance manuals (Aviagen, 2007b, 2014c) or in the form of FCRs in literature (Havenstein et al., 2003b, Mussini, 2012, Zuidhof et al., 2014). The growth data were also derived from experimental data found in the literature. The weight at which the breeds were compared was 2 kg. Where the old-type breed did not reach 2 kg before the end of the trial period, the future weight gain was determined through extrapolation using a Gompertz function to relate weight to time (Emmans and Kyriazakis, 2000). All the feed intake data used in the calculations were based on the most modern diets applied in these publications. The composition of these diets varied slightly between sources but they all had a known ME content. From this it was therefore possible to calculate the total ME requirement of each breed to reach 2 kg by multiplying the ME content of the feed by their total intake.

It can be seen in Table 2.1 that, as the growth rate increased (following the trend of genetic changes over recent decades), so too the energy needed for both the growth and the metabolic heat production of the body per day increased (MJ day$^{-1}$). Thus, the metabolizable energy intake rate (MER) at any given age has been increased via selection. The growth rate has increased over time, but there are some exceptions to this in the limited data available (Table 2.1), notably Mussini (2012) has shown the growth rate to be much greater in the old-type breeds than has been reported by other researchers for later commercially grown breeds (Havenstein et al., 2003b, Zuidhof et al., 2014); this can be simply attributed to different growing conditions and feed compositions between experiments. The trend in the energy intake per day (MJ day$^{-1}$) is to be expected, since modern broilers have an increased feed intake per day resulting in an increased growth rate. However, while the energy intake each day increased, the necessary days for growth to slaughter weight decreased in modern breeds. This means that less energy overall was assigned to heat production. Therefore, a downward trend can be seen in the total ME intake (MJ) between old-type and modern breeds; this can be seen clearly between the results from the same studies.

**Table 2.1**: Growth rate, total metabolizable energy (ME) intake and average metabolizable energy intake rate (MER) for each genotype upon reaching 2 kg, as reported in literature.

| **Genotype** | **1950[1]** | **1959[2]** | **1978[3]** | **2001[2]** | **2005[3]** | **2007[4]** | **2012[1]** | **2014[4]** |
|---|---|---|---|---|---|---|---|---|
| Days required to reach 2 kg | 55 | 87 | 61 | 34 | 35 | 35 | 33 | 34 |
| Total ME intake (MJ) | 51.6 | 66.5 | 55.4 | 38.4 | 40.5 | 40.5 | 42.2 | 39.9 |
| Average MER (MJ $day^{-1}$) | 0.94 | 0.76 | 0.91 | 1.13 | 1.16 | 1.16 | 1.28 | 1.17 |

[1]Mussini (2012), [2]Havenstein et al. (2003a), [3]Zuidhof et al. (2014) and [4]Aviagen (2007b and 2014c)

To determine the distribution in the energy that is stored or released as heat, it was necessary to first understand the body composition at slaughter. Data on body composition of broilers was only sporadically available and was even scarcer when comparing old and modern breeds on the same kind of feed. Only two such sources were identified: Mussini (2012) fed broilers of an old-type breed and a modern breed on the same high quality modern feed and found no overall significant difference in the body composition between the two. The body composition of the birds presented by Mussini (2012) were similar to the body composition of four modern commercial breeds fed on a high quality feed by Danisman and Gous (2013). On the other hand, Fleming et al. (2007) have suggested that the body composition in lipid and protein has changed over the last 65 years due to artificial selection, where there has been an increase in protein accretion by slaughter and a much reduced lipid accretion in modern breeds when compared with an old-type breed on a modern diet. It has been suggested that carcass fat content peaked in the 1970s, due to selection for high body weight at an age, and birds are presently at their leanest (Leclercq, 1988, Havenstein et al., 2003a).

Given this conflicting evidence it was decided that two contrasting scenarios would be tested to appreciate how bioenergetics may have changed over recent decades due to genetic selection. Scenario 1 was based on evidence presented by Mussini (2012) and assumed no change in body composition due to genetic selection. Scenario 2 was based on the findings of (Fleming et al., 2007) and assumed body composition has changed considerably. These two scenarios were used to estimate the energy use efficiency (Figure 2.3) and the MHR (MJ $kg^{-1}$ $day^{-1}$) (Figure 2.4) of the breeds of broiler reported in Table 2.1. For each breed the model presented in Figure 2.2 was used to calculate the energy retention for the extremes of body composition reported in the literature. In order to estimate the body compositions, the ratios of ash to protein and water to protein were assumed to be constant (0.2 and 3.4 kg $kg^{-1}$ respectively) (Gous et al., 1999). The leanest body composition the birds could achieve in the scenarios had 20.2% protein and 7.9% lipid (Mussini, 2012) and the fattest had 16.1% protein and 26.9% lipid (Fleming et al., 2007). Based on these calculations, it was not theoretically possible for the modern breeds (2001-2014) to have the fattest body composition because more energy would have to be stored in the body than would be taken in by the birds, thus the fat extreme body composition was not shown for these modern breeds.

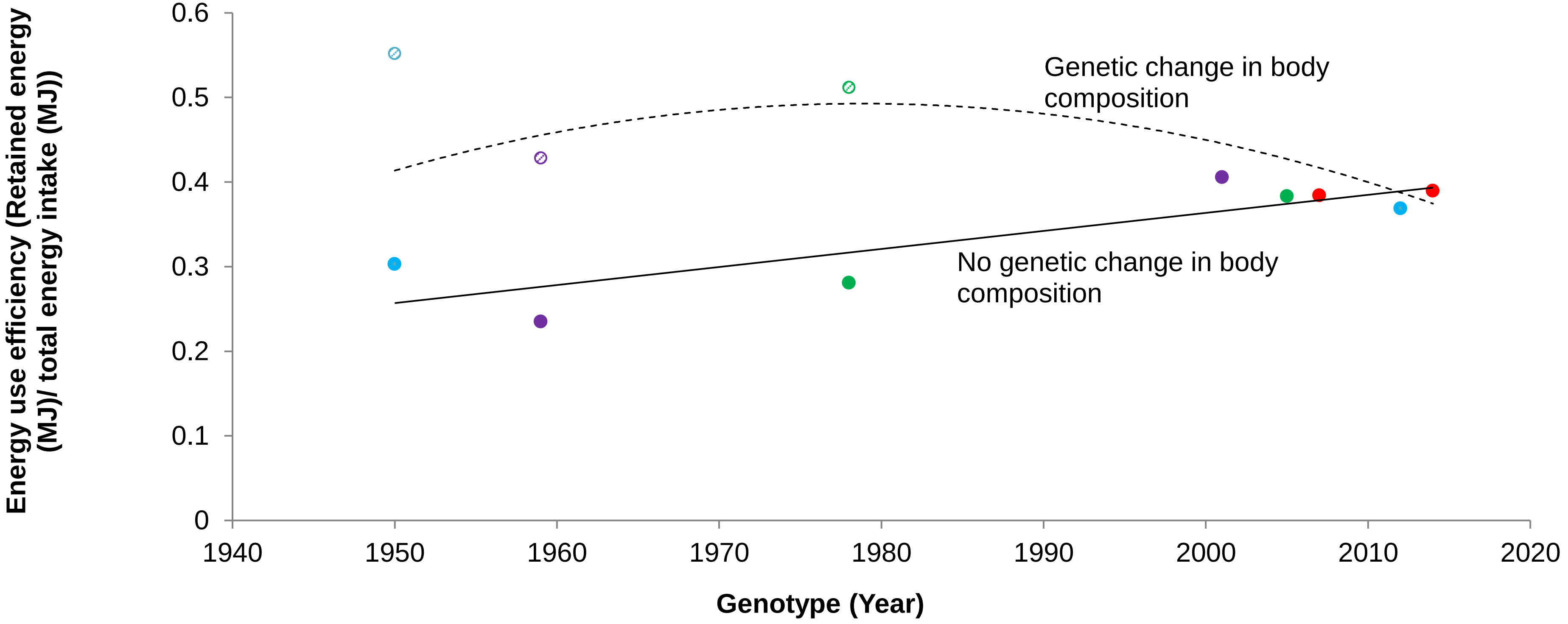

**Figure 2.3**: The genetic trend in energy use efficiency of different broiler genotypes grown commercially from 1950 to 2014 (data in Table 2.1). The energy use efficiency of each genotype is based on performance data for a broiler grown to 2 kg on a modern diet, provided by: Mussini (2012) - ●; Havenstein et al. (2003a) - ●; Zuidhof et al. (2014) - ● and Aviagen (2007b and 2014c) - ●. The hatched symbols represent the energy use efficiency for each genotype assuming the leanest potential body composition (based on Mussini, 2012) and the solid circles represent the energy use efficiency for each genotype assuming the fattest potential body composition (based on Fleming et al., 2007). The lines represent the overall trends of these two potential scenarios: the solid line shows Scenario 1 (no genetic change in body composition) and the broken line represents Scenario 2 (genetic change in body composition).

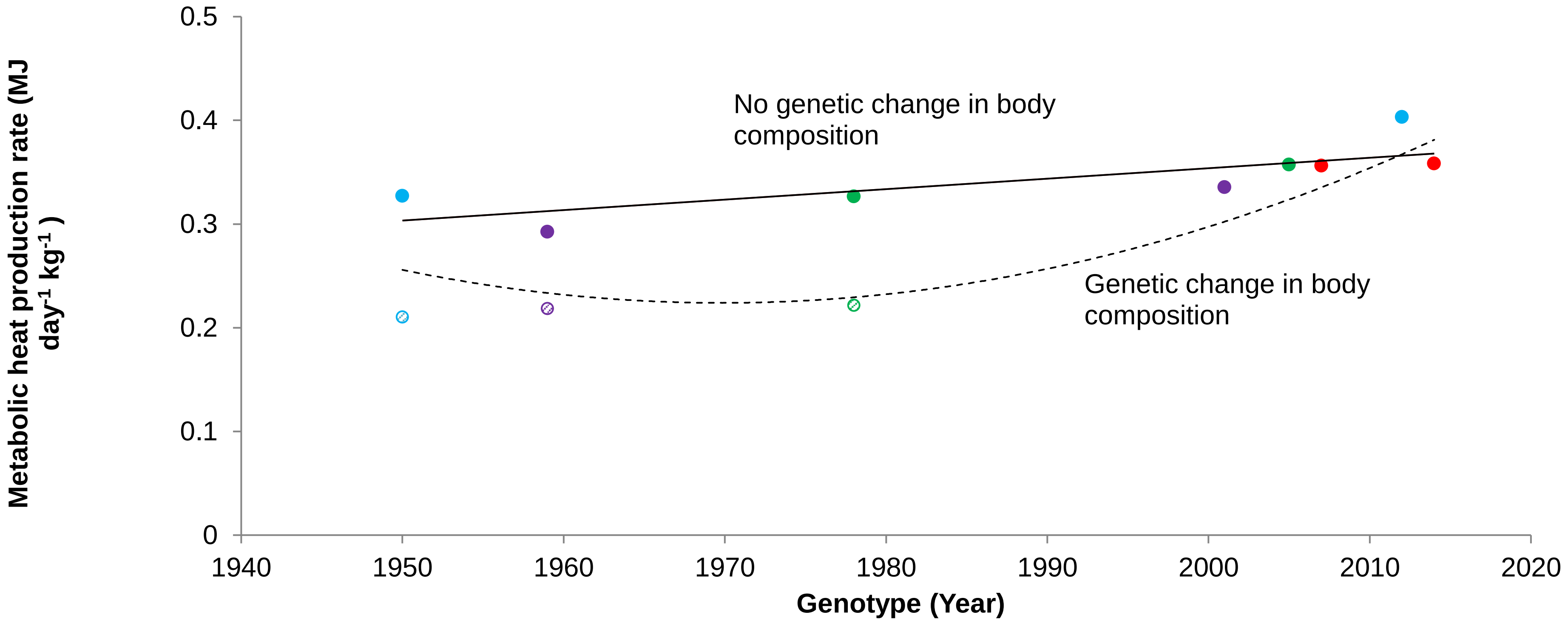

**Figure 2.4**: The genetic trend in the metabolic heat production rate of different broiler genotypes grown commercially from 1950 to 2014 (data in Table 2.1). For each genotype this is based on performance data for a broiler grown to 2 kg on a modern diet, provided by: Mussini (2012) - ●; Havenstein et al. (2003a) - ●; Zuidhof et al. (2014) - ● and Aviagen (2007b and 2014c) - ●. The hatched symbols represent the metabolic heat production rate for each genotype assuming the leanest potential body composition (based on Mussini, 2012) and the solid circles represent the metabolic heat production rate for each genotype assuming the fattest potential body composition (based on Fleming et al., 2007). The lines represent the overall trends of these two potential scenarios: the solid line shows Scenario 1 (no genetic change in body composition) and the broken line represents Scenario 2 (genetic change in body composition).

Scenario 1, where body composition was assumed to have remained unaffected by artificial selection, showed a gradual increase in energy use efficiency (Figure 2.3) and in heat production rate (Figure 2.4), following the genetic changes towards modern breeds. Since the final weight of the bird remained the same for each breed (2 kg), energy use efficiency relative to body composition has increased in modern breeds when compared with old-type breeds due to a decreased total heat production as a result of a shorter production cycle. Scenario 2, where body composition was assumed to have changed, suggests energy use efficiency peaked in the 1978 breed. The reason for this is that considerably more energy is stored in fat birds and the scenario assumed birds were fattest in the 1970s and leanest in the modern day commercial breed. In both scenarios, the heat production rate has increased, but a much more dramatic increase since the 1970s until now was suggested by scenario 2. Again, this is explained by the fact that considerably more energy can be retained in the body as lipid than as protein. Therefore, in the scenario where proportionally more protein was stored in the body in modern breeds (scenario 2), a greater fraction of the energy would be lost as heat when the energy intake remains the same. Even where no body composition change was assumed, it can be concluded that genetic selection has resulted in an increased MHR (MJ $kg^{-1}$ $day^{-1}$) in recent decades due to the considerable increase in growth rate and the higher energy consumption of metabolic processes related to growth e.g. proteinogenesis.

It is clear that the total heat produced by broilers to reach a standard slaughter weight has decreased over the decades. However, it is not clear whether all of this can be ascribed to the short duration of the growth cycle only. Despite artificial selection causing a rise in the heat production rate (MJ $kg^{-1}$ $day^{-1}$), due to an increased rate of metabolic processes associated with growth, basal metabolic rate related to processes other than growth could still have fallen. Nevertheless, it is impossible to separate the energy needed for metabolic processes specifically associated with the growth of protein and lipid and the energy needed for other metabolic functions. Other evidence presented here, however, supports the conjecture that the energy released from metabolic processes excluding growth may have fallen. For instance, it was discussed in section 2.3.3 that the lowering of energetically expensive behaviours, in particular, has been shown to have occurred in fast-growing birds when compared with slow-growing birds (Bizeray et al., 2000, Bokkers and Koene, 2003). A tentative conclusion of this is that, although the overall metabolic rate has increased, the basal metabolic rate may have been reduced to some extent via artificial selection, thus mitigating the increase in the heat production rate (MJ $kg^{-1}$ $day^{-1}$) due to the increase in growth rate.

## 2.5 Conclusion and Implications

It has been over a quarter of a century since genetic variation in the complexities of feed utilization efficiency and growth rate were outlined by Pym (1990), yet until now the magnitude of the genetic change in these biological traits has not been critically reviewed. Although the contribution of the various biological traits to the improvements made is not well understood, the review presented in this chapter provides a more detailed understanding of the interactions between their genetic change and the trends seen in both the energy use efficiency and the heat production rate. This in turn forms the necessary starting point for predicting the future environmental impact of the industry, thereby avoiding unnecessary environmental harm. The results presented in this review demonstrate the fact that the energy use efficiency of broilers has been increased through artificial selection during the last decades, assuming that the scenario according to which there have been no major changes in the body composition of the birds is valid. The results also show that the overall heat production rate of the birds has increased via genetic selection over the decades, a fact that has previously not been demonstrated as far as the scope of this review could reveal.

There is little doubt that broilers now have a leaner body composition by the time they reach slaughter weight than they did in recent decades (Whitehead, 1990, Havenstein et al., 2003a, Fleming et al., 2007). However, it is unclear how much of an influence genetics has had on this. In reality, it is probable that there has been both a genotypic and nutritional influence on body composition, as birds have been selected for high efficiency and low fatness on ever improving diets. Thus, the genetic progression may actually sit somewhere between the trends proposed by Scenario 1 and 2 in Figures 2.3 and 2.4. In the absence of evidence for genetic improvement made in the broilers’ digestive efficiency, the potentially improved energy use efficiency is likely to be mainly the result of a lower total heat production. This, in turn, is the result of increased growth rate, but there may have also been some reduction in the energy consumption of the basal metabolism, which has freed up energy for deposition into growing tissues. Additionally, there is some indication that feed spillage has been reduced in modern breeds when compared with old-type breeds, which may explain part of the apparent increase in energy use efficiency (Zuidhof et al., 2014).

The increased importance placed on global sustainability fits well with the genetic progress made within the poultry industry, which currently has relatively low environmental impacts when compared with other livestock sectors (Williams et al., 2006, Faraday, 2007, Laughlin, 2007). However, in order to make further progress it is important to understand how the improvements in energy use efficiency and growth rate have been achieved up until this point. Rising costs of feed, growing global demand for animal protein and greater awareness of the environmental impacts associated with its production will continue to intensify the focus on developing selection strategies that act upon the variation observed in these poultry traits in order to further increase the efficiency of production.

# Chapter 3. Environmental impact trade-offs in diet formulation for broiler production systems in the UK and USA

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## 3.1 Abstract

The environmental impacts associated with broiler production arise mainly from the production and consumption of feed. The aim was to develop a tool for formulating broiler diets designed to target and reduce individually specific environmental impact categories in two contrasting regions, the UK and USA. Using linear programming, least cost broiler diets were formulated for each region, using the most common genotype specific to each region. The environmental impact of the systems was defined using 6 categories calculated through a LCA method: global warming potential (GWP), fresh water eutrophication potential (FWEP), marine eutrophication potential (MEP), terrestrial acidification potential (TAP), non-renewable energy use (NREU) and agricultural land use (ALU). Diets were then formulated for each region to minimise each impact category, without compromising bird performance. The diets formulated for environmental impact objectives increased their cost in most cases by between 20 and 30% (the cost increase limit), with the exception of the Least GWP (+16%) and the Least NREU (+4%) diets in the UK, and the Least TAP diet in the USA (+14%). The degree of flexibility to reduce simultaneously several environmental impact categories in the UK and the USA differed due to the different feed ingredients available to each region. The results suggested there was potential to minimise several impact categories simultaneously by reducing the impact of one impact category compared with least cost, through diet formulation in the UK; this was shown to a greater and lesser extent in the Least FWEP and the Least NREU diet formulations respectively. In the US, there was no way to minimise one impact category through diet formulation without increasing other impact categories caused by the system. Finally, the wider social implications of adopting different diets in the two regions was assessed. Employing a multi-criteria approach to diet formulation methodologies, where environmental impact as well as economic implications are considered, will form an important pillar in broader efforts to improve the sustainability of animal production.

## 3.2 Introduction

Global poultry meat production grew by 104% between 1990 and 2012 (FAO, 2016c) and is predicted to soon become the world's most consumed form of animal protein (OECD/FAO, 2014). The poultry industry currently has relatively low environmental impacts per kg of meat when compared with other livestock sectors (Williams et al., 2006). This can be attributed, in part, to improvements made in the production systems but is mainly due to artificial selection for improved energy use efficiency (Faraday, 2007, Laughlin, 2007, Zuidhof et al., 2014, Tallentire et al., 2016). Despite its production being amongst the least environmentally impacting livestock commodities produced in the EU and North America, the widespread consumption of poultry products means that further improvements are important and should still be made (Leinonen et al., 2013, MacLeod et al., 2013, Nastasijevic et al., 2015).

As the environmental impacts associated with broiler chicken production arise mainly from the provision and consumption of feed, it is logical to focus on diet formulation and feed ingredient choice in order to mitigate these impacts (Nahm, 2007, Pelletier, 2008, Boggia et al., 2010, Leinonen et al., 2012). For broiler systems, focusing only on GWP would not be sufficient. Due to their reliance on high protein diets, broiler chicken production is associated with a high EP, acidification potential (AP) and ALU (Sutton et al., 2008, Boggia et al., 2010). The majority of the AP and EP caused by broiler production is due to emissions during manure storage and application, as a direct result of the birds' N and P excretion.

The objective of this study was to develop a methodology which enabled broiler diets to be formulated explicitly for different environmental impact objectives and apply it to poultry production systems in two different world regions. A novel methodology was developed to formulate diets for reduced impact in specific environmental categories, while not penalising bird growth, by applying an ELCA approach integrated into a mechanistic diet formulation tool. Environmental impacts caused by both feed production and nutrient excretion associated with each diet had to be accounted for. Thus, the consequences of formulating diets for least impact in one environmental category on the other environmental impact categories and cost were investigated. Additionally, the social implications of these diets were quantified using the SHDB framework outlined by Benoît-Norris et al. (2012). Broilers are fed diets based on very different dietary ingredients in the EU and North America, either because of legislation, trade agreements or climatic conditions, so the opportunities for reduction in specific environmental impact categories may be expected to differ between the two regions (Kebreab et al., 2016). The UK, which represents 12% of broiler meat production in the EU (European Commission, 2014, The Poultry Site, 2014b), was used to represent production in Europe. The top three broiler meat producing regions in North America are the states of Georgia, Arkansas and Alabama (National Chicken Council, 2012); therefore, the south-eastern states of the USA were used to represent the North American broiler systems.

## 3.3 Methods

### *3.3.1 Goal, scope and model structure*

An ELCA methodology was integrated with a diet formulation tool with the goal of investigating the potential for reducing the environmental impacts associated with the production of broiler chicken meat via changes in their diet in the UK and USA. The system considered was conventional indoor broiler production (Figure 3.1), which is the predominant broiler production system in both regions (National Chicken Council, 2012, The British Poultry Council, 2016), from cradle to farm gate. The functional unit was the growth of one metric tonne of broiler chicken LW.

The average broiler was raised to a slaughter weight of 2.2 kg in the UK poultry systems (Defra, 2014b) and 2.8 kg in the USA poultry systems (National Chicken Council, 2016). This took 36 and 44 days respectively based on average as-hatched performance objectives for the corresponding breeds raised in each region (Aviagen, 2014c, 2014e). The broiler strains considered here were the 2014 Ross 308 and Ross 708. The fast-growing Ross 308 strain is used widely in Europe, and therefore was considered appropriate for the purposes of this study to represent UK systems (Borck Høg et al., 2011). The USA market is dominated by high meat yielding strains, such as the Ross 708, driven by the demand for high breast meat yield (Dozier and Gehring, 2014). Each breed had its own unique nutritional requirements; hence three and four growth phases of broiler production were modelled for the UK and the USA systems respectively. The diets were specifically formulated to meet the growth requirements of the birds during each phase in accordance with nutritional requirements (Appendix A, Tables A1 and A2), outlined in the nutrition specification manuals (Aviagen, 2014b, 2014d). The phases were as follows: the starter phase (hatching - day 10); the grower phase (day 11 - 24); the finisher phase (day 25 - 39 or slaughter, i.e. in the UK); and the withdrawal phase, from day 39 until slaughter (USA only). Upstream inputs, such as those associated with feed production, transportation and resource use in the growing facilities were all included within the boundaries of this analysis. The waste produced during production was also included within the boundaries of the LCA; however actual burdens of slaughter and process losses that can occur between the farm gate and the end of the processing line were excluded. Finally, an SLCA was executed to assess the social implications of each diet formulated in this chapter.

The main compartment of material flow in the life cycle inventory consisted of the production of feed ingredients. The ingredients that were available to be incorporated into the poultry diets in each region, along with the recommended maximum and minimum inclusion rates (Appendix B, Table B1), were based on input data from literature, national inventory reports, databases (e.g. Defra, 2015, FAO, 2015, USDA, 2015) and expert knowledge (Aviagen; personal communication). There are differences in the availability and yield of ingredients between the two regions. For instance, wheat yield in the UK is much greater than in the USA; on the other hand, maize yields are much better in the USA than in the UK (Appendix C, Table C1). Other ingredients could be incorporated into the USA diets but not into the UK diets due to EU legislation, such as meat and bone meal (Brookes, 2001). Some high protein crop ingredients were available to be incorporated into the UK diets to stand in for animal co-products, such as field peas and to a lesser extent, sunflower meal. An inventory of feed ingredients specific to each region was then compiled in Simapro and this software was used to conduct the LCA calculations. Resource inputs to fertiliser production and the emissions that arise as a result of their application to fields, as well as the energy inputs to processing and transport of ingredients, all contribute to the impacts associated with feed production and all were accounted for within the boundaries of the model. The impact values of the production of ingredients for the UK and USA systems can be found in Tables 3.1 and 3.2 respectively (section 3.3.4).

It was expected that the broiler housing conditions were maintained in such a way as to provide the birds with the optimum growing conditions for their genotype in each region. The energy and resource inputs into the hatchery and broiler growing facility were included within the scope of the model and were obtained from literature (Leinonen et al., 2012, Dunkley et al., 2015); however, the feed requirements of the breeding stock were not included within the boundaries of the LCA. The feed formulation was not sensitive to the inputs into the hatchery as it was unchanged between feed formulations. The requirement of bedding (wood shavings) per bird was typical of an average conventional UK system (Leinonen et al., 2012) and kept the same between regions and scenarios. The impacts associated with sourcing the bedding material were included; when combined with manure, this is collectively referred to as litter and is a source of emissions associated with poultry production both during and after housing. Average broiler mortality was 3.5% in the UK and 4.5% in the US, with a disproportionately high mortality rate in the starter phase (approx. 2%), and a relatively low mortality rate during the grower phase (approx. 0.7%) and finisher phase (approx. 0.8% and 1.2% in the UK and USA respectively); further, the USA poultry systems experienced an additional 0.6% mortality in the withdrawal phase (Xin et al., 1994, The Poultry Site, 2004, Leinonen et al., 2012). The USA poultry system experienced more mortality only due to a longer growth cycle. Mortality resulted in the consumption of feed with no contribution towards the functional unit, however any emissions associated with the disposal of dead birds was not attributed to the systems.

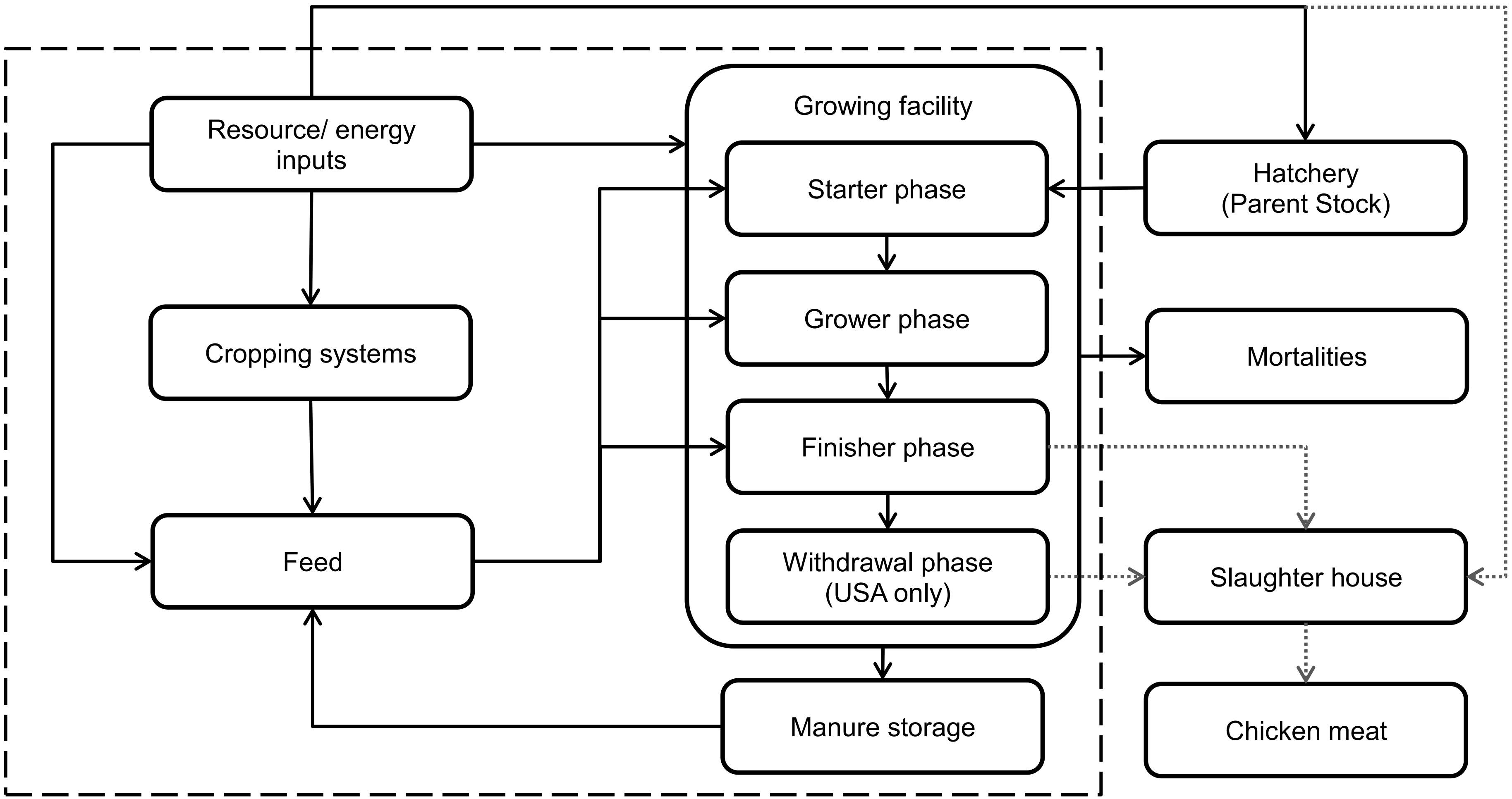

**Figure 3.1**: The structure and main components of the broiler production systems as considered by the Environmental Life Cycle Assessment (ELCA) model; the inputs that were considered (solid line arrows), the inputs that were not considered (dotted line arrows) and the system boundary (dashed line) of the model are shown for both the UK and USA poultry production systems.

### *3.3.2 Manure model*

The N, P and potassium (K) content of the poultry manure was calculated using the mass balance principle; the nutrients retained in the broiler's body (McGahan and Tucker, 2003) were subtracted from the total N, P and K supplied by the diet. A value for each impact category was calculated based on the excretion of one kg of each nutrient and this was utilised in the diet formulation tool. The manure model estimated the emissions of $NH_3$, nitrous oxide ($N_2O$) and $NO_x$, nitrate ($NO_3$) and phosphate ($PO_4$) that occurred during housing, storage, and application to field. The emissions were accounted for in accordance with the methodologies for calculating emissions from managed soils, livestock and manure management and storage, outlined by the IPCC (2006). The total $N_2O$ was assumed to equate to the same value as $NO_x$, as was assumed in the Velthof et al. (2012) model.

After removal from the growing facility, manure was stored in field heaps for 6 months prior to spreading on the land; in the UK and USA it is typical that manure is applied to a field once or twice per year so covered storage is recommended (Gates et al., 2008, Defra, 2011). Due to the limited emissions data available for the USA and to keep the methodologies consistent, the emissions arising from the USA litter at the housing and storage stages were assumed to be the same as those arising from the UK system as a percentage of the nutrients released in the manure (Cabrera and Chiang, 1994, Chadwick et al., 1999, Oenema et al., 2007). The housing and storage stages of the USA manure model were adapted to reflect regional litter management practices and emission factors as part of the sensitivity analysis (Moore et al., 2008) (Appendix C).

Broadcast field spreading, followed by incorporation through tillage (within 24 hours), was assumed for both regions due to manure management statistics and local codes of practice (USDA, 2009, Defra, 2014a). Only 1.6% of K was lost before it reached the field whilst the loss of P before it reached the field was negligible (Defra, 2011). Phosphate emissions at the field ranged between 2% and 15%, as was reported by Struijs et al. (2011). $N_2O$ and $NO_3$ emissions at the field were calculated based on IPCC (2006) emission factors which were adapted to the climatic conditions of each region. The nutrients incorporated into the soil replaced N, P and K, which would have otherwise been delivered in the form of synthetic fertilisers, by 70%, 80% and 100% respectively (Williams et al., 2006, Ritz and Merka, 2013): predominantly in the form of ammonium nitrate, potassium chloride, potassium sulphate and di-ammonium phosphate. Offsetting the need to apply as much synthetic fertiliser can be credited to the poultry production system, as is commonly done in livestock LCAs (Williams et al., 2006, Leinonen et al., 2012, Mackenzie et al., 2015).

### *3.3.3 Environmental impact assessment*

The metrics used to quantify the environmental impacts of the different diet formulations followed the recommendations made by LEAP (FAO, 2016a): GWP, EP, AP, ALU and NREU. GWP was quantified as $CO_2$ equivalent ($CO_2$ equiv) with a 100-year timescale. Under these conditions, 1 kg of $CH_4$ and $N_2O$ emitted were equivalent to 25 and 298 kg of $CO_2$ respectively (IPCC, 2006). The $CO_2$ equiv released due to land transformation was included within the GWP methodology following the PAS2050:2012-1 methodology detailed in BSI (2012). The EP impacts were separated into marine EP (MEP) for N-based emissions and fresh water EP (FWEP) for P emissions, using the ReCiPe midpoint method (Goedkoop et al., 2008), which were taken into account when the Agri-footprint database used in this model was developed. This methodology characterised the emissions of $SO_2$ equiv to air in terms of TAP. The non-renewable energy use was calculated in accordance with the IMPACT 2002+ methodology (Jolliet et al., 2003).

### *3.3.4 Diet formulation rules*

All diets were formulated for a fixed set of minimum nutritional requirements for the different phases modelled (Aviagen, 2014b, 2014d). Since these requirements were met in every diet formulated, it was assumed that growth rate per kg of feed was unaffected. Therefore 454.5 birds and 1595.3 kg of feed were required in the UK and 357.1 birds and 1742.3 kg of feed were required in the USA to achieve the functional unit (discounting birds and the feed they consumed, which die before reaching slaughter). Nutrient contents for all ingredients available to poultry diets in each region were taken from Premier Nutrition (2014) and placed into a diet formulation matrix. The most recent prices of region specific ingredient were obtained from grey literature; for the UK (Table 3.1), most prices were obtained from Defra (2016) and for the USA (Table 3.2) most prices were obtained from the USDA (2016). Information on the prices of oils and more specialist ingredients, which were not reported in national agricultural statistics documents, were obtained from ingredient specific sources (Van Gelder and Dros, 2003, FAO, 2004, MPOB, 2011, PGRO, 2015, Agriculture and Horticulture Development Board, 2016, IndexMundi, 2016, University of Missouri, 2016). The prices of synthetic acids were obtained directly from industry (Evonik; personal communication). Maximum and minimum inclusion limits were placed on the individual ingredients in the diets with the aid of input from industry (Aviagen; personal communication), so that issues of palatability, inhibition of digestibility or variability in specific ingredients did not adversely affect bird performance (Appendix B). For instance, peas contain trypsin inhibitors. Using the linear programming tool “Solver” (Mason, 2012), least cost broiler diets were formulated for each growth phase in each region that met the broiler energy and nutrient specifications. The minimum crude protein requirement of each breed, as was defined by industry for each phase, was at least met by each diet; it was allowed to fluctuate above this level which enabled for more or less synthetic amino acid inclusion. Ingredient background data was derived mainly from the Agri-footprint (2014) database within Simapro, which in turn is a derivative of the Feedprint project, in order to calculate the average GWP, FWEP, MEP, TAP, NREU and ALU per kg of each ingredient (Agri-footprint, 2016). These values were added to the list of ingredient properties in the matrix of the diet formulation tool (Tables 3.1 and 3.2). Fossil fuel inputs to fertiliser production, emissions resulting from the spreading of fertilisers, energy inputs to processing (drying, grinding etc.) and transport, all heavily contributed to the impacts associated with the feed production. Where system separation was not possible (i.e. where there was more than one product produced), co-product allocation within the feed supply chain was conducted using economic allocation, in accordance with the method recommended by FAO (2016a) and used by Mackenzie et al. (2016b).

**Table 3.1**: Environmental impact values and prices for 1 kg of each ingredient produced for use in UK broiler feed. The impact categories tested were global warming potential (GWP; kg $CO_2$ equiv), freshwater eutrophication potential (FWEP; kg P equiv), marine eutrophication potential (MEP; kg N equiv), terrestrial acidification potential (TAP; kg $SO_2$ equiv), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; $m^2$).

| **Ingredients** | **GWP** | **FWEP** | **MEP** | **TAP** | **NREU** | **ALU** | **Price (£/tonne)** |
|---|---|---|---|---|---|---|---|
| Wheat | 0.29 | 1E-04 | 0.009 | 0.0144 | 2.60 | 1.05 | 110 |
| Maize (Corn) | 0.45 | 2E-04 | 0.008 | 0.0152 | 5.78 | 1.13 | 145 |
| Maize gluten meal | 0.76 | 2E-04 | 0.008 | 0.0169 | 10.8 | 1.17 | 510 |
| Rapeseed (Whole) | 1.03 | 5E-04 | 0.028 | 0.0421 | 6.23 | 3.31 | 255 |
| Rapeseed meal | 0.45 | 2E-04 | 0.012 | 0.0173 | 2.90 | 1.35 | 165 |
| Barley | 0.30 | 2E-04 | 0.009 | 0.0148 | 2.77 | 1.36 | 100 |
| Sunflower meal | 0.92 | 7E-04 | 0.012 | 0.0212 | 6.50 | 4.30 | 155 |
| Soybeans | 3.88 | 5E-04 | 0.011 | 0.0255 | 5.93 | 3.94 | 380 |
| Soymeal | 3.05 | 4E-04 | 0.008 | 0.0199 | 4.62 | 3.11 | 280 |
| Field peas | 0.40 | 9E-04 | 0.009 | 0.0186 | 3.23 | 5.51 | 120 |
| Oats | 0.30 | 3E-04 | 0.010 | 0.0189 | 2.68 | 1.23 | 95 |
| Vegetable oil* | 5.31 | 0.002 | 0.042 | 0.0780 | 24.7 | 12.1 | 575 |
| Soy oil | 8.78 | 0.001 | 0.024 | 0.0571 | 14.6 | 8.85 | 600 |
| Limestone | 0.16 | 4E-05 | 3E-05 | 0.0008 | 58.0 | 0.01 | 50 |
| Mono Calcium Phosphate | 1.47 | 5E-06 | 1E-04 | 0.0230 | 21.5 | 0.00 | 470 |
| NaHCO3 | 0.23 | 1E-04 | 2E-04 | 0.0028 | 3.06 | 0.00 | 300 |
| Salt | 0.15 | 1E-06 | 2E-05 | 0.0011 | 1.92 | 0.00 | 120 |
| Lysine HCl | 3.67 | 0.002 | 0.185 | 0.3500 | 23.8 | 5.75 | 940 |
| DL-Methionine | 1.89 | 3E-04 | 0.001 | 0.0080 | 54.7 | 0.02 | 2800 |
| L-Threonine | 5.22 | 1E-03 | 0.005 | 0.0243 | 90.9 | 0.74 | 1240 |
| Valine | 7.35 | 0.005 | 0.370 | 0.7000 | 47.5 | 11.5 | 5200 |
| Fishmeal | 0.95 | 3E-04 | 9E-04 | 0.0016 | 20.0 | 0.00 | 1050 |
| Wheat middlings | 0.18 | 6E-05 | 0.005 | 0.0076 | 1.68 | 0.55 | 140 |
| Wheat bran | 0.18 | 6E-05 | 0.005 | 0.0076 | 1.68 | 0.55 | 130 |
| Brewers grains | 0.79 | 3E-04 | 0.013 | 0.0223 | 10.6 | 1.38 | 55 |
| Premix | 1.30 | 0.023 | 0.040 | 0.0750 | 28.0 | 0.00 | 2000 |
| Enzymes (NSP$^2$/2*Phytase) | 2.28 | 0.003 | 0.004 | 0.0070 | 30.0 | 0.00 | 7000 |

*50:50 ratio blend of Sunflower and Palm oil

**Table 3.2**: Environmental impact values and prices for 1 kg of each ingredient produced for USA broiler feed. The impact categories tested were global warming potential (GWP; kg $CO_2$ equiv), freshwater eutrophication potential (FWEP; kg P equiv), marine eutrophication potential (MEP; kg N equiv), terrestrial acidification potential (TAP; kg $SO_2$ equiv), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; $m^2$).

| **Ingredients** | **GWP** | **FWEP** | **MEP** | **TAP** | **NREU** | **ALU** | **Price ($/tonne)** |
|---|---|---|---|---|---|---|---|
| Wheat | 0.48 | 1E-04 | 0.009 | 0.0156 | 5.29 | 1.90 | 190 |
| Maize (Corn) | 0.36 | 2E-04 | 0.005 | 0.0114 | 4.91 | 1.09 | 130 |
| Maize Gluten meal | 0.72 | 2E-04 | 0.005 | 0.0152 | 10.3 | 1.14 | 465 |
| Rapeseed (Whole) | 1.21 | 0.002 | 0.040 | 0.0555 | 11.5 | 6.68 | 585 |
| Rapeseed meal | 0.53 | 8E-04 | 0.016 | 0.0231 | 5.27 | 2.73 | 540 |
| Barley | 0.30 | 2E-04 | 0.009 | 0.0148 | 2.74 | 1.36 | 265 |
| Soybeans | 0.51 | 4E-04 | 0.010 | 0.0223 | 5.16 | 3.70 | 400 |
| Soymeal | 0.40 | 3E-04 | 0.008 | 0.0176 | 4.08 | 2.92 | 335 |
| Vegetable oil* | 3.50 | 0.001 | 0.022 | 0.0488 | 13.2 | 5.26 | 745 |
| Soy oil | 1.22 | 8E-04 | 0.021 | 0.0508 | 13.1 | 8.31 | 825 |
| Limestone | 0.16 | 4E-05 | 3E-05 | 0.0008 | 58.0 | 0.01 | 50 |
| Mono Calcium Phosphate | 1.47 | 5E-06 | 1E-04 | 0.0230 | 21.5 | 0.00 | 685 |
| NaHCO3 | 0.23 | 1E-04 | 2E-04 | 0.0028 | 3.06 | 0.00 | 440 |
| Salt | 0.15 | 1E-06 | 2E-05 | 0.0011 | 1.92 | 0.00 | 175 |
| Lysine HCl | 3.67 | 0.002 | 0.185 | 0.3500 | 23.8 | 5.75 | 1370 |
| DL-Methionine | 1.89 | 3E-04 | 0.001 | 0.0080 | 54.7 | 0.02 | 4090 |
| L-Threonine | 5.22 | 1E-03 | 0.005 | 0.0243 | 90.9 | 0.74 | 1810 |
| Valine | 7.35 | 0.005 | 0.370 | 0.7000 | 47.5 | 11.5 | 7590 |
| Fishmeal | 0.95 | 3E-04 | 9E-04 | 0.0016 | 20.0 | 0.00 | 1535 |
| Meat and bone meal | 0.65 | 9E-05 | 0.003 | 0.0031 | 6.46 | 0.41 | 275 |
| Poultry offal | 0.34 | 6E-05 | 0.002 | 0.0075 | 1.42 | 0.32 | 455 |
| DDGS (Corn) | 0.70 | 2E-04 | 0.003 | 0.0060 | 8.22 | 0.54 | 190 |
| Brewers grains | 0.64 | 5E-04 | 0.008 | 0.0128 | 10.2 | 1.38 | 140 |
| Premix | 1.30 | 0.023 | 0.040 | 0.0750 | 28.0 | 0.00 | 2920 |
| Enzymes (NSP$^2$/2*Phytase) | 2.28 | 0.003 | 0.004 | 0.0070 | 30.0 | 0.00 | 10220 |

*50:50 ratio blend of Soy and Palm oil

A sum of the environmental impact of feed ingredient production and litter management provided the total environmental impact associated with the diet formulation for each impact category tested. Therefore, by using linear programming, seven diets were formulated for each region including the least cost diets; the mathematical formulation of the linear optimisation procedure is outlined in detail below. The diets formulated to minimise each impact category individually were as follows: Least GWP, Least FWEP, Least MEP, Least TAP, Least NREU and Least ALU. Each diet was compared with the Least cost diet, which would most closely represent a contemporary commercial broiler feed composition. All diets formulated for environmental impact objectives axiomatically resulted in an increased cost as compared with the Least cost diet formulation; therefore, in order to formulate economically viable diets, each least environmental impact diet was subject to a 30% maximum cost increase in comparison to the Least cost diet (Mackenzie et al., 2016a).

### *3.3.5 Optimisation procedure*

Diets were formulated to meet the energy and nutritional requirements of specific modern broiler breeds whilst specific environmental impact categories were minimised. The optimization method (Equation 1) was based on the modified Simplex algorithm presented by Pomar et al. (2007), which itself is an adaption of the methodology applied by dit Bailleul et al. (2001), and shows how to minimise an objective function $(E)$ whilst meeting numerous constraints dictated by feed cost and the broilers' biology. $E$ can be represented by any of the environmental impact categories included in this study separately: GWP, FWEP, MEP, TAP, NREU and ALU. The objective function can also be replaced by cost $(C)$ in order to find the least cost formulation. Where the objective function is defined in order to minimize the environmental impact of the final diet formulation, $E$ equates to the sum total of the environmental impact of the provision of individual ingredients and the nutrients that are excreted in the poultry manure after the consumption of that diet.

For Equation 1, let:

$\underset{X}{\rightarrow} = (x_i)_{i \in I}$ and be the decision vector of ingredients, where each $x_i$ represents the amount of the ith ingredient in the diet and $I$ is the total contribution of ingredients to the diet formulation tool;

$A = \ (a_{ij})_{i\in I, j\in J}$ and be the coefficient matrix of the system where each $a_{ij}$ represents the amount of energy and nutrient $j$ content in the ingredient $i$. Therefore matrix $A$ represents the energy and nutritional composition of the ingredients;

$\underset{b}{\rightarrow} = (b_i)_{j\in J}$ and be the vector of nutrient requirements, where each $b_j$ represents the total amount of nutrient j required in the final diet formulation;

$\underset{e}{\rightarrow} = (e_i)_{i\in I}$ and be the vector of the objective function, where $e_i$ is the environmental impact value associated with the $i$th ingredient and accounts for the impact of both that ingredient’s provision and the nutrients in that ingredient which are not stored in the animal’s body but excreted into the manure.

**Equation 1**)

$$\min E = (\sum\nolimits_{i\in I} e_i x_i)$$

$$A \ \underset{X}{\rightarrow} = \left( \begin{pmatrix} \sum_{i\in I} a_{i1}\, x_i \\ \sum_{i\in I} a_{i2}\, x_i \\ \vdots \\ \sum_{i\in I} a_{iJ}\, x_I \end{pmatrix} \geq \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_J \end{pmatrix} \right) = \underset{b}{\rightarrow}$$

Where:

$\sum_{i\in I} x_i = 1;$

$x_i \ \geq 0;$

$(\min x_i)_{i\in I} \leq (x_i)_{i\in I} \leq (\max x_i)_{i\in I}$ and

$\sum_{i\in I} x_i c_i \ \leq \min C * 1.3.$

All ingredients included in the diet must add up to exactly 100% of the diet, no ingredient could be included at lower than 0%, the total inclusion of each ingredient must fall between its maximum (max) and minimum (min) inclusion rate and, finally, each least environmental impact diet must not increase the total cost $(C)$ of the diet by more than 30% above the Least cost diet (the latter is not needed in Least cost diet formulation).

### ***3.3.6 Social life cycle assessment of diets***

The goal of the SLCA was to assess the social impacts of the meat-producing chicken industry and to compare the social implications of formulating diets for the different environmental objectives discussed herein. Thus, the functional unit was identical to the ELCA element of the chapter: 1 metric tonne of broiler chicken LW. The system boundary was also the same (Figure 3.1). The social impacts of diet formulation on the following stakeholders were assessed: the workforce, the local community and society in general. Since the system boundary of the study was cradle to farm gate, the social impacts on customers were not included within the SLCA.

The social impact categories used in this study were based on those outlined by Benoít-Norris et al. (2015): “Labour Rights and Decent Work”, “Health and Safety”, “Human Rights”, “Governance” and “Community Infrastructure”. Hence, in this model, positive impacts were not assessed; all issues used were considered to pose a negative impact to sustainability. The value of each social impact category was calculated using a weighted sum methodology, whereby each social indicator associated with that social impact category was assigned a level of risk. The vast majority of the risk levels assigned to the social indicators were based on quartiles or obvious transitions in the data and defined as low, medium, high and very high risk; these were weighted by a factor of 0.1, 1, 5 and 10 respectively. The contribution of a social indicator to the social impact category to which it belongs was determined by the collective risk levels and work hours within the system processes. Following this framework, product category supply chains were modelled by emphasizing processes with the greatest social impacts based on worker hours, assessing the potential social impacts that may be greater in particular countries and for specific sectors within that supply chain (Benoît-Norris et al., 2010, Benoît-Norris et al., 2011). The social impacts were expressed as medium risk hour equivalent (mrh equiv), for a defined social indicator belonging to each category; hence, the number of work hours augmented depends on the level of risk throughout the system that is being assessed (Pelletier et al., 2018).

There can be many social issues that affect each stakeholder group, hence each one may be affected by multiple interacting subcategories. The social implications on the workforce stakeholder group was based on the following subcategories of social indicators: child labour, forced labour, migrant labour, excessive working time, injuries and fatalities, exposure to toxic/ hazardous conditions, wage, gender equality, collective bargaining, freedom to strike, freedom from association rights and social benefits. The workforce was represented by three of the social impact categories: Labour Rights and Decent Work, Health and Safety and Human Rights. The social implications on the local community stakeholder group were based on the following subcategories of social indicators: indigenous rights and community access to drinking water, improved sanitation and hospital beds. The local community was represented by the Human Rights and Community Infrastructure social impact categories. The social implications on society was based on a country specific risk of high conflict, the fragility of its legal system and corruption. Hence, society was represented by the Human Rights and the Governance social impact categories. Each of these social indicators is explained comprehensively, and the characterisation of their levels of risk have been outlined, by Benoít-Norris et al. (2015).

### *3.3.7 Sensitivity Analysis*

A sensitivity analysis was performed on the model based on the Least cost diet formulations for both the UK and USA; hence the sensitivity analysis identified the parameters that have the most influence on the model outputs. The sensitivity analysis was conducted on all input parameters to the foreground LCA model on an individual basis at the upper/lower 95% confidence bounds of their distributions, as is appropriate for models which contain linear relationships (Mackenzie et al., 2015). The distributions of the parameters were derived from appropriate sources, such as published industry benchmark data for flock performance characteristics and crop yields, as well as peer reviewed studies and IPCC guidelines on emission factors from manure management (see Appendix C for a full list of the parameters tested, their means and distributions). If the upper or lower bounds for any parameter resulted in ≥5% change in any impact value in comparison to the mean result of the LCA for the Least cost diets then this was reported as a sensitive input to the LCA model (Mackenzie et al., 2016a, Tallentire et al., 2017).

In the first instance, emissions in the manure model were accounted for in accordance with the IPCC (2006) methodologies using the same emissions factors for the housing and storage stages in both regions; in reality, however, litter management practices vary between the two regions. Since the base model assumed UK storage and housing emission values as a percentage of the nutrients released by the birds in both regions, the manure model was adapted to reflect emission values recorded in USA poultry housing and manure storage (e.g. Coufal et al., 2006, Moore et al., 2011) to assess the sensitivity of the USA Least cost diet to the potential difference in litter management practices and emissions between the regions. Where environmental impact categories were sensitive to this change (i.e. ≥5% compared with the base model), the corresponding least impact diets were reformulated using the USA specific manure model.

### *3.3.8 Uncertainty*

In order to make it possible to evaluate differences between the Least cost diet and the diets formulated for environmental impact objectives a Monte Carlo approach (Figure 3.2) was applied to the model to quantify the potential uncertainties in the study (e.g. measurement errors, variation in production data due to differences in crop yield, feed intake, bird mortality etc.). Uncertainties in LCA calculations can be classified as either system "α" or shared calculation "β" uncertainties (Wiltshire et al. 2009): α uncertainties are those considered to vary between systems, while β uncertainties are the same for both systems and in some earlier studies they have simply been ignored (e.g. Leinonen et al., 2012). The comparisons made in the LCA model were between different diets tested in the same regional production scenario (for USA and UK systems respectively), as such most of the uncertainty contained in this LCA model was shared between the comparisons and classed as β uncertainty (Leinonen et al., 2012, Mackenzie et al., 2016a). In order to assess whether dietary scenarios were significantly different from each other in terms of their environmental impacts once they were applied to the poultry production system within each region, the LCA model was run in parallel 1000 times and, during each run, a value of each input variable was randomly selected from a predetermined distribution for said variable; the method is described comprehensively in Mackenzie et al. (2015). The price uncertainty of commodities, such as the feed ingredients, was beyond the scope of this study. A full list of mean values and distributions for the input parameters to the LCA model can be found in Appendix C. Environmental impact results were reported as significantly different where one diet had a greater impact than the other in more than 95% of the parallel simulations of the LCA model ($p<0.05$).

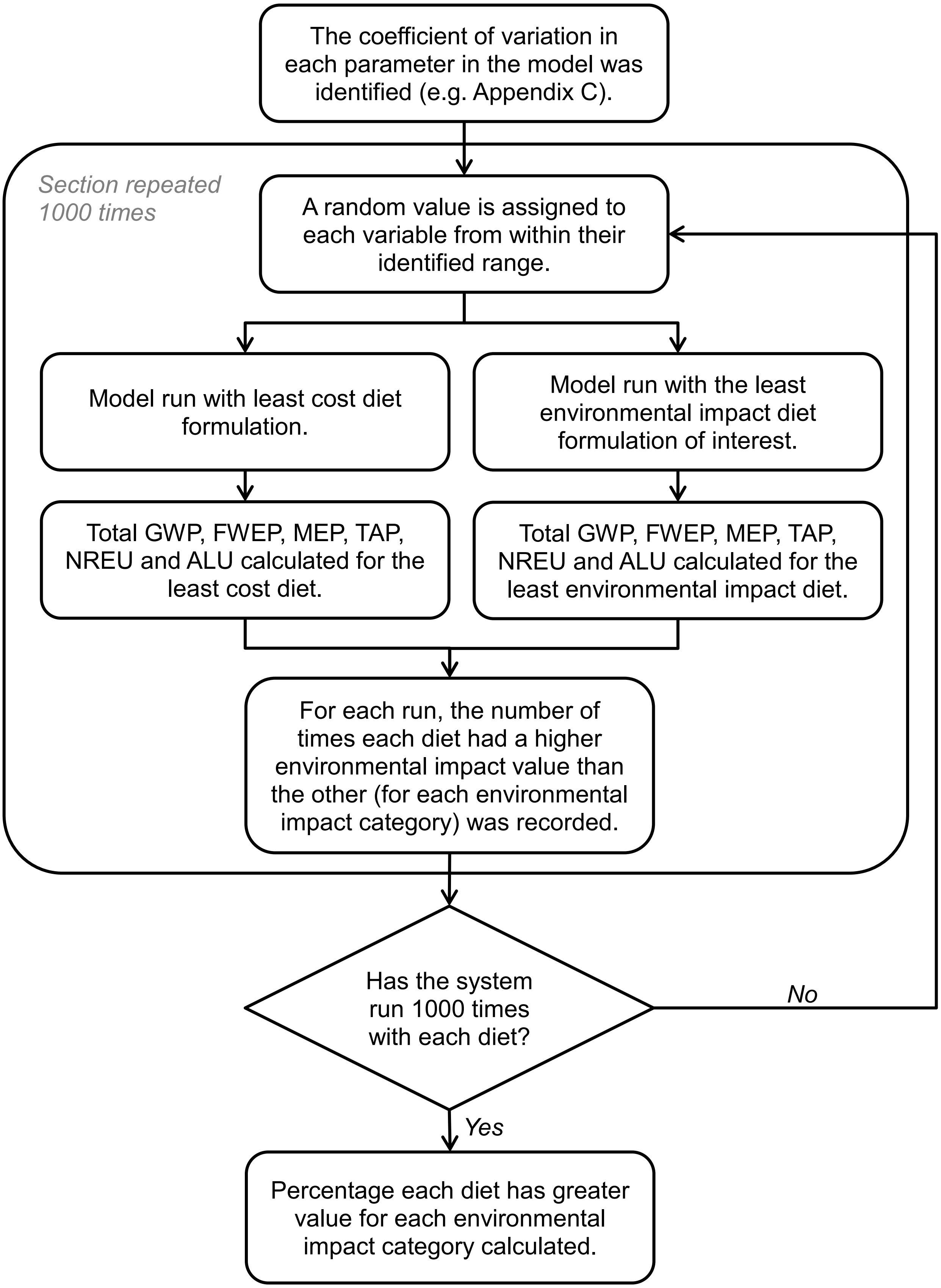

**Figure 3.2**: Flow diagram to illustrate how the Monte Carlo simulations were run. The impact categories tested were global warming potential (GWP; kg $CO_2$ equiv), freshwater eutrophication potential (FWEP; kg P equiv), marine eutrophication potential (MEP; kg N equiv), terrestrial acidification potential (TAP; kg $SO_2$ equiv), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; $m^2$).

## 3.4 Results

### *3.4.1 Least cost diet formulation and sensitivity analysis*

In the UK a standard Least cost diet, across all three stages, was composed of 483 g kg$^{-1}$ wheat, 66.8 g kg$^{-1}$ rapeseed, 241 g kg$^{-1}$ soymeal and 124 g kg$^{-1}$ field peas, plus oil and specialist ingredients. The production of the functional unit on the Least cost diet had a GWP, FWEP, MEP, TAP, NREU and ALU impact value of 3060 kg $CO_2$ equiv, 0.6657 kg P equiv, 27.38 kg N equiv, 69.61 kg $SO_2$ equiv, 16.63 GJ and 4675 m$^2$ respectively. The cost of feed with a least cost formulation was £0.21 per kg in the UK. In the US, a standard Least cost diet was composed of 611 g kg$^{-1}$ maize and 208 g kg$^{-1}$ soymeal plus oil, animal co-products and additives. The production of the functional unit on the Least cost diet had a GWP, FWEP, MEP, TAP, NREU and ALU impact value of 917.7 kg $CO_2$ equiv, 0.4154 kg P equiv, 20.66 kg N equiv, 63.16 kg $SO_2$ equiv, 12.24 GJ and 2775 m$^2$ respectively. The cost of feed with a least cost formulation was $0.24 per kg.

In the UK, every impact category was sensitive to the LW achieved for a given feed intake, otherwise known as FCR (Table 3.3). No impact category was sensitive to changes in mortality or feed spillage. Variation in soybean yield caused sensitivity in GWP and ALU in the UK, whilst FWEP and ALU were sensitive to field pea yield. The results for TAP were sensitive to variation in $NH_3$ emissions released at the UK housing and storage stages; the TAP was also sensitive to the retention of N in the birds' bodies and the minimum replacement rate of N that would have been otherwise delivered via the spreading of synthetic fertilisers. FWEP was sensitive to the variation in the replacement rate of P that would have been otherwise delivered via the spreading of synthetic fertilisers in the UK. NREU was sensitive to gas consumption at the UK facilities. MEP and FWEP were highly sensitive to assumptions regarding any net difference in leaching of $NO_3$ and $PO_4$ respectively, caused by applying manure to land in place of inorganic fertiliser in the UK.

In the USA system there was also no impact category that was sensitive to potential differences in mortality or feed spillage (Table 3.4). Furthermore, every impact category was sensitive to the birds' FCR. The FWEP was sensitive to high and low USA maize yield. The results for TAP were sensitive to variation in $NH_3$ emissions at every stage of the manure model. TAP was also sensitive to the minimum replacement rate of N. FWEP was sensitive to the variation in the replacement rate of P. MEP and FWEP were highly sensitive to assumptions regarding any net difference in leaching of $NO_3$ and $PO_4$ respectively, caused by applying manure to land in place of inorganic fertiliser. There was no sensitivity in any impact category for P and K retention in the USA broilers' bodies; however, MEP and TAP were sensitive to variation in N retention.

Finally, adapting the manure model so that the emissions values from the USA system were distinctly different than those from the UK, reflecting measurements taken from USA production systems at both the housing and storage stages (see Appendix C, Table C3), led to a 39.2% significant increase in TAP in the USA Least cost diet scenario compared with the USA least cost scenario where the emissions at housing and storage were equitable with those in the UK. All other impact categories were not sensitive to this adaptation.

**Table 3.3**: The effect of increasing each variable to the maximum and minimum value in its range on each environmental impact category in the UK systems. Results are presented as the percentage increase (+) or decrease (-) from the median.

| **Variable** | **GWP** | | **FWEP** | | **MEP** | | **TAP** | | **NREU** | | **ALU** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Max** | **Min** | **Max** | **Min** | **Max** | **Min** | **Max** | **Min** | **Max** | **Min** | **Max** | **Min** |
| Live weight at slaughter | -7.4 | +8.7 | -7.4 | +8.7 | -7.4 | +8.7 | -7.4 | +8.7 | -7.4 | +8.7 | -7.4 | +8.7 |
| Feed intake | +8.2 | -8.2 | +9.7 | -9.7 | +9.7 | -9.7 | +9.6 | -9.6 | +5.0 | -5.0 | +9.7 | -9.7 |
| Mortality | +0.2 | -0.2 | +0.2 | -0.2 | +0.2 | -0.2 | +0.1 | -0.1 | +0.1 | -0.1 | +0.2 | -0.2 |
| Feed spillage | +0.2 | -0.2 | +0.2 | -0.2 | +0.2 | -0.2 | +0.2 | -0.2 | +0.1 | -0.1 | +0.2 | -0.2 |
| Wheat yield | -0.9 | +0.9 | -1.7 | +1.7 | -3.6 | +3.6 | -2.2 | +2.2 | -1.2 | +1.2 | -2.4 | +2.4 |
| Maize yield | -1.3 | +1.3 | -4.2 | +4.2 | -5.0 | +5.0 | -2.9 | +2.9 | -2.5 | +2.5 | -3.9 | +3.9 |
| Rapeseed yield | -0.5 | +0.5 | -1.1 | +1.1 | -1.5 | +1.5 | -0.9 | +0.9 | -0.5 | +0.5 | -1.0 | +1.0 |
| Sunflower yield | -0.5 | +0.6 | -0.6 | +1.2 | -0.6 | +0.6 | -0.5 | +0.5 | -0.4 | +0.4 | -1.5 | +1.5 |
| Soybean yield | -6.4 | +6.4 | -4.3 | +4.3 | -2.4 | +2.4 | -2.1 | +2.1 | -1.2 | +1.2 | -5.2 | +5.2 |
| Field pea yield | -0.5 | +0.5 | -5.8 | +5.8 | -1.5 | +1.5 | -1.2 | +1.2 | -0.7 | +0.7 | -5.4 | +5.4 |
| Vegetable oil | -1.8 | +1.8 | -1.5 | +1.5 | -1.1 | +1.1 | -0.8 | +0.8 | -0.6 | +0.6 | -1.8 | +1.8 |
| $NH_3$ lost at housing | -0.8 | 0.0 | 0.0 | 0.0 | -0.3 | -0.5 | -2.7 | -5.9 | -1.5 | 0.0 | 0.0 | 0.0 |
| $NH_3$ lost at storage | -0.8 | 0.0 | 0.0 | 0.0 | +0.7 | -1.3 | +0.2 | -8.3 | -1.5 | 0.0 | 0.0 | 0.0 |
| $NH_3$ lost at field | 0.0 | 0.0 | 0.0 | 0.0 | +0.2 | -0.2 | +2.6 | -2.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| $N_2O$ emission | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | +0.1 | -0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| Electricity consumption | +1.1 | -1.1 | 0.0 | 0.0 | 0.0 | 0.0 | +0.3 | -0.3 | +3.8 | -3.8 | 0.0 | 0.0 |
| Gas/Oil consumption | +3.7 | -3.7 | 0.0 | 0.0 | 0.0 | 0.0 | +0.1 | -0.1 | +11.8 | -11.8 | 0.0 | 0.0 |
| N retention | +0.3 | -0.3 | 0.0 | 0.0 | -3.5 | +3.5 | -5.6 | +5.6 | +0.5 | -0.5 | 0.0 | 0.0 |
| P retention | 0.0 | 0.0 | -0.5 | +0.5 | 0.0 | 0.0 | -0.1 | +0.1 | +0.1 | -0.1 | 0.0 | 0.0 |
| K retention | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| N replacement rate | -0.3 | +0.9 | 0.0 | 0.0 | -0.3 | +0.8 | -3.2 | +9.9 | -0.5 | +1.6 | 0.0 | 0.0 |
| P replacement rate | 0.0 | 0.0 | -6.8 | +6.8 | 0.0 | 0.0 | +0.3 | -0.3 | -0.3 | +0.3 | 0.0 | 0.0 |
| $NO_3$ emissions | 0.0 | 0.0 | 0.0 | 0.0 | +1.1 | -7.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $PO_4$ emissions | 0.0 | 0.0 | +66.3 | -19.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

**Table 3.4**: The effect of increasing each variable to the maximum and minimum value in its range on each environmental impact category in the USA systems. Results are presented as the percentage increase (+) or decrease (-) from the median.

| **Variable** | **GWP** | | **FWEP** | | **MEP** | | **TAP** | | **NREU** | | **ALU** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Max** | **Min** | **Max** | **Min** | **Max** | **Min** | **Max** | **Min** | **Max** | **Min** | **Max** | **Min** |
| Live weight at slaughter | -7.4 | +8.7 | -7.4 | +8.7 | -7.4 | +8.7 | -7.4 | +8.7 | -7.4 | +8.7 | -7.4 | +8.7 |
| Feed intake | +8.1 | -8.1 | +9.7 | -9.7 | +9.8 | -9.8 | +9.7 | -9.7 | +7.6 | -7.6 | +9.7 | -9.7 |
| Mortality | +0.3 | -0.3 | +0.3 | -0.3 | +0.2 | -0.2 | +0.1 | -0.1 | +0.3 | -0.3 | +0.3 | -0.3 |
| Feed spillage | +0.2 | -0.2 | +0.2 | -0.2 | +0.2 | -0.2 | +0.2 | -0.2 | +0.2 | -0.2 | +0.2 | -0.2 |
| Wheat yield | -4.7 | +4.7 | -6.5 | +6.5 | -6.8 | +6.8 | -4.0 | +4.0 | -2.7 | +2.7 | -10.6 | +10.6 |
| Maize yield | -4.0 | +4.0 | -5.6 | +5.6 | -3.0 | +3.0 | -2.1 | +2.1 | -4.0 | +4.0 | -4.9 | +4.9 |
| Barley yield | -0.9 | +0.9 | -1.2 | +1.2 | -1.1 | +1.1 | -0.6 | +0.6 | -0.5 | +0.5 | -1.2 | +1.2 |
| Soybean yield | -2.4 | +2.4 | -4.9 | +4.9 | -2.8 | +2.8 | -2.1 | +2.1 | -1.6 | +1.6 | -8.2 | +8.2 |
| $NH_3$ lost at housing | 0.0 | 0.0 | 0.0 | 0.0 | +2.5 | -1.7 | +10.0 | -8.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| $NH_3$ lost at storage | -3.0 | 0.0 | 0.0 | 0.0 | +4.0 | -3.9 | +3.5 | -12.1 | -2.3 | 0.0 | 0.0 | 0.0 |
| $NH_3$ lost at field | 0.0 | 0.0 | 0.0 | 0.0 | +0.7 | -0.7 | +7.3 | -7.3 | 0.0 | 0.0 | 0.0 | 0.0 |
| $N_2O$ emission | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | +0.1 | -0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| Electricity consumption | +1.7 | -1.7 | 0.0 | 0.0 | 0.0 | 0.0 | +0.1 | -0.1 | +2.3 | -2.3 | 0.0 | 0.0 |
| Gas/Oil consumption | +3.2 | -3.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | +4.2 | -4.2 | 0.0 | 0.0 |
| N retention | +0.7 | -0.7 | 0.0 | 0.0 | -5.1 | +5.1 | -6.1 | +6.1 | +0.6 | -0.6 | 0.0 | 0.0 |
| P retention | 0.0 | 0.0 | -0.5 | +0.5 | 0.0 | 0.0 | -0.1 | +0.1 | +0.1 | -0.1 | 0.0 | 0.0 |
| K retention | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| N replacement rate | -1.0 | +3.0 | 0.0 | 0.0 | -0.4 | +1.2 | -3.8 | +11.7 | -0.7 | +2.3 | 0.0 | 0.0 |
| P replacement rate | -0.2 | +0.2 | -16.0 | +16.0 | 0.0 | 0.0 | +0.4 | -0.4 | -0.5 | +0.5 | 0.0 | 0.0 |
| $NO_3$ emissions | 0.0 | 0.0 | 0.0 | 0.0 | +2.0 | -14.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $PO_4$ emissions | 0.0 | 0.0 | +70.8 | -49.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

### *3.4.2 Least environmental impact diet formulations - UK*

When compared with the Least cost diet, soymeal was reduced in the Least GWP diet in favour of maize gluten meal, rapeseed meal and sunflower meal, which were incorporated at inclusions of 48.3, 34.2 and 88.6 g kg$^{-1}$ respectively; wheat was also reduced, when compared with the Least cost diet, at 453 g kg$^{-1}$, but whole rapeseed remained the same (Table 3.5). In the Least FWEP diet, wheat inclusion was increased, but rapeseed was removed completely. In the Least MEP and TAP diets maize usurped wheat as the primary energy ingredient (577 and 630 g kg$^{-1}$ respectively) and had an increased soy oil content relative to the least cost and Least GWP diets. The NREU diet had a greater inclusion of wheat and soymeal when compared with the Least cost diet. Like the Least MEP and TAP diets, the Least ALU diet was primarily maize based, but also contained 66.3 g kg$^{-1}$ of whole rapeseed.

All least environmental impact diets had increased costs of between 16 and 30% when compared with the Least cost diet, except for the NREU diet which had an increased cost of just under 4% (Figure 3.3). The Least MEP and ALU diets were 29% and 30% more expensive than the Least cost diet, at the top end of the upper economic limit applied to the diet formulation tool. The Least GWP diet decreased the GWP by 37%, but increased NREU by 31% and TAP by 8.2%. The Least FWEP diet decreased the values of all impact categories, when compared with the Least cost diet, with the exception of TAP which increased by 0.07% and the NREU, which was not significantly different. The Least MEP and TAP diets showed similar trends in the reduction of environmental impacts; however, every impact category except MEP was lower in the Least TAP diet. The Least NREU diet was the only diet which had a significantly lower NREU value than the Least cost diet. The Least ALU diet significantly reduced the GWP, FWEP and MEP compared with the Least cost diet, but resulted in a small significant increase in TAP (0.62%) and a 53.2% significant increase in NREU.

**Table 3.5**: Percentage inclusion of each ingredient in each diet formulated for the UK poultry systems. The diets were formulated for least global warming potential (GWP; kg $CO_2$ equiv), least freshwater eutrophication potential (FWEP; kg P equiv), least marine eutrophication potential (MEP; kg N equiv), least terrestrial acidification potential (TAP; kg $SO_2$ equiv), least non-renewable energy use (NREU; MJ) and least agricultural land use (ALU; $m^2$).

| | **Diet** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Ingredient** | **Least Cost** | **Least GWP** | **Least FWEP** | **Least MEP** | **Least TAP** | **Least NREU** | **Least ALU** |
| Wheat | 48.3 | 45.3 | 63.3 | 0.00 | 0.00 | 55.0 | 0.00 |
| Maize (Corn) | 0.00 | 0.00 | 0.00 | 57.8 | 63.0 | 0.00 | 58.9 |
| Maize gluten meal | 0.33 | 4.83 | 4.83 | 0.00 | 0.00 | 0.18 | 4.83 |
| Rapeseed (Whole) | 6.68 | 6.68 | 0.00 | 0.00 | 0.00 | 6.68 | 6.63 |
| Rapeseed meal | 0.00 | 3.42 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Barley | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sunflower meal | 0.00 | 8.86 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Soybeans | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Soymeal | 24.1 | 5.94 | 20.1 | 26.8 | 26.2 | 29.9 | 20.8 |
| Field peas | 12.4 | 12.4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Oats | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Vegetable oil* | 0.00 | 4.58 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Soy oil | 4.18 | 0.16 | 3.69 | 4.71 | 3.02 | 4.17 | 0.53 |
| Limestone | 1.15 | 1.00 | 1.00 | 1.75 | 1.00 | 1.00 | 1.00 |
| Mono Calcium Phosphate | 1.29 | 0.71 | 0.78 | 1.24 | 0.85 | 1.57 | 0.86 |
| NaHCO3 | 0.00 | 0.00 | 0.00 | 0.13 | 0.00 | 0.00 | 0.00 |
| Salt | 0.37 | 0.27 | 0.28 | 1.85 | 0.28 | 0.37 | 0.27 |
| Lysine HCl | 0.17 | 0.32 | 0.24 | 0.14 | 0.14 | 0.15 | 0.20 |
| DL-Methionine | 0.28 | 0.18 | 0.50 | 0.26 | 0.25 | 0.24 | 0.50 |
| L-Threonine | 0.09 | 0.06 | 0.04 | 0.05 | 0.05 | 0.06 | 0.21 |
| Valine | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| Fishmeal | 0.42 | 5.00 | 5.00 | 5.00 | 5.00 | 0.42 | 5.00 |
| Brewers grains | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Wheat middlings | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Wheat bran | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Premix | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| Enzymes (NSP$^2$/ 2*Phytase) | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |

*50:50 ratio blend of Sunflower and Palm oil

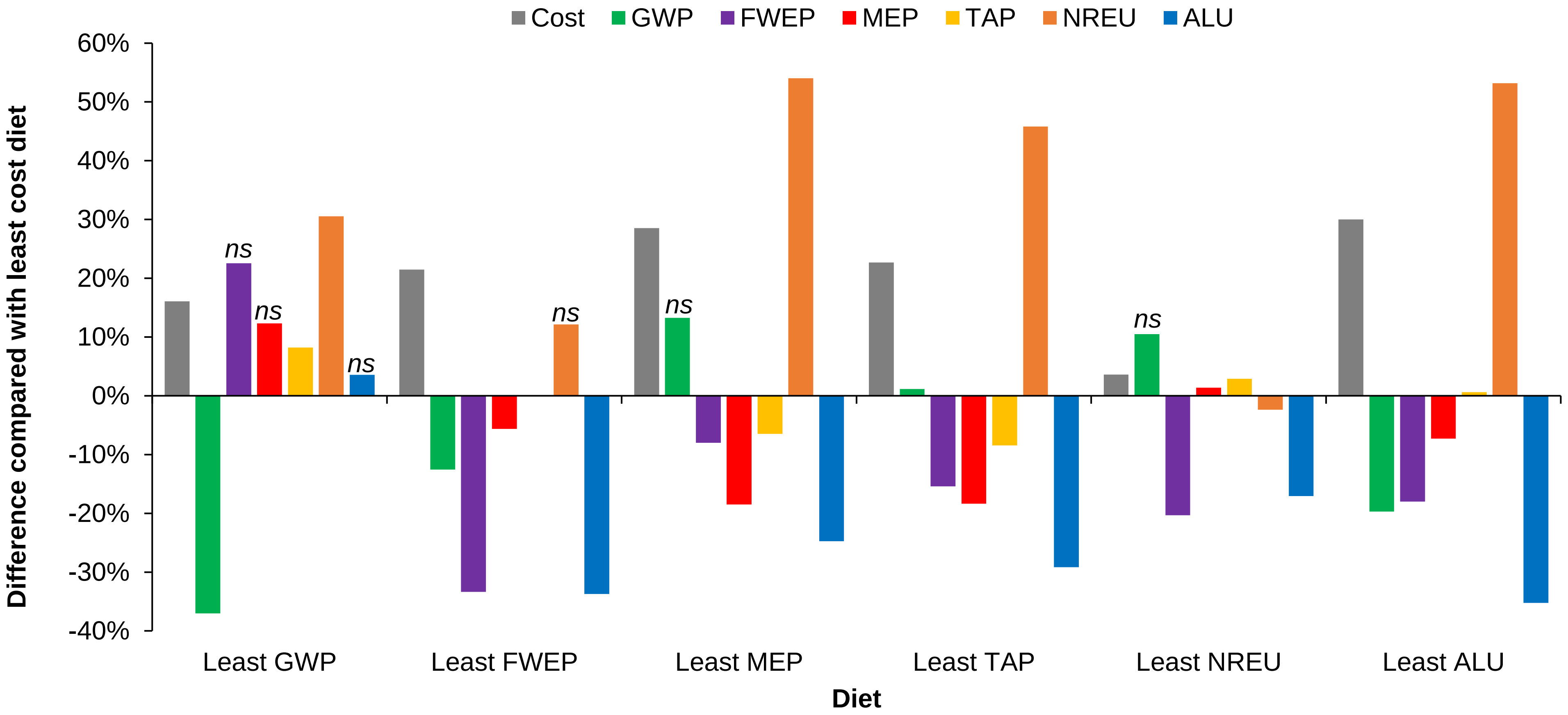

**Figure 3.3**: Environmental impacts of different UK broiler diets, each formulated to reduce a specific environmental impact category, as compared with a least cost formulation baseline. The price is also included for each diet (£).The impact categories tested were global warming potential (GWP; kg $CO_2$ equiv), freshwater eutrophication potential (FWEP; kg P equiv), marine eutrophication potential (MEP; kg N equiv), terrestrial acidification potential (TAP; kg $SO_2$ equiv), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; $m^2$). All impact category values were significantly different ($p < 0.05$) from their corresponding value produced by the functional unit on the Least cost diet unless otherwise stated as being nonsignificant (*ns*).

### *3.4.3 Least environmental impact diet formulations - USA*

In contrast to the UK diets, the USA diets consisted of a higher percentage of soymeal in the starter phase, and lower percentage inclusions in the later phases (Table 3.6). In the Least GWP diet maize incorporation was reduced dramatically (307 g $kg^{-1}$) when compared with the least cost baseline and instead barley was included as an additional energy source (262 g $kg^{-1}$). Ingredients derived from soybeans increased, which was the opposite of what happened in the UK Least GWP diet. In the Least FWEP diet wheat usurped maize as the primary energy ingredient and was included at a rate of 664 g $kg^{-1}$. The incorporation of maize and fishmeal was high in the Least MEP and TAP diets when compared with other diet formulations. The Least NREU incorporated 277 g $kg^{-1}$ of maize and 262 g $kg^{-1}$ of barley, much like the Least GWP diet, but contained more soybeans (106 g $kg^{-1}$) and slightly less soymeal (228 g $kg^{-1}$) than that diet. The Least ALU contained the least soybeans and their derivatives when compared with all other USA diet formulations and the highest incorporation of specialist ingredients.

All least environmental impact diets had increased costs of between 23% (Least TAP) and 30% (Least FWEP), when compared with the Least cost diet (Figure 3.4). The Least GWP diet decreased GWP significantly by 6.7% and NREU by 15%, but increased significantly every other impact category. The Least FWEP diet caused an 18% decrease in MEP but increased every other impact category when compared with the Least cost diet. The Least MEP diet increased the FWEP and NREU when compared with the Least cost diet. In the Least TAP diet only, MEP and TAP were significantly reduced when compared with the Least cost diet. The Least NREU diet had a reduced GWP and NREU when compared with the Least cost diet, but increased every other impact category. The Least ALU diet significantly increased every impact category except the FWEP (insignificant change) and ALU (reduced by 18%).

**Table 3.6**: Percentage inclusion of each ingredient in each diet formulated for the USA poultry systems. The diets were formulated for least global warming potential (GWP; kg $CO_2$ equiv), least freshwater eutrophication potential (FWEP; kg P equiv), least marine eutrophication potential (MEP; kg N equiv), least terrestrial acidification potential (TAP; kg $SO_2$ equiv), least non-renewable energy use (NREU; MJ) and least agricultural land use (ALU; $m^2$).

| | **Diet** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Ingredient** | **Least Cost** | **Least GWP** | **Least FWEP** | **Least MEP** | **Least TAP** | **Least NREU** | **Least ALU** |
| Wheat | 0.00 | 0.00 | 66.4 | 0.00 | 0.00 | 0.00 | 0.00 |
| Maize (Corn) | 61.1 | 30.7 | 0.00 | 66.0 | 63.8 | 27.7 | 61.4 |
| Maize gluten meal | 2.39 | 0.00 | 4.89 | 0.00 | 0.00 | 0.00 | 4.89 |
| Rapeseed (Whole) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Rapeseed meal | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Barley | 0.00 | 26.2 | 0.00 | 0.00 | 0.00 | 26.2 | 0.00 |
| Soybeans | 0.00 | 4.37 | 0.00 | 0.00 | 0.00 | 10.6 | 0.00 |
| Soymeal | 20.8 | 25.5 | 14.6 | 21.1 | 27.2 | 22.8 | 13.8 |
| Vegetable oil* | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Soy oil | 2.19 | 4.65 | 2.84 | 1.95 | 3.28 | 4.09 | 0.91 |
| Limestone | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Mono Calcium Phosphate | 0.49 | 0.44 | 0.12 | 0.50 | 1.08 | 0.43 | 0.08 |
| NaHCO3 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Salt | 0.27 | 0.29 | 0.24 | 0.24 | 0.33 | 0.29 | 0.16 |
| Lysine HCl | 0.26 | 0.03 | 0.27 | 0.11 | 0.15 | 0.03 | 0.22 |
| DL-Methionine | 0.21 | 0.22 | 0.15 | 0.21 | 0.25 | 0.21 | 0.50 |
| L-Threonine | 0.05 | 0.01 | 0.05 | 0.03 | 0.05 | 0.01 | 0.50 |
| Valine | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fishmeal | 0.00 | 0.04 | 2.85 | 5.00 | 2.62 | 0.00 | 5.00 |
| Meat and bone meal | 2.65 | 2.65 | 2.65 | 0.00 | 0.00 | 2.65 | 2.65 |
| Poultry offal | 3.65 | 3.65 | 3.65 | 3.65 | 0.00 | 3.65 | 3.65 |
| DDGS (Corn) | 4.72 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 5.00 |
| Brewers grains | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Premix | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| Enzymes (NSP[2]/ 2*Phytase) | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |

*50:50 ratio blend of Soy and Palm oil

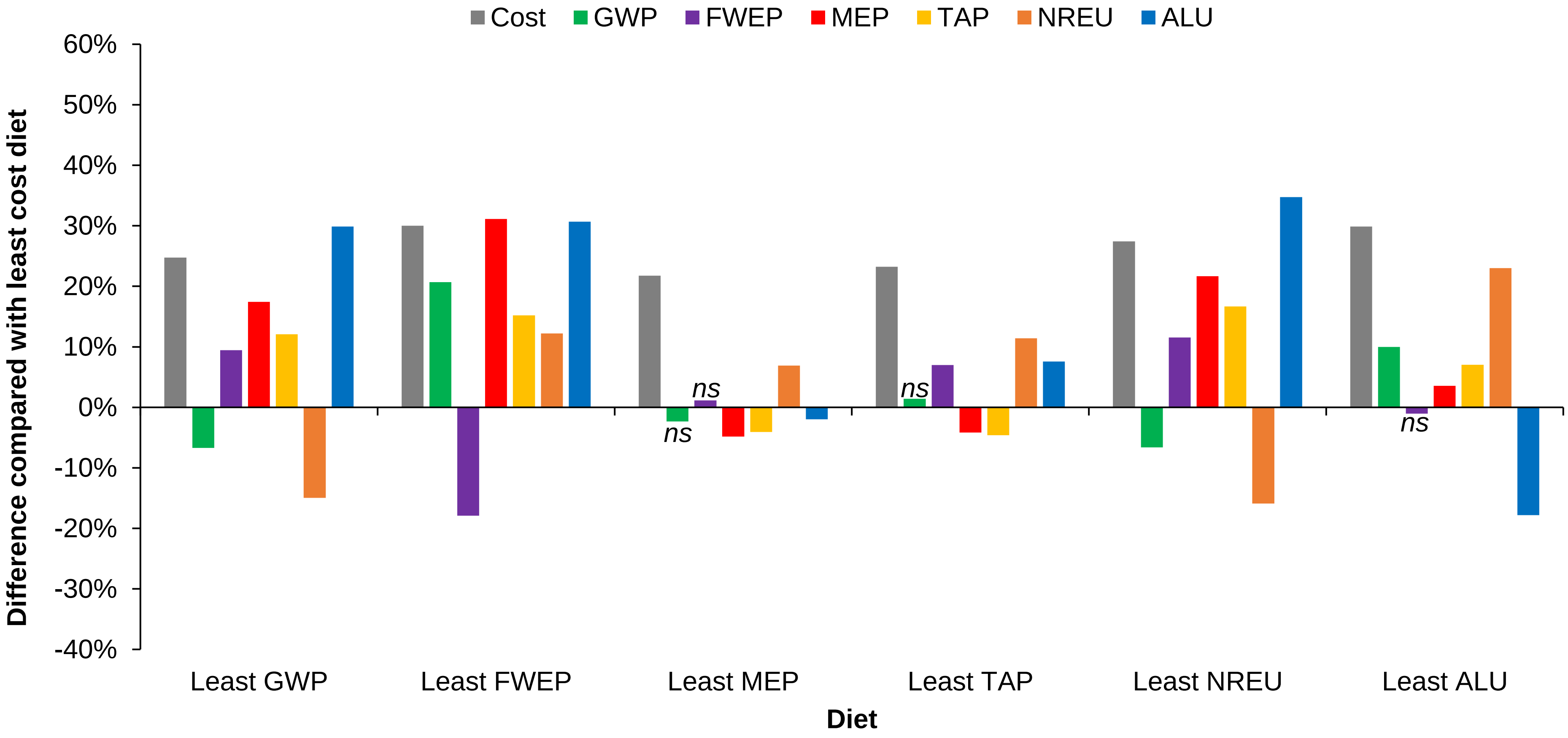

**Figure 3.4**: Environmental impacts of different USA broiler diets, each formulated to reduce a specific environmental impact category, as compared with a least cost formulation baseline. The price is also included for each diet ($). The impact categories tested were global warming potential (GWP; kg $CO_2$ equiv), freshwater eutrophication potential (FWEP; kg P equiv), marine eutrophication potential (MEP; kg N equiv), terrestrial acidification potential (TAP; kg $SO_2$ equiv), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; $m^2$). All impact category values were significantly different ($p < 0.05$) from their corresponding value produced by the functional unit on the Least cost diet unless otherwise stated as being nonsignificant (*ns*).

### *3.4.4 Social impacts of diet formulations*

The UK Least cost diet had a social impact of 524.0 child labour mrh equiv, 159.9 injury and fatality mrh equiv, 58.41 gender equality mrh equiv, 60.98 legal system mrh equiv and 32.24 drinking water mrh equiv for Labour Rights and Decent work, Health and Safety, Human Rights, Governance and Community Infrastructure respectively. The USA Least cost diet had a social impact of 1874 child labour mrh equiv, 2493 injury and fatality mrh equiv, 274.7 gender equality mrh equiv, 764.2 legal system mrh equiv and 141.5 drinking water mrh equiv for Labour Rights and Decent work, Health and Safety, Human Rights, Governance and Community Infrastructure respectively.

The greatest increases in social impacts compared with the Least cost diet in the UK were produced by the Least GWP diet, followed by the Least FWEP diet (Figure 3.5). All social impact increases in the Least MEP, Least TAP, Least NREU and Least ALU diets were below 30%. The UK Least ALU diet was the only diet in the study to reduce any impact. The Health and Safety, Human Rights and Governance associated with the production of broilers was reduced by the Least ALU diet compared with the Least cost diet, whilst Labour Rights and Decent work and Community Infrastructure were not significantly affected.

The greatest increases in social impacts compared with the Least cost diet in the USA were produced by the Least ALU diet (Figure 3.6). The social impacts associated with the Least MEP, Least TAP and Least NREU diets were more greatly increased in the USA than in the UK when compared with their corresponding Least cost diet formulations. Every USA diet formulation had lower social impacts than the UK diet that was formulated for the same objective except for the Least ALU diet; the UK Least ALU diet had lower Human Rights and Community Infrastructure impacts than the USA ALU diet.

It is important to mention that such results are indicative only. Worker exposure to 1 hour of very high risk is treated as being equal to a worker being exposed to 10 hours of medium risk and 100 hours of low risk. For example, in a situation where the production of two ingredients are associated with only low risk at every stage in the supply chain, the ingredient with the lowest number of collective work hours will have the lowest associated social impacts. The methodology is developed further in Chapter 6 with regards to animal welfare.

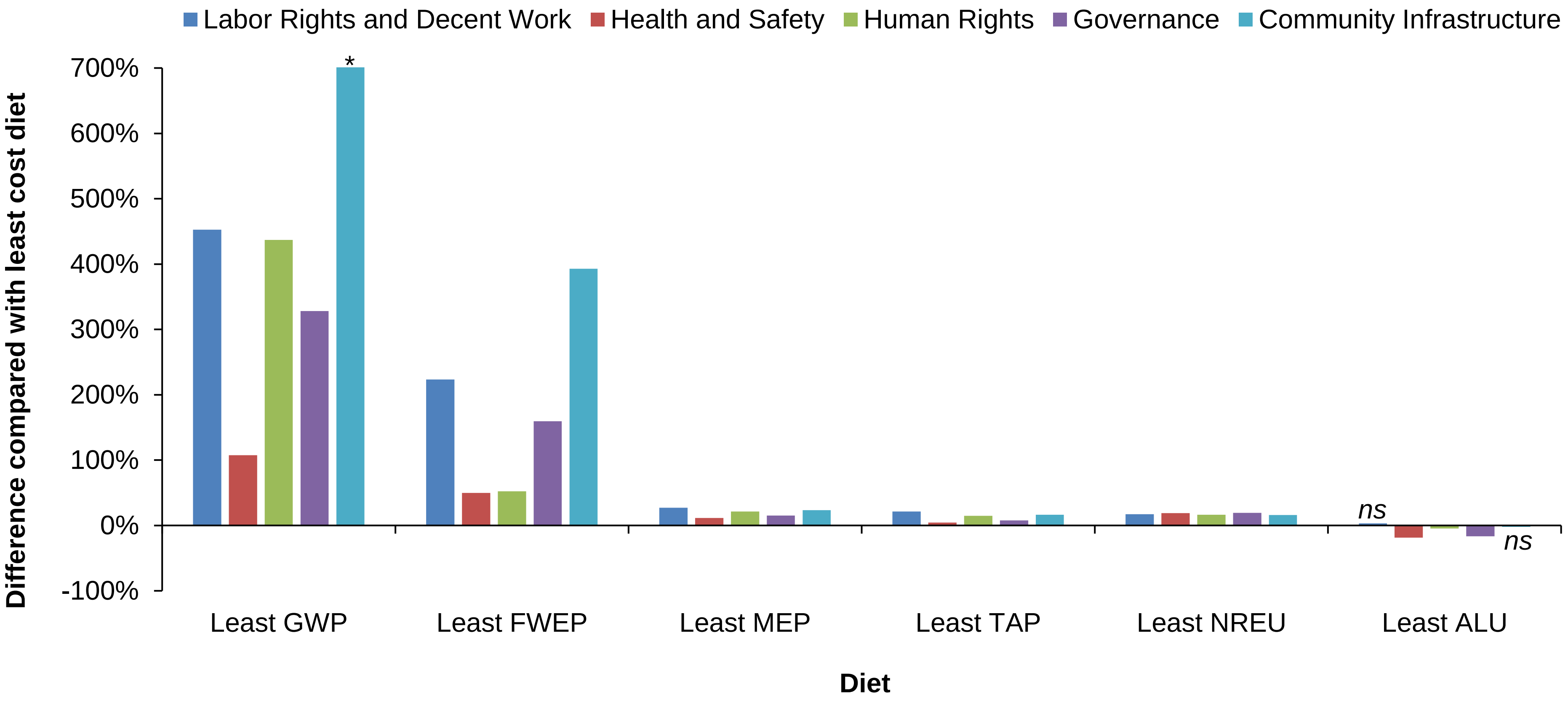

**Figure 3.5**: Social impacts of different UK broiler diets, each formulated to reduce a specific environmental impact category, as compared with a least cost formulation baseline. The diets were formulated to reduce global warming potential (GWP; kg $CO_2$ equiv), freshwater eutrophication potential (FWEP; kg P equiv), marine eutrophication potential (MEP; kg N equiv), terrestrial acidification potential (TAP; kg $SO_2$ equiv), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; $m^2$). The social impacts were Labour Rights and Decent work, Health and Safety, Human Rights, Governance and Community Infrastructure and were all calculated in medium risk hour equivalents. Nonsignificant differences are shown (*ns*). *Community infrastructure for Least GWP is increased by 1088% compared with the Least cost diet.

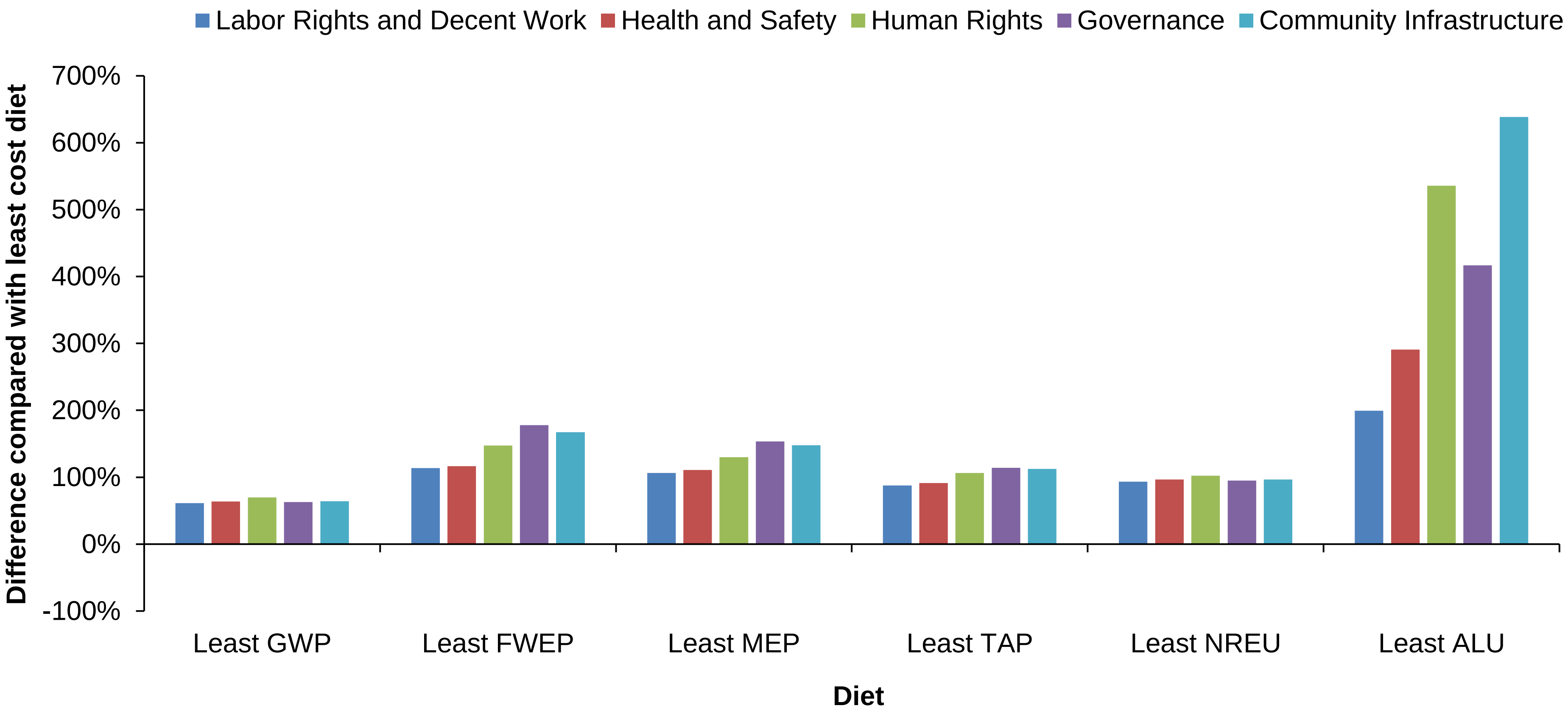

**Figure 3.6**: Social impacts of different USA broiler diets, each formulated to reduce a specific environmental impact category, as compared with a least cost formulation baseline. The diets were formulated to reduce global warming potential (GWP; kg $CO_2$ equiv), freshwater eutrophication potential (FWEP; kg P equiv), marine eutrophication potential (MEP; kg N equiv), terrestrial acidification potential (TAP; kg $SO_2$ equiv), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; $m^2$). The social impacts were Labour Rights and Decent work, Health and Safety, Human Rights, Governance and Community Infrastructure and were all calculated in medium risk hour equivalents.

## 3.5 Discussion

In this study the potential for lowering the impact values of different environmental impact categories of broiler production in different world regions through diet formulation was explored. Due to legislation, trade agreements and climatic conditions, broilers are fed diets composed of different ingredients in the EU and North America (Van Horne and Bondt, 2013). The inclusion of animal derived co-products in broiler diets, such as meat and bone meal, is a good case in point: this is not allowed in the EU, but is used routinely in North America (Brookes, 2001). It was therefore hypothesised that the potential reduction in specific environmental impact categories, associated with the formulation of the diets, would differ between these two regions. To test this, a whole systems model was developed to formulate broiler diets for environmental impact objectives in the UK and the USA as a case in point for EU and North American broiler systems respectively. Least cost diets were formulated for each region to represent the baseline diet which can be considered typical of current broiler production practices; the UK Least cost diet was based on wheat and soy and the USA Least cost diet was based on maize and soy. Although a direct comparison between the two regions was not the intention of this research, the USA least cost feed formulation notably had a GWP, FWEP, MEP, TAP and ALU that was 68%, 37%, 46%, 32% and 39% lower per kg than the UK least cost feed diet formulation respectively. From this contrast it might be expected that the UK would show more potential for environmental improvement via feed formulation.

As the LCA model itself contained only linear relationships, a simple analysis that tested parameters on an individual basis was suitable for identifying the inputs to which the environmental impact categories were most sensitive. Based on the inputs of the Least cost diets, the sensitivity analysis identified 13 parameters for each region in the model containing uncertainty that affected the results for any impact category greater than ±5%. Of these, 7 and 8 variables were associated with the assumptions made as part of the manure model in the UK and USA respectively. In both regions the FWEP was sensitive to P replacement rates of equivalent synthetic fertiliser and the level of $PO_4$ emissions. MEP was sensitive to $NO_3$ leaching in both regions and bird N retention levels in the USA only. TAP was sensitive to $NH_3$ emissions, N retention in the birds and N replacement rates of equivalent synthetic fertiliser in both regions. The N in the litter could replace synthetic N fertiliser (i.e. ammonium nitrate) by a maximum of 80%. This was to account for the over application to fields that often occurs with poultry litter (Williams et al., 2006). The on-farm energy use in both regions were assigned relatively high levels of variability due to the approximate nature of the energy use values available (Pelletier, 2008, Leinonen et al., 2012, Dunkley et al., 2015, University of Arkansas, 2016). Despite this only the NREU in the UK was sensitive to gas consumption; this is because systems in this region require more gas for maintaining the temperature of the growing facilities for best broiler growth rates. No impact category was sensitive to mortality despite it showing high levels of variability in both regions, this is due to most of the mortality being witnessed in the starter phase, when very little feed had been consumed. In both regions every impact category was sensitive to the assumptions made for FCR.

The methodologies that defined the housing and storage parts of the manure model were kept consistent between the two regions. However, in reality, housing emissions reported in LCAs of USA poultry systems (Coufal et al., 2006, Moore et al., 2011) have been consistently higher, and the emissions arising from storage lower, than those reported in the LCAs of UK poultry systems (Demmers et al., 1999, Robertson et al., 2002, Webb and Misselbrook, 2004, Misselbrook et al., 2010). For instance, in the USA more $NH_3$ is released at the housing stage. This could be due to differences in measurement methodologies or in-house litter management practices; in the EU it is standard practice that litter be completely removed after each flock (Compassion in World Farming, 2013). However, in the USA it has been reported that only one third of contracts state this as a requirement, with about a quarter of growing facilities not being fully cleaned out over the course of a year (MacDonald, 2008). Recycling more litter would result in higher $NH_3$ emissions at the housing stage and result in less N reaching the storage stage, thus less $NH_3$ volatilization and leach from the storage process. The only environmental impact category that was sensitive to using USA emission factors in the manure model was TAP when both methodologies were compared in a Least cost diet formation. Reformulating the USA Least TAP diet using the USA specific manure model reduced the inclusion of maize and fish meal, whilst the inclusion of soybean derivatives and synthetic amino acids were increased, when compared with the USA Least TAP diet formulated using UK housing and storage emission values. The only environmental impact category that was sensitive to this change was the ALU, which was 6% higher when USA specific emission factors were applied to the Least TAP diet.

Diets were formulated that aimed to reduce one environmental impact category value at a time. The environmental impact values for each diet were calculated holistically using LCA, and were the sum of the total environmental impact of the provision of the feed ingredients and the management of the manure associated with such a diet. In most cases, diets formulated for the USA system increased at least three impact categories significantly when compared with the Least cost diet. The UK on the other hand showed more potential: in most cases at least three impact categories were reduced by targeting one specifically, with the Least GWP diet being the only exception in this case. Surprisingly, the least environmental impact diets forced the inclusion of some alternative cereals in both regions that would not be routinely incorporated into least cost formulations. For instance, maize was incorporated into the UK Least MEP, TAP and ALU diets. This is because wheat has a greater associated MEP impact value than maize. Although maize has a slightly higher TAP and ALU value than wheat in the UK (Table 3.1), it was included in the UK Least TAP diet as a trade-off for meeting bird nutritional requirements with a lower inclusion of other high TAP and ALU ingredients, such as soy oil.

The UK broiler production system was associated with a much greater GWP than the USA system. This is because in European livestock systems, including the one modelled in this study, the majority of soymeal used in animal feed is imported from South America (Kebreab et al., 2016). This is associated with recent land use change, such as deforestation, which results in the release of carbon deposits from carbon sinks (Leinonen et al., 2012). In the UK, the GWP associated with broiler feed production was reduced considerably in the Least GWP diet by incorporating protein sources which have a lower embedded $CO_2$ equiv burden associated with them than soy, namely sunflower meal and field peas; furthermore, vegetable oil was used instead of soy oil in this diet (Leinonen et al., 2013). This has been addressed in Chapter 5, where novel protein alternatives to soybeans are considered.

In contrast, 100% of the soybeans used in the USA system are grown domestically and not associated with land use change. Despite this, the USA utilised less soybeans as a protein source, even with maize having a lower protein content, because more protein could be incorporated in the form of animal co-products, banned in poultry feed in the EU since the mid-1990s (Brookes, 2001). GWP was minimised in the USA by including barley, which is a cereal associated with a low GWP and NREU but a high MEP when compared with maize, and removing DDGS corn, a product with moderately high GWP. Minimising GWP through diet formulation in the USA significantly increased FWEP, MEP, TAP and ALU compared with the Least cost diet. It is important to acknowledge this when attempting to target GWP only, particularly with regards to the USA system which showed high significant increases in other impact categories with only a small reduction in the GWP (Figure 3.4), as this impact category is often paid the most attention; e.g. in corporate social responsibility reporting or participation in voluntary carbon labelling schemes (Tan et al., 2014). Wheat was used as the primary energy crop in the USA Least FWEP diet due to its lower associated P emissions compared with maize; this diet had an increased MEP relative to all other diet formulations due to wheat's higher MEP. The diet formulated for least NREU in the USA was similar to that formulated for Least GWP, in that barley was incorporated and maize was halved when compared with the USA Least cost diet formulation.

Optimization methodologies, such as the one developed here, have been used in the past to reduce feed cost and total P content in pig systems based on traditional least-cost formulation programs (dit Bailleul et al., 2001, Pomar et al., 2007). The model developed in this study was similar in structure to that developed by Mackenzie et al. (2016a) for Canadian pig systems. Although poultry diet formulation for reduced environmental impacts has recently been attempted for Europe and North America by Kebreab et al. (2016), the novelty of the methodology applied here is that the diets formulated were the output of the model. In their study Kebreab et al. (2016) used LCA to demonstrate that increasing the inclusion of specialty ingredients, such as synthetic amino acids, could reduce the GWP, EP and AP of production when compared with a basal diet; the basal diet was formulated for methionine as the first limiting nutrient and contained no synthetic amino acids. In contrast, in the study presented in this chapter the Least cost diets, to which all the other diets were compared (Figures 3.3 and 3.4), were formulated to meet the requirements of the birds using the same rules as every diet formulated to target specific environmental impact categories. Finally, through development of the manure model element of the tool, the methodological challenge of prospectively accounting for the aggregated environmental impacts caused by N, P and K excretion when formulating diets for environmental impact objectives has been overcome. In this way, comparisons of the least environmentally impacting diets to the Least cost diets in each region were realistic and allow nutritionists and livestock producers alike to easily integrate environmental objectives into current feeding strategies. Although this might seem an obvious point to make, the methodology has not been universally respected.

The least environmental impact diets had an axiomatic increased cost when compared with the Least cost diets; in most cases this increase was considerable with the exception of NREU in the UK. Two diets had an increased cost of 30%, the upper limit; these were the Least ALU diet in the UK and the Least FWEP diet in the USA. For every other diet formulated for environmental impact objectives the cost limit was not reached; in these cases, it was not cost which prevented further reduction in the environmental impact, these were the maximum reductions possible for those impact categories given the systems considered. In several other cases the increase was close to the limit, e.g. the UK Least MEP, the USA least NREU and the USA Least ALU. Although the limit was set arbitrarily it would be unrealistic to consider higher increases in diet costs when the business must consider its bottom line (Elkington, 1997, Mackenzie et al., 2016a).

It was not possible in either region to minimise one impact category through diet formulation without increasing at least one other impact category. Although the tool, as described in the methodology of this chapter, was not able to formulate a diet that would have reduced environmental impact values for some categories without increasing others, adding post hoc constraints to the tool could do so. For instance, this could be achieved by constraining the maximum TAP increase from the UK Least cost diet to zero when formulating the UK Least FWEP diet. This diet would be 21% more expensive than the least cost formulation, but would reduce the GWP (by 0.13%), FWEP (by 33%), MEP (by 5.6%) and ALU (by 44%) when compared with the UK Least cost diet. This diet would have an unchanged TAP value and would not significantly affect the NREU value compared with the UK Least cost diet. Similarly, if the UK least NREU diet was formulated, whilst the MEP and TAP were constrained so that they may not increase above the levels they were at in the Least cost diet, a diet could be formulated that would decrease the FWEP (by 22%), TAP (by 2.2%) and ALU (by 19%) compared with the Least cost diet; the GWP would be insignificantly increased. This diet would cost 2.1% more than the Least cost diet. By comparison, the potential of such a diet formulation tool, which incorporated post hoc constraints, for environmental impact reduction in the USA was relatively limited. This shows that it would be possible to reduce several impact categories without simultaneously increasing others significantly in the UK; however, the USA has less room for environmental impact improvement. There is currently discussion on how to account for multiple environmental impact categories at the same time (Soares et al., 2006, Finnveden et al., 2009, Mackenzie et al., 2016a). Further development of the diet formulation model, to integrate a multiple criteria decision-making approach for formulating broiler diets, would enable multiple environmental impact objectives to be considered to help resolve this issue.

Finally, the social implications of formulating diets for least specific environmental impacts were assessed. Along the supply chain for chicken production, different groups of workers were affected. Whereas cereals were produced locally, the soybeans and soybean derivatives imported into Europe placed workers at greater risk of being impacted by land grabbing, forced labour, disrespect of indigenous rights and health impacts caused by pesticides (Neugebauer et al., 2014). Hence, the UK also showed more potential than the USA for reducing environmental impacts whilst not increasing the social risks associated with feed production. Certain ingredients were associated with high risks due to where they were assumed to be sourced, e.g. sunflower meal and sunflower oil were assumed to come from the Ukraine where conflict has severely affected socio-economic development in recent years (The World Bank, 2017). Since the UK Least GWP diet incorporated sunflower meal and sunflower oil, it was associated with the highest increases in social impacts. As discussed previously, such results are only indicative. When comparing two different, but equally performing systems in terms of risk for each process, the system with the lowest collective work hours associated with the functional unit will be shown to perform better. Similarly, if the efficiency of a system is improved, without changing the risk levels associated with the processes, then the social impact of that system will be reduced. One justification for this is that exposure to even low risk for a social impact indicator is still human exposure to risk associated with the functional unit. This has been addressed further in Chapter 6 (section 6.4.4).

## 3.6 Conclusion and Implications

Methodologies such as the one applied here, in which a cradle to farm gate LCA model was integrated into a diet formulation tool, can allow nutritionists and livestock producers to integrate environmental objectives into diet formulation, facilitating sustainable feeding strategies and management choices. For instance, it is clear that there is potential to reduce most environmental impact categories through diet formulation in the UK. For the results presented here, there was no way to minimise the impact of feed production for one impact category without adversely affecting another through diet formulation in the USA, therefore it might be reasonable to suggest a multifaceted approach that targets more than one impact category at a time. Depending on environmental impact objectives, consideration of the effect of diets beyond GWP might be something to take into account. For non-ruminant production systems there is increasing concern regarding the associated EP and AP impacts (FAO, 2016a). What this study emphasises clearly is that targeting GWP only is not necessarily a sustainable solution to mitigating the environmental impact or the social impact of the poultry industry. Targeting GWP without taking other environmental impact categories into account can inadvertently be detrimental to environmental objectives. A multi-criteria approach to diet formulation methodologies which accounts for both environmental impact and economic constraints, such as the one presented here, will be crucial in efforts to improve the sustainability of livestock systems.

# Chapter 4. Artificial selection for improved energy efficiency is reaching its limits in broiler chickens

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## 4.1 Abstract

The reduction in the amount of time a broiler requires to reach a specific LW in recent decades has been considerable. However, continuing artificial selection for both efficiency and rapid growth will be subject to both biological limits and animal welfare concerns. Using a novel analytical energy flow modelling approach, how far such selection can go was predicted, given the biological limits of bird energy intake and partitioning of the energy. It was found that the biological potential for further improvements in efficiency, and hence environmental impact reduction, is minimal relative to past progress already made via artificial selection. An alternative breeding strategy to produce birds that grow more slowly to meet new welfare standards increases environmental burdens, compared with current birds. This unique analytic approach provides biologically sound guidelines for strategic planning of sustainable broiler production.

## 4.2 Introduction

Livestock production systems have a considerable impact on the environment (Steinfeld et al., 2006). However, amongst different livestock systems, chicken meat production has been found to have relatively low environmental impacts per kg of meat (Williams et al., 2006, De Vries and De Boer, 2009). This is in part due to artificial selection over the recent decades, aiming for increased energy use efficiency and faster growth rates (Laughlin, 2007, Mussini, 2012, Zuidhof et al., 2014). As a result of increased growth rate, the birds reach their slaughter weight earlier than ever before. As discussed in Chapter 2, this has reduced the resource use of the bird, mainly because during the shorter growth cycle less energy is now needed to maintain the body functions (Emmans, 1994, Tallentire et al., 2016). This improved energy use efficiency has considerably reduced the feed consumption of the birds and therefore improved the environmental sustainability of broiler production per unit of meat production.

The worldwide demand for chicken meat continues to grow substantially (Alexandratos and Bruinsma, 2012); this is in part due to associated health claims, lack of cultural limitations on its consumption, the efficiency at which it is produced and human population growth (Magdelaine et al., 2008, European Commission, 2017b). The key questions are: how will this predicted increase in chicken meat production be achieved, and what will be the consequences of this change on the sustainability of the production system? The poultry industry is confident that further improvements in growth rate and resource use efficiency can be achieved via genetic selection into the foreseeable future (Defra, 2008, Hill, 2008, Muir et al., 2008, Leinonen and Kyriazakis, 2016, Leinonen et al., 2016). However, these predictions are not substantiated with biological evidence in the scientific literature, with some suggesting that growth rate will soon reach a maximum biological threshold that may be insurmountable with conventional breeding (Pollock, 1999, Albers et al., 2006, MacRae et al., 2006, Gous, 2010). Industry data suggest that the actual rate of annual improvement in daily weight gain of birds has begun to decrease in recent years (Aviagen, 2007b, Laughlin, 2007, Mussini, 2012, 2014c). This may be partly explained by the changing objectives of artificial selection. Consumer concerns about the welfare of fast-growing chickens (Clark et al., 2016, 2017) and their meat quality (Kuttappan et al., 2012, Kuttappan et al., 2013, Petracci et al., 2015, Kuttappan et al., 2016), for instance, may have shifted selection pressures away from increasing growth rate in favour of other traits (RSPCA, 2008, 2015, Compassion in World

Farming, 2017), e.g. robustness, reproduction and adaptability (Neeteson-van Nieuwenhoven et al., 2013). On the other hand, selection for increased growth rate will ultimately be subject to limitations dictated by the biology of the bird and, as a matter of course, a plateau will inevitably be reached. Such biological limits have not generally been considered by the poultry industry, when making predictions on the potential and the consequences of further genetic improvements of the birds in the future.

The growth of an animal is ultimately driven by the following thermodynamic processes: 1) energy (feed) intake; 2) transfer of the energy to the metabolic system (digestion); 3) loss of energy in metabolic heat production and; 4) partitioning the chemical energy within the body. For this study a modelling framework was constructed based on evidence of the apparent biological limit of each of these processes to systematically analyse the potential for breeding for increased efficiency and concomitant changes in the associated environmental burdens. The environmental burdens considered were the GHG emissions, used to determine the GWP, ALU associated with feed production and the excretion of N and P; each of these indicators has potential implications on environmental impacts (e.g. global warming, eutrophication and acidification) and food security. The analysis presented in this chapter shows that the physical limits of the biological processes determining bird growth are likely to be reached much earlier than currently predicted by the poultry industry. As a result, the potential to improve the environmental sustainability of broiler production through further conventional artificial selection is limited. On the other hand, an alternative breeding strategy to produce slow-growing birds to meet expectations of improved animal welfare, via reducing growth rate so that slaughter weight is not reached until 56 days, will inevitably lead to increased resource use and therefore higher environmental burdens.

## 4.3 Methods

### *4.3.1 Energy flow model*

The energy flow through the chicken body was described using a simple analytical model consisting of the following thermodynamic processes: 1) energy intake in the form of feed; 2) transfer of the energy to metabolic systems, i.e. making a proportion of the combustible energy of feed utilizable in metabolic processes through the process of digestion; 3) loss of energy in metabolic heat production, including all life-sustaining biochemical transformations within the cells, such as those related to physical activity, protein turnover and the maintenance of energetically expensive systems and; 4) partitioning the chemical energy within the body, i.e. storing the energy in the form of lipid and protein (Figure 2.2).

If the energy use efficiency is to increase further, and consequently the environmental impact of broiler systems is to reduce through reduced resource use, this will be achieved through changes in the above processes. Hence, the biological limits of efficiency were assessed with an analytical energy flow model, which was used to predict possible future broiler growth trends based on the apparent biological limits of these processes incorporated into the model.

The structure of the energy flow model was as follows (Figure 2.2): The “gross” energy intake (GEI) equated to the total combustion energy in the feed consumed by the bird. Increasing feed intake towards the bird’s apparent intake capacity axiomatically increases the GEI rate (GER; MJ $d^{-1}$). A proportion of this energy is not utilised by the bird and is lost in the excreta. The net energy intake which is available to the bird is hence referred to as the ME intake. The MER (MJ $d^{-1}$) was thus determined by the coefficient of digestive efficiency ($D_{efficiency}$); increased digestive efficiency will increase the amount of the GEI that can be utilised by the bird and therefore increase the energy use efficiency (Equation 2). The ME must then be distributed between what is stored, as protein and lipids, and what is lost as heat. The chemical energy retained in the body as protein and lipid can be quantified based on their heats of combustion, i.e. 23.8 and 39.6 MJ $kg^{-1}$ respectively (Boekholt et al., 1994, Emmans, 1994). The overall fat-free body composition (i.e. water, protein and minerals) can be approximated based on allometric relationships (Gous et al., 1999), and as a result, the combustion energy content of the body for birds with a certain body weight and a given fat content can be calculated. Since less chemical energy is stored in fat-free body components compared with lipid, the energy that is taken in can be used more efficiently for weight gain when leanness is increased. Energy is lost as heat through the metabolic processes related to lean and fat body growth, as well as other metabolic pathways, such as those essential processes for maintaining normal bodily functioning. Thus, the total energy lost as heat is the ME intake minus the energy stored by the body in protein and lipids and is accounted for by the coefficient for the MHR, which can be calculated on the basis of the total energy intake and the composition of the total LW (Gouveia et al., 2009).

**Equation 2**)

$$
\begin{aligned}
MER\ [\mathrm{MJ\ d^{-1}}] &= GER\ [\mathrm{MJ\ d^{-1}}] * D_{efficiency} \\
&= (23.8\ [\mathrm{MJ\ kg^{-1}}] * \Delta Protein[\mathrm{kg\ d^{-1}}]) \\
&\quad + (39.6\ [\mathrm{MJ\ kg^{-1}}] * \Delta Lipid[\mathrm{kg\ d^{-1}}]) + (MHR\ [\mathrm{MJ\ kg^{-1}d^{-1}}] * LW\ [\mathrm{kg}])
\end{aligned}
$$

Where:

$MER$ = Metabolizable energy intake rate;

$GER$ = Gross energy intake rate;

$D_{efficiency}$ = Coefficient of digestive efficiency;

$MHR$ = Rate of metabolic heat production;

$LW$ = Live weight;

$\Delta Protein$ and $\Delta Lipid$ = The daily increase of the protein and lipid mass, respectively.

To determine the coefficients $D_{\mathrm{efficiency}}$ and MHR, the available literature on the energy use efficiency of the current broiler breeds, and the trends of their genetic changes over the recent decades, were comprehensively reviewed in Chapter 2 (Tallentire et al., 2016). Based on this analysis, the values of these constants were specified for the current, fast-growing birds and any possible changes in the current values compared with the historic data could be identified. If no past trends in these coefficients were found, it was expected that they cannot be affected by artificial selection and will therefore remain unchanged also in the future breeding programmes.

### *4.3.2 Daily feed intake and growth*

Literature on feeding experiments, where the birds were forced to increase their feed intake, was used to determine their maximum daily feed intake capacity. This was then converted to GER, assuming that the composition of feed will remain unchanged (i.e. the production would be based on high-energy concentrate feed). The relationship between LW and the average daily feed intake for a current fast-growing bird was then quantified using a nonlinear curve (Aviagen, 2014c, Cobb, 2014) (Figure 4.1). This relationship is linear between 0.3 kg LW and the average slaughter weight of standard indoor broilers, i.e. 2.2 kg (Defra, 2014b), therefore the potential feed intake each day beyond 0.3 kg LW was derived from the regression line equation for the maximum average daily feed intake limit each day presented in the literature (Leeson et al., 1996b). As an outcome of this analysis, the daily LW gain for the birds resulting from future breeding scenarios was calculated using Equation 2, with the expected values of GEI, $D_{efficiency}$ and MHR, and ΔProtein and ΔLipid, based on the expected changes in the body composition.

### *4.3.3 Future broiler production scenarios*

Two potential broiler breeding scenarios were addressed in this study. The first was based on the continuation of artificial selection for increased energy use efficiency, as applied to current fast-growing breeds reared commercially (Aviagen, 2014c, Cobb, 2014). The performance of broilers subjected to further selection for increased energy use efficiency was calculated based on evidence of current genetic trends and apparent biological limits in the underlying biology (Tallentire et al., 2016). In order to improve the energy use efficiency and increase the growth rate of the breed further, the apparent biological limit of feed intake was applied to the current genotype, and the potential of the other energy flow processes (digestive efficiency, body composition and MHR) were changed to their apparent biological limits to facilitate this breeding strategy's objectives. Finally, using the model shown in Equation 2, the growth rate of the bird produced as an outcome of this scenario was specified, and the time and energy intake needed to reach the 2.2 kg slaughter weight was calculated.

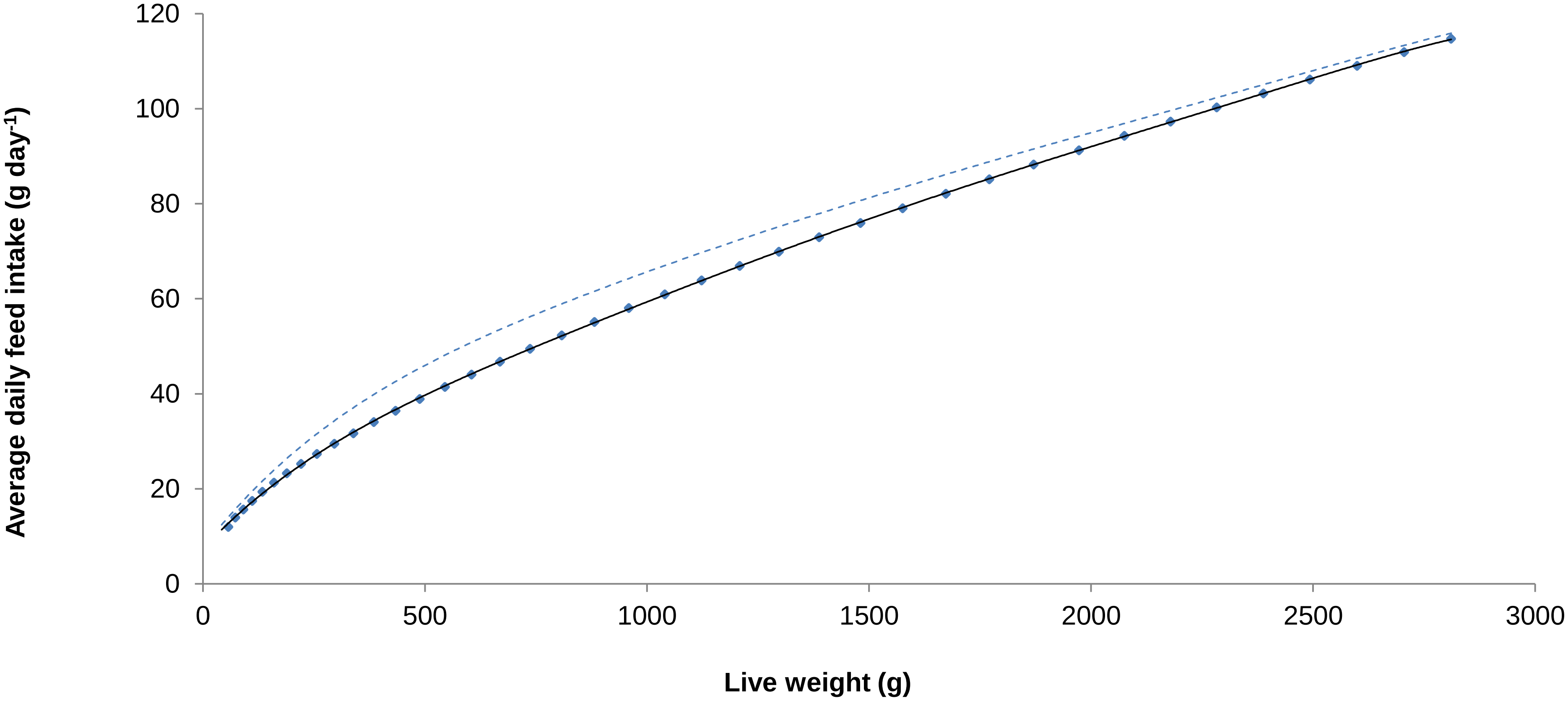

**Figure 4.1**: The average daily feed intake of a current fast-growing broiler (◆) and the potential average daily feed intake defined by the apparent biological limit of feed intake (broken line). Based on the data presented by Leeson et al. (1996b).

In an alternative future breeding scenario, the growth rate of the birds was reduced according to proposed welfare standards. In order to meet the requirement of this, birds must be selected so that they reach slaughter weight no sooner than in 56 days (Neilson, 2016, van der Aar et al., 2016); this is also the minimum slaughter age currently required in free range chickens (RSPCA, 2013). It is reasonable to assume, however, that for economic reasons the breeders will try to produce the most efficient birds possible within the limits of the welfare standard envelope, as well as the biological limits, via placing selective pressure on other traits than growth, i.e. body composition. Therefore, for the future slow-growing birds, the following scenario was applied: 1) the body fat content was reduced to its apparent biological limit; 2) the age when the slaughter weight is reached was set to be 56 days; 3) for other constants in Equation 2, the same procedure was applied as for the increased energy use efficiency scenario and; 4) finally, Equation 2 was used to calculate the energy intake of the birds needed to reach a slaughter weight of 2.2 kg with a growth rate specified by the welfare standards. Hence, due to different selection strategy objectives, this procedure differed from that used in the scenario for the increased energy use efficiency, where the rate of energy intake was specified according to biological limits of the bird only.

For the purpose of this study, the composition of the broiler feed was represented by two alternative feeding programmes (Table 4.1). The first was based on the standard nutritional recommendations for current fast-growing birds (Aviagen, 2014b, Cobb, 2014); this feed had an average energy and crude protein content of 13.2 MJ kg$^{-1}$ and 21% respectively. It was presumed to be fed to birds representing both of the future breeding scenarios; this was done in order to show the environmental implications of the artificial selection only. The second feeding programme was based on current nutritional specifications recommended for current slow-growing birds (Aviagen, 2016); this “alternative feed” had a lower crude protein content (19.6%) when compared with the standard feed and was fed to the increased welfare breeding scenario only (Table 4.1). The compositions of both the feeds were formulated using a least cost formulation method, on the basis of current UK ingredient prices (Tallentire et al., 2017). The feeds used in this study were, therefore, expected to be typical of current UK broiler production as a case in point for European systems. The primary energy ingredient of both feeds was wheat, whilst the main source of protein was provided by soymeal, which is mainly imported to Europe from South America (Kebreab et al., 2016).

**Table 4.1**: Least cost broiler feed formulations, and their corresponding nutrient contents, typical of European production systems. The standard feed is formulated specifically for the requirements of current fast-growing broilers. The alternative feed is formulated specifically for slower growing birds.

| **Ingredient** | **Standard feed** | **Alternative feed** |
|---|---|---|
| Wheat (%) | 47.9 | 51.2 |
| Rapeseed (%) | 6.7 | 7.1 |
| Field peas (%) | 12.3 | 13.2 |
| Soymeal (%) | 24.6 | 21.0 |
| Soy Oil (%) | 4.3 | 4.1 |
| Minor ingredients and additives (%) | 4.2 | 3.4 |
| **Nutrient content** | | |
| Metabolizable Energy (MJ kg$^{-1}$) | 13.2 | 13.2 |
| Crude Protein (%) | 21.0 | 19.6 |
| Digestible Lysine (%) | 1.09 | 1.00 |
| Digestible Methionine (%) | 0.54 | 0.48 |
| Digestible Methionine + Cystine (%) | 0.84 | 0.77 |
| Digestible Threonine (%) | 0.73 | 0.67 |
| Digestible Valine (%) | 0.83 | 0.77 |
| Digestible Isoleucine (%) | 0.75 | 0.69 |
| Digestible Arginine (%) | 1.23 | 1.14 |
| Digestible Tryptophan (%) | 0.22 | 0.21 |
| Digestible Leucine (%) | 1.34 | 1.22 |
| Available Phosphorus (%) | 0.42 | 0.37 |
| Potassium (%) | 0.88 | 0.83 |
| Calcium (%) | 0.83 | 0.74 |
| Chloride (%) | 0.23 | 0.23 |
| Magnesium (%) | 0.17 | 0.17 |
| Sodium (%) | 0.16 | 0.16 |

### *4.3.4 Environmental indicators*

Energy provision (in the form of feed) represents the poultry industry's greatest environmental hotspot (Leinonen et al., 2012, Tallentire et al., 2017), hence the environmental indicators considered include inputs and outputs related to producing the feed required by one broiler bird to achieve a slaughter LW of 2.2 kg (Defra, 2014b). The methodology that was applied to calculate the environmental burdens of the feed was based on the ELCA framework discussed in Chapter 3 (Figure 4.2). Hence, all upstream processes associated with feed production, such as resource inputs to fertiliser production and the emissions that arise as a result of their application to fields, as well as the energy inputs to processing and transport of ingredients, were based on current practices.

For the purpose of this study, the differences in the most relevant feed-related environmental indicators of broiler production were quantified. As such the environmental burdens of GHG emissions, measured in $CO_2$ equiv with a 100-year timescale, and the ALU ($m^2$), both associated with the feed provision, were calculated. The main agricultural sources of GHG are nitrous oxide ($N_2O$) together with $CO_2$ from fossil fuel and $CH_4$, although non-ruminant species produce negligible amounts of enteric $CH_4$ (Williams et al., 2006). GHG emissions were used to determine the GWP. 1 kg of $CH_4$ and $N_2O$ emitted was considered to be equivalent to 25 and 298 kg of $CO_2$ respectively (IPCC, 2006). The $CO_2$ released due to land transformation was included following the PAS2050:2012-1 methodology (BSI, 2012). The emission data for feed ingredients were based on national inventory reports, SimaPro databases and literature collated for the study discussed in Chapter 3 (Tallentire et al., 2017).

The excretion of the environmentally important nutrients N and P were also considered as environmental indicators. Although the manure containing these nutrients can be used in the place of synthetic fertilisers (especially important in organic farming), excess of nutrients is associated with acidification and localised eutrophication, whilst N is responsible for the $NH_3$ emissions at housing, manure storage and field spreading (IPCC, 2006). The N and P deposition in manure were calculated using the mass balance principle; the nutrients retained in the broiler's body were subtracted from the total N and P supplied in the feed.

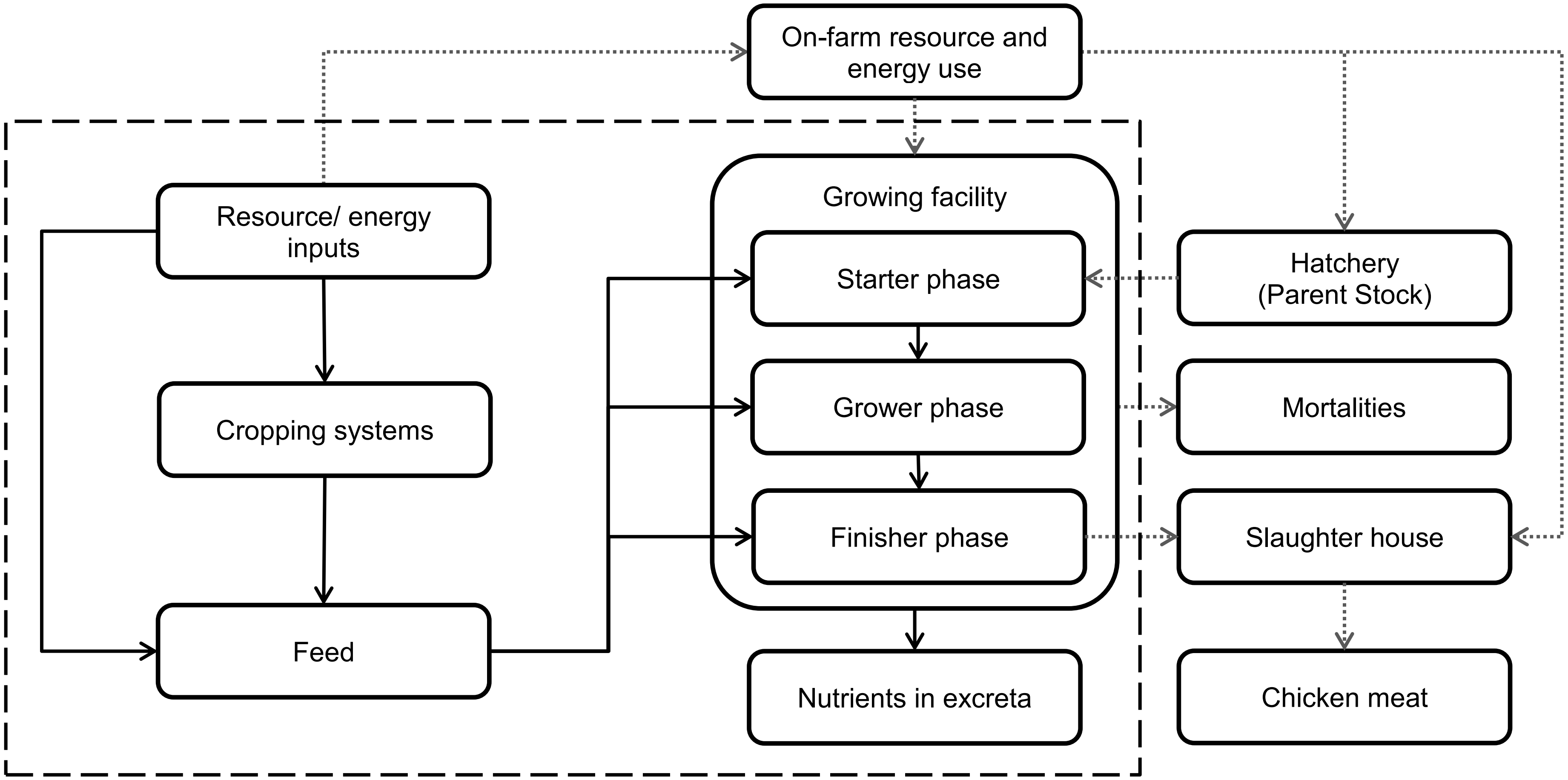

**Figure 4.2**: The structure and main components of the broiler production systems as considered by the Environmental Life Cycle Assessment (ELCA) model; the inputs that were considered (solid line arrows), the inputs that were not considered (dotted line arrows) and the system boundary (dashed line) of the model (adapted from Figure 3.1).

## 4.4 Results

### *4.4.1 Limits of feed intake.*

In order to increase broiler growth rate, and therefore increase the energy use efficiency towards the biological limit, the daily ME intake must be increased to facilitate growth (Equation 2). This can be achieved by increasing the daily feed intake and this has actually been the trend in commercial broiler breeding over recent decades (Siegel and Wisman, 1966, Pym and Nicholls, 1979, Havenstein et al., 2003a, 2003b, Schmidt et al., 2009). In practice, this means that the birds must eat increasingly higher amounts at an increasingly younger age, which is biologically challenging.

Ultimately, the maximum feed intake would be limited by the capacity of the digestive system. Experiments where the energy density of the feed was reduced (so the birds are forced to increase their feed intake) provide data on the fast-growing broiler feed intake limit (Leeson et al., 1996b, Linares and Huang, 2010, Pauwels et al., 2015). The highest potential feed intake shown in literature was presented by Leeson et al. (1996b). In that study, broilers increased their gross feed intake by a total of 25% upon reaching a LW of 2.8 kg on a low energy content feed when compared with a control group fed a high energy feed. The potential daily feed intake can therefore be determined from these data. As an outcome, the average daily feed intake at a LW of 1.0 kg and 2.8 kg could be increased by 10% and 1.1% respectively compared with current fast-growing birds (Aviagen, 2014c) (Figure 4.1). This indicates that younger birds have the greatest potential to increase feed intake which reduces as they approach slaughter weight (2.2 kg). Although much genetic progress has been achieved since the study of Leeson et al. (1996b), more recently Linares and Huang (2010) showed that the feed intake of current fast-growing broilers could be increased by a further 6% between day 10 and day 42 when fed on a low energy content feed, when this was compared with the feed intake of the birds placed on a high energy content feed. The limit to feed intake considered here is consistent with the latter study (Linares and Huang, 2010).

### *4.4.2 Limits of digestive efficiency*

In artificial selection programmes, emphasis has been placed on the growth of certain body parts, such as the breast muscles, in order to increase carcass yield (Havenstein et al., 2003a, Carré et al., 2008, Mussini, 2012). Consequently, the morphometries of the internal structures, in particular the organs that comprise the digestive system, have been shown to differ between high digestive efficiency genotypes and birds bred for high commercial performance (Péron et al., 2006), i.e. increased energy use efficiency. In modern fast-growing birds, digesta throughput each day has increased to facilitate growth. Despite this, there is no evidence that breeding for increased commercial performance has led to any change in overall digestive efficiency per unit mass of digesta (Tallentire et al., 2016); thus, selection pressures placed on increasing energy use efficiency and carcass yield at the very least must have conserved digestive efficiency whilst the size of the system has not increased at the same rate as other components of the body. Hence, the digestive efficiency as used in the energy flow model was expected to remain at its current level despite continuing selection for increasing energy use efficiency. Since the digestible energy content of the feed per unit mass does not appear to be substantially compromised by augmented throughput (Mussini, 2012, Tallentire et al., 2016), nor does it appear to be improved genetically via selection for increased energy use efficiency (Carré et al., 2005, Péron et al., 2006, Rougière and Carré, 2010), it follows that the ME available to the broiler will be limited only by the capacity of feed intake.

### *4.4.3 Potential changes in energy partitioning*

Broilers currently have a body protein and lipid content of around 20% and 8%, respectively, based on recent data presented by Mussini (2012). The abdominal fat pad constitutes about 2% of the body weight (Gaya et al., 2006, Grosso et al., 2010). Reducing this feature to zero (as an example of where further fat reduction may be achieved) would result in a bird with a body lipid content of around 6%. This value places the animal firmly at the lower end of the estimated biological limit for fatness (Emmans, 1987, Schiavon et al., 2007). Less energy is required to grow a leaner bird than a fatter bird at the same overall growth rate (Equation 2). Therefore, reducing the body lipid content to its minimum redirects a higher proportion of the ME into the growth of the fat-free body components, thus allowing the bird to reach slaughter weight faster. As a result, reducing the fat content from the current level to the apparent biological limit would reduce the necessary energy intake upon reaching slaughter by 1.7% (Table 4.2).

In Chapter 2 it was shown that, over recent decades, the MHR (MJ $kg^{-1}$ $d^{-1}$) of commercial broilers has either remained the same or been weakly positively correlated with the increase in growth rate (Tallentire et al., 2016), indicating that selection has not reduced the energy used for metabolic processes. Based on performance data for the current fast-growing birds (Aviagen, 2014c), the MHR was calculated to be 0.36 $kg^{-1}d^{-1}$. This same value was used to determine the energy distribution in the birds with maximum energy use efficiency, as a conservative estimate for the further change.

### *4.4.4 Predicted future broiler performance*

The average age modern fast-growing broiler breeds reach a LW of 2.2 kg (slaughter weight) is currently between 34 and 35 days of growth (Aviagen, 2014a, 2014c, Cobb, 2014). The outcome of this analysis shows that even if the broiler growth rate is increased to the apparent biological limit, this will result in birds that reach their slaughter weight only 1.2 days sooner (Figure 4.3). This results in an 8% reduction in the total feed energy intake of the bird upon reaching slaughter weight (Table 4.2).

The results shown above can be considered to represent a broiler bird with a maximum energy use efficiency (and maximum growth rate). In an alternative scenario, representing a slow-growing bird (resulting from a higher welfare breeding strategy where birds reach slaughter weight 23 days later than the current fast-growing bird), 5.7 MJ more energy per g of LW gain would be required to reach slaughter weight than is required by current fast-growing birds; that equates to 27% more total feed energy upon reaching slaughter than current fast-growing birds (Table 4.2).

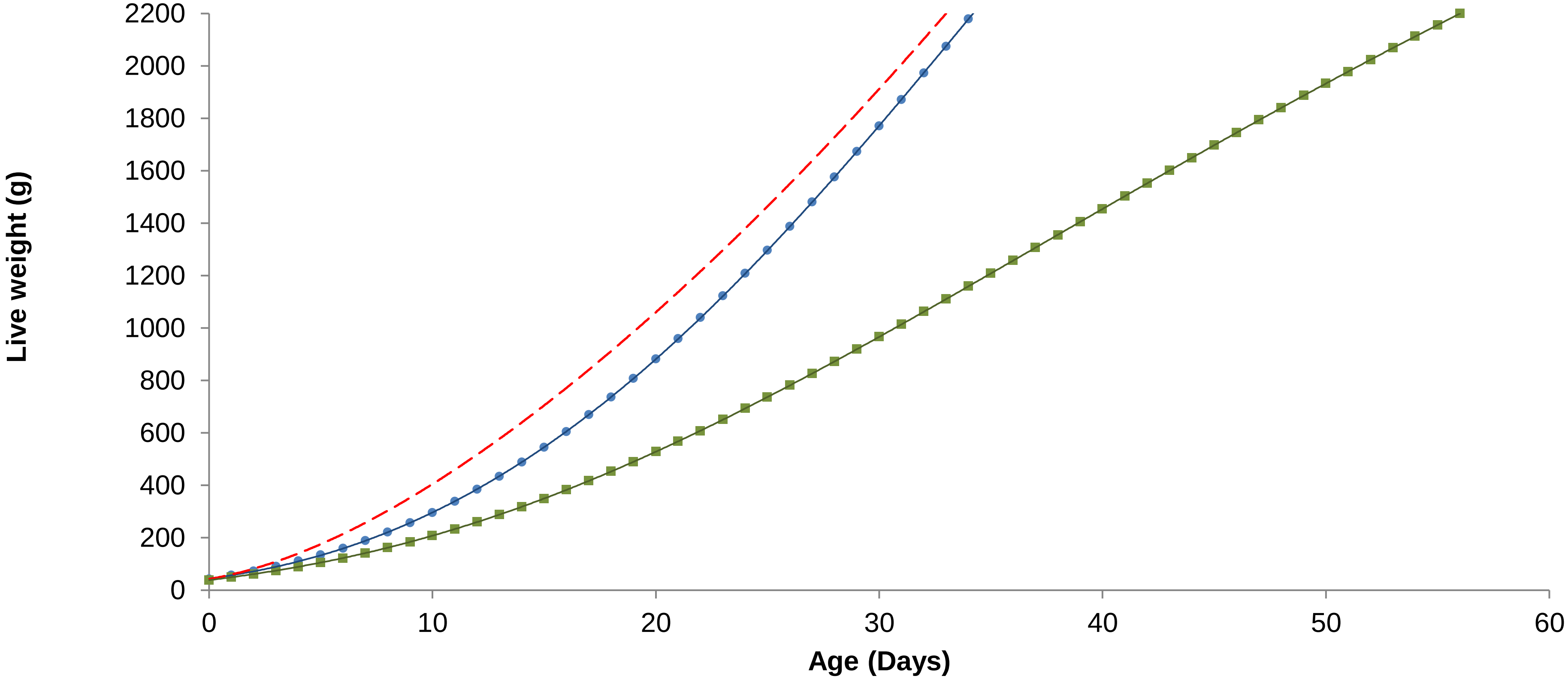

**Figure 4.3**: The growth rate of a current fast-growing broiler (●) and the potential growth rate of future birds as defined by the different scenarios assessed; maximum energy use efficiency (broken line) and increased welfare scenario (🟩).

**Table 4.2**: The effects of changing different processes of energy flow on the growth rate, total metabolizable energy (ME) intake and ME intake per unit mass of gain of a broiler grown to 2.2 kg. When changed, the feed intake and leanness are increased to their apparent biological limits.

| **Scenario** | **Age at 2.2 kg slaughter weight (days)** | **Growth rate (g day$^{-1}$)** | **Total ME intake (MJ)** | **ME intake per unit gain (kJ g$^{-1}$)** |
|---|---|---|---|---|
| Current fast-growing broiler | 34.2 | 63.1 | 45.9 | 21.3 |
| Increased feed intake only | 33.6 | 64.2 | 43.8 | 20.3 |
| Increased leanness only | 34.1 | 63.2 | 45.1 | 20.9 |
| Increased feed intake and leanness (maximum energy use efficiency breeding strategy) | 33.0 | 65.3 | 42.0 | 19.4 |
| Reduced growth rate and increased leanness (Increased welfare breeding strategy) | 57.0 | 38.6 | 58.3 | 27.0 |

### *4.4.5 Environmental impact assessment of future breeding scenarios*

The maximum energy use efficiency scenario showed slightly reduced environmental burdens compared with current fast-growing birds, whereas the opposite was true for the scenario aiming to produce increased welfare birds. The GWP (Figure 4.4a) and the ALU (Figure 4.4b) associated with feed production in the maximum energy use efficiency scenario were reduced by 8% when compared with current production. For the increased welfare scenario, both of these environmental indicators were increased by 27% when compared with current production on a standard feed. When an alternative feeding programme with a lower protein content was applied in the increased welfare scenario, GWP and ALU were increased by 16% and 24% respectively compared with current fast-growers reared on a standard feed (Figure 4.4).

The excretion of N and P were reduced by 23% and 15% respectively in the maximum energy use efficiency scenario compared with current production, whereas these nutrients were excreted in higher quantities in the increased welfare scenario: an increase of 64% and 50% in the total N and P excretion was shown compared with current production on a standard feeding programme (Figure 4.5). Applying the alternative feeding programme increased N and P excretion less than when the birds were raised on the standard feed, although this increase was still substantial (43% and 26% respectively).

Compared on a standard feeding programme with the maximum energy use efficiency scenario, the slow-growing birds (increased welfare scenario) were associated with 37% more GWP and ALU, along with a 115% and 77% increase in N and P excretion respectively. When the alternative feeding programme was applied, with reduced feed protein content, the difference between the environmental burdens of the two future breeds were reduced to 26%, 35%, 87% and 48% for GWP, ALU, N and P respectively.

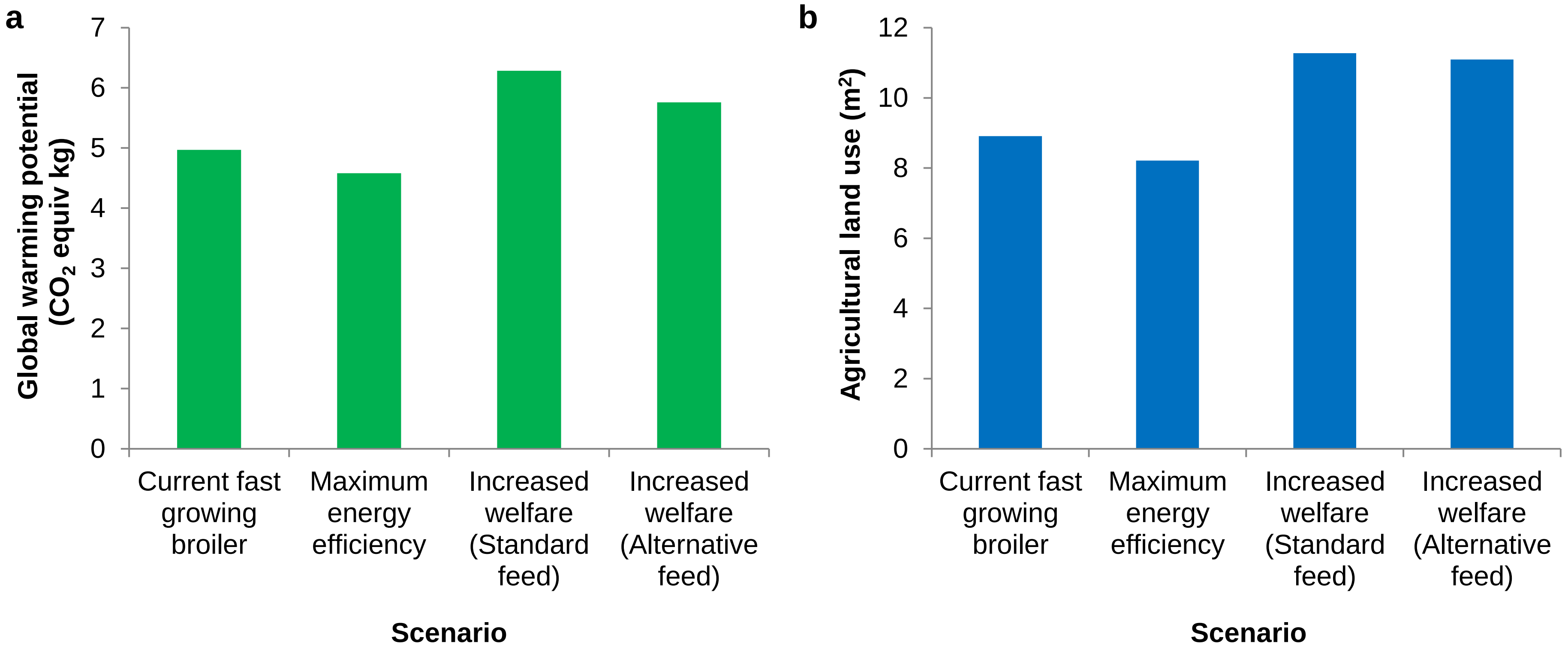

**Figure 4.4**: The environmental impact implications associated with feed provision for one broiler of each scenario grown to 2.2 kg. 3a shows global warming potential ($CO_2$ equiv) and 3b shows the agricultural land use ($m^2$). The following four scenarios are presented: current fast-growing birds, maximum energy use efficiency birds and slow-growing (increased welfare) birds placed on a standard feed, as well as the slow-growing (increased welfare) birds placed on an alternative feed formulated specifically for slow-growing birds.

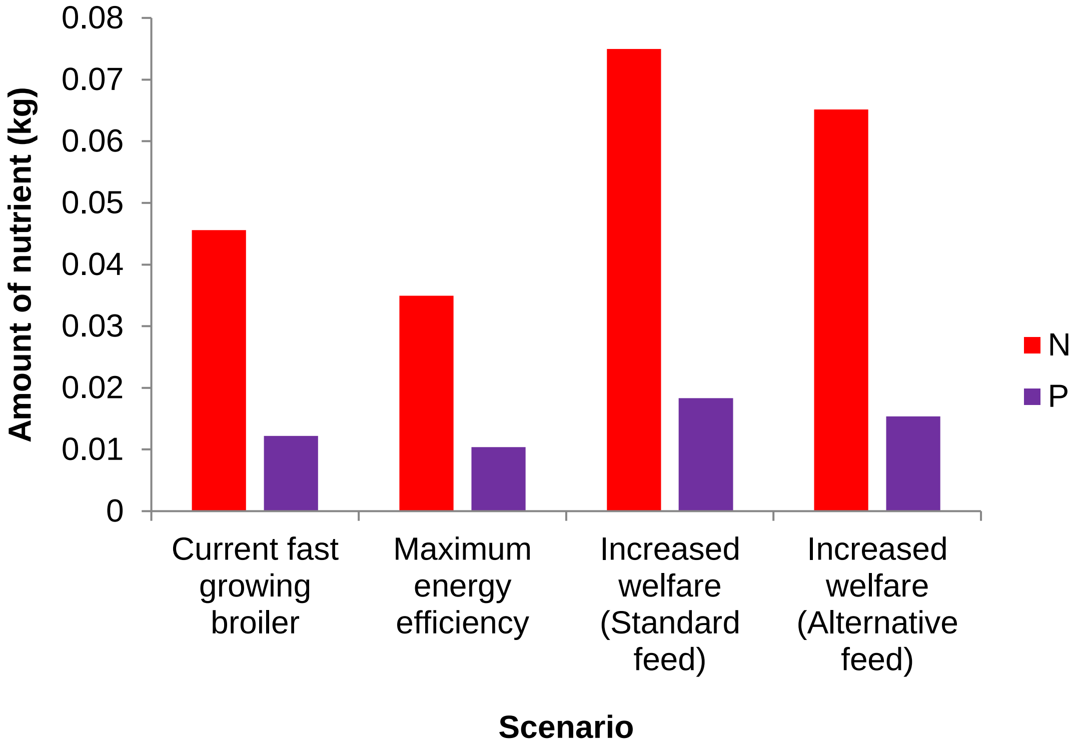

**Figure 4.5**: The nutrients (N and P) that are expected to be excreted when one broiler is raised to 2.2 kg slaughter weight. The following four scenarios are presented: current fast-growing birds, maximum energy use efficiency birds and slow-growing (increased welfare) birds placed on a standard feed, as well as the slow-growing (increased welfare) birds placed on an alternative feed formulated specifically for slow-growing birds.

## 4.5 Discussion

The results discussed in this chapter contrast with previous predictions (Defra, 2008, Leinonen et al., 2016) and indicate that the biological potential for further improvements in energy use efficiency of broiler production via conventional artificial selection is low. Of the energy flow processes determining growth, no evidence was found that either the digestive efficiency or the MHR have changed as a result of recent artificial selection in a way that could improve the energy use efficiency of the bird. In contrast, an earlier analysis shows that the MHR may have slightly increased (thus allowing less energy to be allocated to growth) during the recent decades (Tallentire et al., 2016). Therefore, the current analysis may even overestimate the energy use efficiency of the future bird. Overall, it would be very difficult to improve the bird energy use efficiency by changing the MHR through artificial selection. In practice, this would require producing less active birds that use less energy for physical movement. This direction in future artificial selection is not very likely, taking into account the animal welfare concerns.

Reducing the carcass fat allows more energy to be allocated to the growth of fat-free body components. As the energy density of these components (consisting mainly of water and protein), is much lower than that of fat, this allows the bird to be grown to a certain slaughter weight with lower energy intake. Although reducing the fat content of the body to its apparent minimum can improve the energy use efficiency of the bird, this effect is rather small (Table 4.2) because the fat content of the current broiler birds is already low. This is due to their young slaughter age, and probably also due to continued artificial selection during the recent decades (Fleming et al., 2007, Zuidhof et al., 2014). As a result, the only component of energy flow that can still substantially affect the bird growth and efficiency is the intake of energy. Therefore, the potential to increase the feed intake of the future bird largely determines the potential to increase its energy use efficiency. Obviously, there are physical and biological limits in this process; although increased feed intake inevitably facilitates faster growth, it should be kept in mind that faster growing birds are also getting younger at any specific LW, which sets limits on their feed intake capacity. Furthermore, the faster growth is largely allocated to certain parts of the body (e.g. breast muscle), and therefore the growth of the digestive system does not follow the increased growth of the bird as a whole (Tallentire et al., 2016). The potential of the increase in feed intake, as applied in this study, is based on the highest value found in literature for the current broiler bird (Leeson et al., 1996b). It cannot be stated with absolute certainty that the maximum intake capacity was reached in the study carried out by Leeson et al. (1996b) and therefore whether the maximum energy use efficiency bird represents the absolute maximum that is achievable. Increasing the feed intake beyond this value can facilitate even faster growth and more efficient birds, but there is no evidence in literature to indicate birds can increase feed intake beyond this level.

The results show that even if the full potential of increasing growth rate and energy use efficiency of the broiler birds is utilized, there is apparently very little room for improvement in the considered environmental sustainability indicators, relative to the total improvement in recent decades (Mussini, 2012, Zuidhof et al., 2014) and when compared with earlier predictions of further selection (Defra, 2008, Leinonen et al., 2016). For instance, when raised to a LW of 2.2 kg, a commercial broiler in 1978 could be estimated to be responsible for 25% more GWP and ALU associated with feed provision than a modern commercial fast-growing line (Zuidhof et al., 2014). In contrast, according to this study, the improvements still available to be made via artificial selection equate to only a further 8% reduction in GWP and ALU (Figure 4.4). However, since only the environmental burdens of growing one bird from each line to 2.2 kg was compared, no changes in the incidences of mortality or carcass quality (e.g. white striping, woody breast and green muscle disease), which can occur with increased growth rate and breast muscle yield were considered (Havenstein et al., 2003a, Bilgili and Hess, 2008, EFSA Panel on Animal Health and Welfare, 2010, Kuttappan et al., 2013, Kuttappan et al., 2016). The need to produce a higher number of birds to replace the rejected meat would result in increased environmental burdens.

It is widely acknowledged that many instances of bird ill-health are associated with fast growth rate, e.g. musculoskeletal disorders, myopathies and organ failures (Bessei, 2006, Fanatico et al., 2008, EFSA Panel on Animal Health and Welfare, 2010, Mikulski et al., 2011, Rodenburg and Turner, 2012, Meseret, 2016). Hence, 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 (Stichting Wakker Dier, 2012, RSPCA, 2013, Clarke, 2014, Jansen, 2014, Neilson, 2016). The alternative future breeding scenario presented in this study followed the recommendation of ‘welfare-friendly’ policies adopted by some businesses across Europe (Jansen, 2014). Such policies stipulate that chickens must have a reduced growth rate and live a minimum of 56 days (EFSA Panel on Animal Health and Welfare, 2010, Neilson, 2016). Growing this slow-growing line would result in a substantial increase of environmental burdens in every environmental indicator considered in this study due to its increased feed consumption. The difference in the environmental burdens between the two breeding scenarios was found to be slightly reduced when the slow-growing line was predicted to be fed the alternative feed, which had a reduced protein inclusion, instead of the standard feed. The alternative feed incorporated less soymeal, which is associated with high ALU relative to other crops (e.g. wheat and rapeseed) and high GHG emissions arising from land use change. The alternative feed also resulted in less N and P that would be excreted by the birds, as this diet matched the slow-growing birds’ nutritional requirements more closely than the standard feed. However, it should be noted that such an outcome is indicative only, as the future composition of the feed and the cultivation techniques of future feed crops are very difficult to predict.

This study demonstrates the apparent biological potential for environmental impact reduction in the poultry industry that is still available via conventional artificial selection of broiler chickens. However, it is possible that the resource inputs into the broiler growing facilities could change in the future due to technological advancements and policy (animal welfare). Such changes will have environmental impact implications. Furthermore, producing slow-growing birds will also change the amounts of other resources spent on them besides feed, e.g. energy needed for heating of the growing facility and to power ventilation, lights and feed dispensers. The scenarios described in this study may also produce differences in mortality rates (Havenstein et al., 2003a); in conventional broiler systems, the proportional environmental impact of bird mortality is currently very low (Leinonen et al., 2012) and is intrinsically linked to factors that may change in the future in order to optimise production efficiency or meet different welfare standards, such as stocking density (combined weight of birds allowed per floor area). Furthermore, despite there being no evidence that digestive efficiency can be increased via artificial selection for current performance objectives, the digestibility of feed ingredients could be increased in the future, e.g. via advancements in the understanding and application of exogenous enzymes and prebiotics (Pourabedin and Zhao, 2015). The increased growth rate of broilers can only be facilitated by feed with high inclusions of highly digestible protein. In Europe, imported soybean is incorporated as the main protein source in broiler feeds (Table 4.1). The GWP associated with chicken meat may therefore be mitigated in the future by incorporating protein alternatives to imported soybean, such as European grown soybean, microalgae or insect meal (van Krimpen et al., 2013). This has been discussed further in Chapter 5.

## 4.6 Conclusion and Implications

This study shows that the potential to increase the environmental sustainability of broiler production through artificial selection for higher energy use efficiency is low compared with what has been achieved in recent decades. It is the first time that the biological limits have been analytically considered and applied to predict the potential environmental consequences of breeding strategies in this way, despite the fact that there is a substantial interest in predicting the environmental impacts of future livestock scenarios (Besson et al., 2014, van Middelaar et al., 2014, 2016). These results raise important questions as to whether the magnitude of the potential can justify the continuation down the route of artificial selection towards maximum energy use efficiency, until the biological limits of the birds are reached. Such a breeding strategy may prove unsustainable for the industry considering the market shift in Europe in favour of slow-growing broilers. On the other hand, reducing the growth rate of the birds following the consumers’ expectations of increased bird welfare will unequivocally result in a less efficient bird with higher environmental impact than current fast-growers. Balancing these social, economic and environmental aspects of the sustainability of livestock production will continue to challenge the poultry industry in the foreseeable future. It is therefore in the poultry industry’s interest to continue to pay close attention to both consumer demands and their associated environmental impact implications.

# Chapter 5. Can novel ingredients replace soybeans and reduce the environmental burdens of future chicken meat production?

## 5.1 Abstract.

Much of the protein in the diets of European livestock is sourced from imported soybeans produced in the Americas. This protein deficit in livestock production presents a risk to social, economic and environmental progress in Europe. In this study the impact of incorporating novel ingredients into future chicken diet formulations to serve as European sourced alternatives to imported soybeans was investigated. The novel ingredients considered were: microalgae, macroalgae, duckweed, yeast protein concentrate, bacterial protein meal, leaf protein concentrate and insects. Using horizon scanning and a modelling approach, the nutritional requirements of two potential chicken meat-producing lines were simulated. The two chicken lines were a fast-growing line based on the apparent maximum feed efficiency that could be achieved through further conventional artificial selection, and a reduced growth rate for high welfare line. Diets were formulated to include the novel ingredients, whilst meeting the nutritional requirements of the birds. The effects of diet composition on indicators of environmental burdens, associated with feed production for the livestock industry, were then assessed. It was shown that soybean products can be completely replaced by novel feed ingredients, while reducing the greenhouse gas emissions and arable land requirements for feed provision relative to conventional diets formulated for both chicken lines. Switching from conventional diets to diets which incorporate novel ingredients was also shown to mitigate the increased environmental burdens associated with moving towards higher welfare livestock systems. Incorporation of novel ingredients in diet formulations offers a viable option for providing sustainable and nutritionally balanced livestock feed in the future and thus provides huge potential for facilitating bespoke feeding strategies and specific management choices for mitigating environmental impacts of chicken systems.

## 5.2 Introduction

Europe’s reliance on imported protein, particularly soybeans, to feed livestock is inconsistent with sustainability objectives (Leinonen et al., 2012, de Boer et al., 2014, de Visser et al., 2014, Kebreab et al., 2016). In Chapter 4, two future chicken lines were hypothesized, but what will these chickens eat? The poultry industry (meat-producing chickens, egg-laying hens, turkeys etc.) collectively consumes the most soybeans of any livestock sector in Europe (van Gelder et al., 2008). This protein requirement is set to increase further as the demand for chicken meat, in particular, continues to grow (Alexandratos and Bruinsma, 2012, FAO, 2016c). In addition, the inclusion of valuable conventional protein sources of animal origin in livestock feed are either limited (e.g. fishmeal) or banned (e.g. meat and bone meal) in the EU (Brookes, 2001, European Commission, 2001), whilst growing soybeans in Europe is non-competitive with imports due to relatively low yields and a long growing season (van Krimpen et al., 2013). Thus, the poultry industry is presented with the challenge of providing an adequate and more sustainable supply of protein to feed broiler chickens in Europe.

In seeking a long-term solution to this protein deficit, the following second or third generation protein sources were identified for future application in poultry diets: microalgae, macroalgae, duckweed, yeast protein concentrates (YPC), bacterial protein meal (BPM), leaf protein concentrate (LPC) and insect meal. All these novel ingredients are characterised by their potential to be cultivated in Europe and their low ALU requirement; each of the novel technologies that produce them is in a different phase of development. The novel ingredients were included individually (at a fixed inclusion level) and combined into mixtures of ingredients in alternative diet formulations.

The nutrient requirements of two future meat-producing chicken lines, which are likely to arise from breeding strategies with different objectives, were considered: a fast-growing and slow-growing line. The “fast-growing line” would be the result of the current, globally predominant selection strategy which is based on the continuation of artificial selection for increased energy use efficiency. The performance and therefore the energy and nutritional intake of the fast-growing birds can be calculated based on evidence of current genetic trends and apparent biological limits in their underlying biology, as was discussed in the previous chapter (Tallentire et al., 2018a). The “slow-growing line” would have a reduced growth rate according to higher welfare standards (Tallentire et al., 2018a), representing a market shift in response to growing societal concerns about animal welfare (EFSA Panel on Animal Health and Welfare, 2010, Clark et al., 2016, Clark et al., 2017).

Thus, the overall aim of this study was to assess the environmental implications of incorporating novel ingredients into the feeding strategy of future chicken meat production systems. The novel ingredient inventory was modelled in feeding scenarios, based on the nutritional requirements of future meat-producing chicken lines which were predicted in a previous study (Tallentire et al., 2018a). Whilst the environmental impacts of some of these novel ingredients have been assessed in the past (Jorquera et al., 2010, Oonincx and de Boer, 2012, e.g. Aitken et al., 2014, de Boer et al., 2014), this is the first time the environmental burdens of all seven ingredients have been calculated systematically by applying a common methodology and reported in contrast to the use of imported soybeans as the main protein source in chicken feed. A sensitivity analysis methodology developed in previous studies was also employed here to identify any substantial uncertainty in the projections (Mackenzie et al., 2015, Tallentire et al., 2017). This is the first study to demonstrate and compare the potential environmental trade-offs of incorporating novel ingredients into chicken meat production systems, whilst also accounting for the requirements of future genetic lines and their implications.

## 5.3 Methods

### *5.3.1 Goal, scope and model structure*

The goal of this study was to assess the environmental implications of replacing soybeans with novel ingredients in chicken feed formulations. From this analysis the most sustainable technologies were identified for use in livestock production; this information is crucial for nutritionists, livestock producers, breeders, policy makers and potential investors. The scope of the study was to propose potential diets, which incorporated novel protein sources, for future chicken meat production systems in Europe based on analysis of trends in recent genetic change and the apparent physical limits of the biological processes (Tallentire et al., 2018a), i.e. energy (feed) intake, digestion, metabolic heat production and chemical energy partitioning. To achieve this an ELCA methodology with an integrated diet formulation tool was used which was developed in Chapter 3 (Tallentire et al., 2017). The functional unit of this study was one bird grown to a LW of 2.2 kg, the average slaughter weight of broiler chickens in the UK (Defra, 2014b), raised in a standard European indoor system i.e. climate-controlled (e.g. fan-ventilated), artificially lit buildings.

The model inputs included: a detailed inventory of feed production (section 5.3.2), the total feed intake and body composition of future chicken lines, their nutritional requirements and the nutrient content of all ingredients included within the feed formulation calculation. The model structure can be summarised as follows: all diets were formulated for a fixed set of minimum nutritional requirements for the different growth phases modelled, i.e. the starter, grower and finisher phases. Two meat-producing lines were considered. Since the nutritional requirement of each line was met in every diet formulated, it was presumed that bird growth rate per kg of feed consumed was unaffected between different diets. The methodology for calculating the nutritional requirements of these two future meat-producing chicken lines has been discussed in section 5.3.3. Maximum and minimum limits constrained the inclusion of each ingredient in each diet to ensure that issues of palatability, inhibition of digestibility or variability in specific ingredients did not adversely affect bird performance i.e. growth rate or carcass composition. The methodology also assumed meat quality would not be adversely affected. Although some of the novel ingredients have been shown to have a positive effect on bird health (Qureshi et al., 1996, Pulz and Gross, 2004, Bovera et al., 2016) and performance (Shanmugapriya and Saravana Babu, 2014), this was not included within the scope of this study. Environmental burden values were assigned to each ingredient, conventional and novel, in order to determine the environmental implications of formulating each diet for future chicken meat production. Finally, the environmentally important nutrients excreted by the bird were calculated based on mass balance.

### *5.3.2 Model inventory and system boundary*

An inventory of conventional feed ingredients was compiled and used to build system processes in Simapro based mainly on the Agri-footprint database (Vellinga et al., 2013, Durlinger et al., 2014, Blonk Agri Footprint, 2015) and previous studies (Tallentire et al. 2017, 2018a). Inventory data for the processes involved in the production of a few minor ingredients were adapted from the Ecoinvent database, e.g. limestone (Swiss Centre for Life Cycle Inventories, 2007). An inventory was compiled for the novel ingredients using peer-reviewed sources and industry supplied primary data (Appendix D). All upstream system processes associated with the feed production were included within the boundary of the LCA analysis (Figure 5.1). All resource and energy inputs to fertiliser, herbicide and pesticide production and the various processing requirements of the ingredients (harvesting, separation, grinding and drying) were included in the analysis. The direct and indirect emissions that arise as a result of these system processes, including any land transformation associated with production, were all accounted for within the boundaries of the model (Vellinga et al., 2013, Blonk Agri Footprint, 2015, Defra, 2015, FAO, 2015). The production of conventional ingredients was based on current practices (i.e. Conventional cropping systems) as in Chapter 3, whilst novel ingredient production was based on potential upscaled processing scenarios based on novel technologies. A life cycle inventory for the production of the seven novel ingredients was compiled based on a number of peer-reviewed sources and industry supplied primary data. Each is discussed in detail below.

The cultivation of microalgae (*Chlorella sp.*) was presumed to be undertaken in raceway ponds (Brune et al., 2009, Jorquera et al., 2010, Benemann, 2013, Rickman et al., 2013). When the algal broth is ready, the cells are harvested, dewatered and the oil is extracted for biofuel production. The remaining cellular residue, consisting mainly of proteins and carbohydrates, could be used respectively as an animal feed (Microalgae meal) and anaerobically digested to produce biogas (Stephenson et al., 2010, Gnansounou and Kenthorai Raman, 2016). The latter can be used on site to mitigate some of the system's energy demand. Glycerol is also produced as a co-product of the system in small quantities which can be used by the pharmaceutical industry (Gnansounou and Kenthorai Raman, 2016) (Appendix D, Table D1).

Macroalgae meal too, can be produced as a co-product of a bio-refinery approach that uses algal feedstock (*Ulva sp.*). Upscaling animal feed co-production from seaweed cultivation can be assumed to be comparable with the established process of the production of DDGS from a cereal origin (Wargacki et al., 2012, Trivedi et al., 2013, Wei et al., 2013, Aitken et al., 2014, Cappelli et al., 2015). Since the unfermented components in seaweed are similar in composition, and in the way they are processed, to the unfermented components of corn that comprise DDGSs it has been assumed that the unfermented components of seaweed are used exclusively as animal feed (Yaich et al., 2011, Philippsen et al., 2014, Bikker et al., 2016) (Appendix D, Table D2).

The final aquatically cultivated novel ingredient, duckweed (*Lemna sp.*), occurs naturally in highly eutrophied water bodies. Hence, the ideal nutrient source for a duckweed production system is effluent (slurry) from livestock production (van Marrewijk, 2017); the amount required for optimum growth was estimated based on the average N and P content of pig slurry and the uptake of these nutrients by duckweed (Cheng et al., 2002, Zimmo et al., 2004, Krishna and Polprasert, 2008, Cheng and Stomp, 2009). Duckweed propagates rapidly via asexual reproduction in nutrient rich water to form a floating photosynthetic mat on the surface of the water; this blocks out light and thus competing algae cease to grow. A system which harvested 20% of duckweed twice a week was modelled. Harvesting low amounts of duckweed at shorter intervals in this way, rather than harvesting larger amounts less frequently, results in a higher biomass density; this improves nutrient recovery from the effluent and increases the production of duckweed (Xu and Shen, 2011) (Appendix D, Table D3).

Yeast protein concentrate (YPC) is derived from the stillage from which conventional DDGSs are obtained as a co-product of bioethanol production (Punter et al., 2004, Williams et al., 2009, Scacchi et al., 2010, Borrion et al., 2012, Burton et al., 2013), using wheat as the feedstock. Whole stillage is fed through two stages of separation which separates the fibrous components of the stillage from a supernatant and a high concentrate yeast cream. This yeast cream may then be dried to produce YPC (Omar et al., 2012, Burton et al., 2013), whilst the fibrous components are used to produce a material similar to the traditional DDGS product, which can be fed to ruminant species of livestock (Appendix D, Table D4).

Bacterial protein meal (BPM) is produced by the fermentation of natural gas using a bacterial culture consisting chiefly of *Methylococcus capsulatus* (88%) and *Alcaligenes acidovorans* (de Boer et al., 2014). $CH_4$ is the main raw material used as the carbon and energy source. The oxygenation fermentation process requires pure oxygen and $NH_3$ is used as the N source. In addition to these substrates, the BPM culture requires water and phosphate as well as other minerals (Appendix D, Table D5).

The major material input to the leaf protein concentrate (LPC) production system was fresh green biomass. This can come in numerous forms, but alfalfa (*Medicago sp.*) was chosen as the model feedstock. Alfalfa was chosen because: it would be readily available in Europe, it has suitable physiochemical properties for high quality LPC production and good data on its production and use in bio refineries was available (Parajuli et al., 2017). The process flow followed the technical considerations outlined by previous studies (Kamm et al., 2009, O'Keeffe et al., 2011, Hermansen et al., 2017) and yielded lactic acid, silage fodder, fertiliser and biogas as co-products, the latter of which can be used on site to mitigate some of the system's energy demand, whilst the fertiliser that was coproduced avoided the production of some synthetic fertiliser (Appendix D Table D6).

Insect meal can be produced from the rearing, harvesting, drying and grinding of mealworms (*Tenebrio molitor*) (Oonincx and de Boer, 2012, Schiavone et al., 2014, De Marco et al., 2015, Smetana et al., 2015). Mealworms have the ability to recycle plant waste materials of low quality into high quality feed rich in energy and protein (Feedipedia, 2017). A potential insect diet was formulated that consisted of fruit and vegetable waste streams (60%), wheat (27%), rice (8%) and fava beans (5%) (Ramos-Elorduy et al., 2002, Oonincx and de Boer, 2012). Much research is still needed to optimize the diets to support optimal insect performance and nutrient composition, which should improve mealworm performance as the industry matures (Józefiak and Engberg, 2015). Furthermore, mealworms produce waste in the form of faeces and the moulting of their exoskeletons as they grow known as castings. The nutrient content of this waste can be calculated via the mass balance principle described previously in this thesis. Based on the diet formulated for the mealworms, their reported feed efficiency (Oonincx and de Boer, 2012) and the crude protein and gross P content of the insect meal (Makkar, 2014), mealworms would excrete N and P at 4.74 and 1.42 g kg$^{-1}$ of insect meal respectively. These nutrients can be used to offset some synthetic fertiliser production. The environmental burdens of insect meal production were fully allocated to mealworms (Oonincx and de Boer, 2012) (Appendix D, Table D7).

It was expected that the housing conditions were maintained in such a way as to provide each chicken line with the optimum growing conditions for its genotype. However, with the exception of the feed, the resource and energy inputs to the birds' growing facility and beyond the farmgate were not included within the boundary of this study (Figure 5.1). Finally, since the functional unit was only one bird raised to a LW of 2.2 kg, the effects of bird mortality were not considered within the boundary of the model.

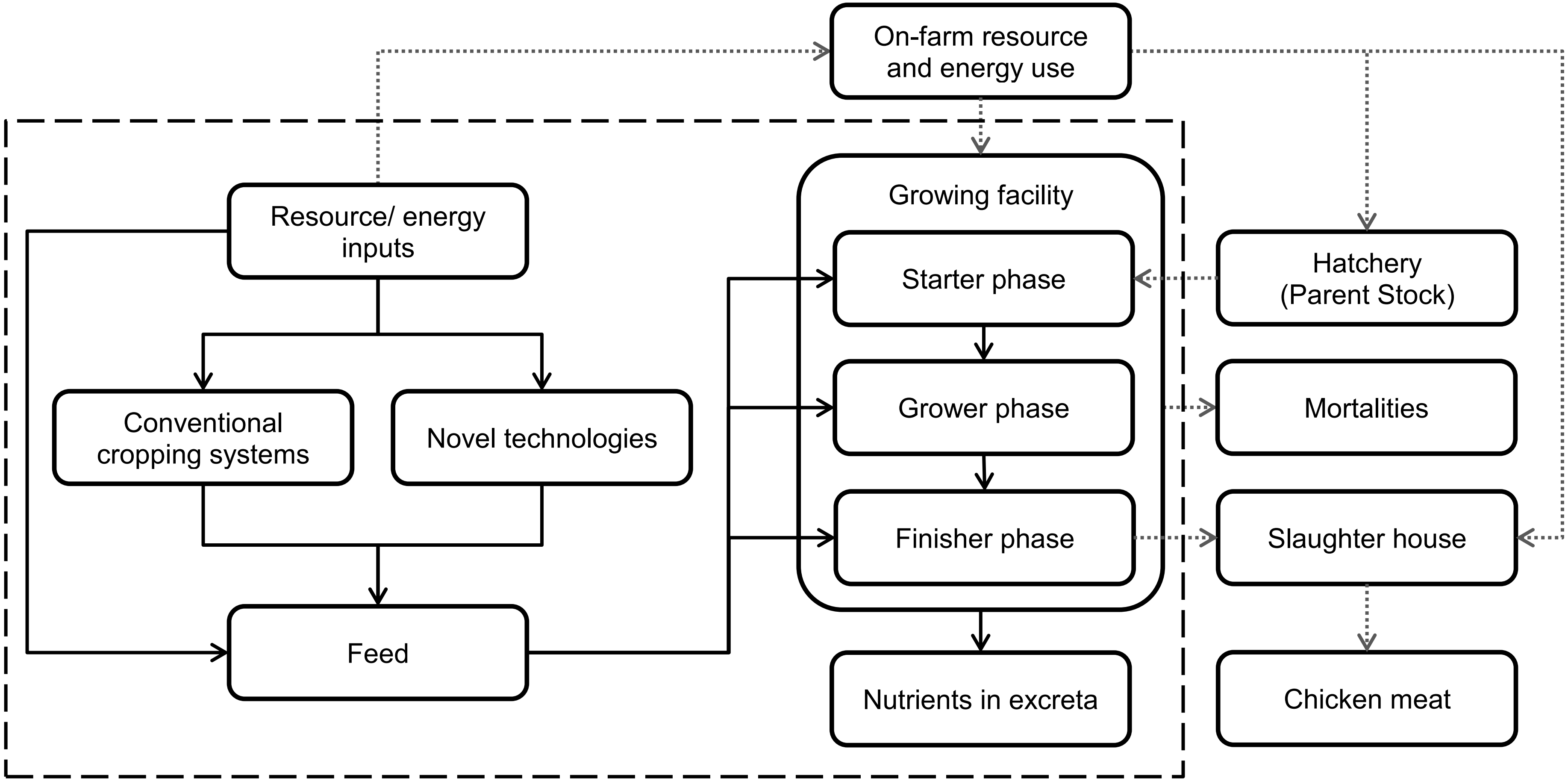

**Figure 5.1**: The structure and main components of the chicken meat production systems as considered by the Life Cycle Assessment (LCA) model in Chapter 5 (adapted from Figure 3.1 and 4.2); the inputs that were considered (solid line arrows), the inputs that were not considered (dotted line arrows) and the system boundary (dashed line) are clearly illustrated.

### *5.3.3 Future bird nutritional requirements*

The nutritional specifications were based on two breeding scenarios that were presented in Chapter 4 via horizon scanning (Tallentire et al. 2018a), which result in: 1) a fast-growing line based on the apparent maximum feed efficiency that could be achieved through further conventional artificial selection and 2) a reduced growth rate for high welfare line (Table 5.1). For the two scenarios, total energy requirement was quantified based on predictions of the biological limits of digestive efficiency, protein and lipid growth and the metabolic rate of heat production (Tallentire et al., 2018a). The difference in the traits between these future meat-producing lines and current commercial broiler chickens is low (Aviagen, 2014a, Fancher, 2014, Aviagen, 2016), thus it is reasonable to expect these lines will be achieved before the novel technologies outlined in this study come into wide scale operation. Since there is no evidence that the efficiency of protein utilization has changed as a result of selective breeding, the protein requirements of the meat-producing chicken lines were calculated based on the current baselines for feed intake, feed protein content and body composition (Aviagen, 2014b, Aviagen, 2016). In this way the protein utilization efficiency equates to the protein retained in the body (Gouveia et al., 2009) divided by the protein intake (Gouveia et al., 2009) of one bird. The requirements of the future lines could therefore be calculated as follows: first the change in energy requirement, and therefore the feed intake, was calculated while keeping the feed energy content unchanged from current requirements. Then, the nutrient requirements of the new birds were estimated based on the changes in feed intake and in bird requirements, (the change of nutrient requirement was assumed to be proportional to the change of protein requirement). The new diets could then be constructed to meet these requirements (Appendix A, Table A3 and A4).

**Table 5.1**: Characteristics of birds at a live weight of 2.2 kg at slaughter for two potential future lines. The fast-growing line assumes that the current trends in chicken genetic selection continue, whereas the slow-growing line results from societal pressures to reduce the growth rate, giving higher priority to animal welfare.

| **Characteristic** | **Fast-growing line** | **Slow-growing line** |
|---|---|---|
| Growth rate (g day$^{-1}$) | 65.3 | 38.6 |
| Age at slaughter (days) | 33 | 57 |
| Total Metabolizable energy intake (MJ) | 42.0 | 58.3 |
| Total protein content of body (%) | 20.6 | 20.6 |

Since the fast-growing line was selected for increased growth rate, it follows that an increased proportion of its life would be spent in the starter phase (days 0 - 10) and a reduced period of time in the finisher phase (days 25 - slaughter). Hence, the bird required a substantially increased protein intake in the starter phase (266.6 g $kg^{-1}$), in order to achieve this higher growth rate, than a slow-growing bird (225.0 g $kg^{-1}$). Therefore, the average energy and crude protein content requirement of the feed for the fast-growing birds was 13.1 MJ $kg^{-1}$ and 205.4 g $kg^{-1}$ respectively. The average energy and crude protein content requirement of the feed for the slow-growing birds was 13.3 MJ $kg^{-1}$ and 187.7 g $kg^{-1}$ respectively.

### *5.3.4 Diet formulation rules*

The novel ingredients were selected based on five criteria: 1) The ingredient could potentially serve as an alternative to imported soybeans in livestock diets. 2) The incorporation of the ingredient into chicken diets was not common practice already. 3) The maximum inclusion limit of the novel ingredient, its digestible amino acid profile and ME content were available in the literature. 4) Production in Europe is a realistic option for the future. 5) Enough data was available to compile an inventory of relevant energy and material inputs and environmental releases related to the novel ingredient. Seven novel ingredients were identified for inclusion within the scope of this study: microalgae, macroalgae, duckweed, yeast protein concentrates (YPC), bacterial protein meal (BPM), leaf protein concentrate (LPC) and insect meal. For each of these ingredients a production inventory (Appendix D) and nutritional profile (Table 5.2) was compiled.

For each chicken meat-producing line a “Conventional diet” was formulated. Both these diets were formulated for least cost, using only ingredients currently used in the UK as a case study for western European systems, as was developed in Chapter 3 (Tallentire et al., 2017); both diets included soymeal. For each line, a further 11 “alternative diets” were formulated. 7 of these alternative diets each incorporated one novel ingredient fixed at its potential maximum inclusion rate; these alternative diets were formulated to match the nutritional requirements of the birds using linear programming for least cost. The prices of the conventional ingredients were obtained from commodity price indexes for animal feeds (Defra, 2016, Tallentire et al., 2017). Since their inclusion values were fixed in these diets, the prices of the novel ingredients were not relevant to the diet formulation procedure. Each of the remaining 4 diets for each line was formulated to reduce a specific environmental burden. When formulating these diets any of the 7 novel ingredients, as well as any of the conventional ingredients, were able to be incorporated within their corresponding inclusion limits in order to optimise the diet to minimise a specific environmental burden. Therefore 12 diets were formulated for each line and 24 diets were formulated in this study in total.

Inclusion limits of conventional ingredients were based on input data from literature, national inventory reports, databases and expert advice (FAO, 2015, Tallentire et al., 2017). The maximum inclusion of each novel ingredient in the grower-finisher phases was determined from assessing literature, in which the effects of inclusion rates on bird performance were measured; the maximum inclusion in the starter phases was 50% of this value as a conservative estimate (Leinonen et al., 2013). For the three ingredients sourced from aquatic based systems, microalgae (venkataraman et al., 1994), duckweed (Haustein et al., 2009) and macroalgae meal (Ventura et al., 1994), the maximum inclusion limit was consistent at 18%. Maximum YPC inclusion rates are particularly variable due to issues with its nutritional characterisation; an inclusion of 20% was determined to be feasible without negatively affecting performance (Scholey et al., 2014, Scholey et al., 2016). BPM has been shown to be able to be included in the diets at a 10% inclusion level with no negative effect on chicken growth performance (Whittemore et al., 1978, Skrede et al., 2003, Schøyen et al., 2007). It is expected that LPC should have very similar properties to other plant protein and replace soymeal completely in the grower-finisher phases at a maximum inclusion level of 40% (Ameenuddin et al., 1983). Insect meal had a maximum inclusion of 30% (Bovera et al., 2016); although beneficial to the immune system, chitin can limit digestibility beyond this inclusion level. It should be kept in mind that insect meal would not be allowed to be incorporated into poultry diets under current EU law, however the regulation has recently been relaxed so that insects can be utilised in aquaculture systems (European Commission, 2017a) and its incorporation into other livestock feeds continues to be championed in scientific literature (Marberg et al., 2017). The maximum and minimum inclusion levels of each novel ingredient considered in this thesis have been presented in Appendix B, Table B1 alongside the conventional ingredient inclusion levels.

**Table 5.2**: The as fed nutritional specification of dried microalgae, macroalgae, duckweed, yeast protein concentrate (YPC), bacterial protein meal (BPM), leaf protein concentrate (LPC) and insect meal presumed for the analysis of future meat-producing chicken diet compositions. The table includes the metabolizable energy (ME) content, the crude protein content, the digestible amino acid content, the total and available phosphorus content and the calcium content of each ingredient.

| Novel Ingredient | Dry matter (%) | ME (MJ kg$^{-1}$) | Crude Protein (%) | *Lysine (%) | *Methionine (%) | *Threonine (%) | *Valine (%) | *Isoleucine (%) | *Arginine (%) | *Leucine (%) | Ca (%) | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Microalgae | 94.8 | 15.6 | 58.0 | 3.94 | 1.44 | 1.82 | 2.14 | 1.44 | 2.88 | 3.60 | 0.10 | (Alvarenga et al., 2011, Christaki et al., 2011, Kang et al., 2013, Ekmay et al., 2014, Feedipedia, 2017) |
| Macroalgae | 79.5 | 7.86 | 23.1 | 0.63 | 0.27 | 0.66 | 0.77 | 0.41 | 0.83 | 0.95 | 2.20 | (Hong et al., 2011, Abudabos et al., 2013, Feedipedia, 2017) |
| Duckweed | 80.2 | 6.16 | 30.1 | 0.75 | 0.34 | 0.67 | 0.93 | 0.75 | 1.10 | 1.40 | 1.92 | (Rusoff et al., 1980, Leng et al., 1995, Ahammad et al., 2003, Olorunfemi, 2006, Mwale and Gwaze, 2013, van Krimpen et al., 2013, Feedipedia, 2017) |
| YPC | 91.4 | 11.2 | 67.6 | 0.83 | 0.60 | 0.86 | 1.67 | 1.27 | 1.63 | 2.57 | 0.25 | (Burton et al., 2013) |
| BPM | 95.9 | 13.5 | 72.9 | 3.55 | 1.72 | 2.54 | 3.52 | 2.71 | 3.89 | 4.42 | 0.24 | (Skrede et al., 1998, Øverland et al., 2010) |
| LPC | 98.0 | 12.1 | 58.0 | 3.10 | 1.06 | 2.35 | 2.94 | 1.86 | 3.13 | 4.24 | 2.00 | (Meissner et al., 1995) |
| Insect meal | 94.8 | 16.0 | 52.4 | 2.89 | 0.77 | 1.40 | 2.19 | 1.72 | 2.39 | 2.45 | 0.27 | (Ramos-Elorduy et al., 2002, Makkar, 2014, Makkar et al., 2014, De Marco et al., 2015) |

*Digestible

### *5.3.5 Environmental burden assessment*

The Simapro software was used to conduct LCA calculations. Due to the novelty of some of the ingredient production processes assessed for the purpose of this study, the differences in the potential environmental burdens of each diet were limited to the most relevant feed-related environmental indicators, as in Chapter 4 (Tallentire et al. 2018a). As such, the environmental parameters used to compare the environmental impact potential of each potential diet formulation was represented by the GWP, the ALU and the total N and P that would be excreted.

Over 70% of the GWP associated with chicken meat production can be attributed to feed provision (Leinonen et al., 2012). In this study the GWP was measured in $CO_2$ equiv with a 100-year timescale in accordance with the IPCC (2006) emissions factors. The ALU was calculated based on the total occupation of an area of land and the total area of land which was transformed for the functional unit. Calculation of the GHG emissions and ALU followed the ReCiPe methodology (Goedkoop et al., 2008). Notably, soybeans and soymeal carry a high GHG footprint due to associated deforestation; the $CO_2$ equiv released due to land transformation, such as for soybean production, was included according to the PAS2050:2012-1 methodology (BSI, 2012).

Whilst the GWP and ALU burdens were restricted to the direct result of feed provision, the quantities of the environmentally important nutrients (N and P) were calculated based on what ends up in bird excreta. To calculate these, a mass balance principle was applied; the nutrients retained in the animals' body were subtracted from the total N and P supplied by their diet, where the total N content of the protein in the body was assumed to be 16%. These nutrients are associated with acidification and localised eutrophication, whilst N is responsible for the $NH_3$ emissions at housing, manure storage and field spreading. On the other hand, these nutrients can be used in the place of synthetic fertilisers, this is especially important in organic farming where manure is a major source of nutrients (Leinonen et al., 2012).

### *5.3.6 Analysis*

In total, 24 diets were formulated in the study described in this chapter; 12 for each future chicken meat-producing line. The results were analysed by comparing the environmental burdens caused by each alternative diet scenario with those of the Conventional diet from the corresponding line using the mean values produced by the model. An uncertainty analysis was also conducted using parallel Monte Carlo simulations (Figure 3.2). For each alternative diet scenario, the model was simulated 1000 times to calculate the environmental burdens of the alternative diet as compared with those of the Conventional diet from the corresponding line. Input parameters were randomly assigned a value along their defined distribution in each simulation; parallel simulations were used to account for shared uncertainty between the two diet scenarios (Mackenzie et al., 2015, Tallentire et al., 2017). The output of the uncertainty analysis was the probability that the environmental burdens of each diet were larger or smaller than the Conventional diet for each impact category.

### *5.3.7 Sensitivity*

Since this model contained only linear relationships, a local sensitivity analysis was suitable for identifying the inputs to which the environmental burdens were most sensitive (Tallentire et al., 2017). This was carried out on the assumptions of the model in three important areas in recognition of both their importance to the results of this study and the unavoidable uncertainty in the assumptions made. These were: 1) the efficiency of the manufacturing process for the novel ingredients; 2) the co-product allocation methodology used to calculate the environmental impact of producing these novel ingredients; and 3) the maximum levels to which these ingredients could be included in poultry diets without negatively affecting bird performance.

To test the sensitivity of process efficiency in producing the novel ingredients the yield of each novel ingredient was depressed and increased. While upscaling these system processes is likely to increase the efficiency of their production in the future, this is not a certainty and other considerations (e.g. quality control) can change the incentives which drive process changes. For some novel ingredients there was large variation in the process yields because they are in their development phase; the coefficients of variation in the yields were expected to range from 15% for insect meal to 50% for the more variable LPC produced from alfalfa (Lamb et al., 2003). The coefficients of variation for the other novel ingredients were estimated to be 33% for microalgae and for duckweed, and 20% for macroalgae and YPC (Philippsen et al., 2014, Wen, 2014, Feedipedia, 2017); yield data was not available to determine the coefficient of variation of BPM production, therefore it was presumed to be at the top of the range (50%).

Where system separation was not possible in the model, co-product allocation within the supply chain was conducted using economic allocation (Mackenzie et al., 2016b) using commodity prices available on e-commerce sites and recent alternative fuel price data (European Biomass Association, 2017) (Appendix D, Tables D1, D2, D4 and E6). Sensitivity analysis was carried out on this economic allocation strategy where the value of the novel ingredients produced with co-products were altered so that their value was equitable with soymeal per kg of lysine. This methodology was chosen to represent a scenario where the novel ingredients would be produced and utilised on a scale that makes them competitors of soymeal as a protein source in the animal feed market. Such a scenario would likely drive price increases for these products and thus alter calculations made when using economic allocation.

Finally, in order to account for discrepancies in the maximum inclusion levels shown in literature (Rusoff et al., 1980, Gijzen and Khondker, 1997, Olorunfemi, 2006, Hoving et al., 2012, Mwale and Gwaze, 2013), the maximum inclusion limit of each novel ingredient was reduced by 15%.

## 5.4 Results

### *5.4.1 Environmental burdens of diets*

Of all the novel ingredients included in the study, insect meal had the highest GWP associated with its production; this was caused by the requirement for a suitable ambient temperature for insect growth and development (47%), insect feed provision (13%) and other energy inputs to the rearing and processing of the mealworms into insect meal. Micro- and macroalgae had the second and third highest GWP respectively (Table 5.3), due to considerable process energy input requirements e.g. drying. LPC was the novel ingredient with lowest GWP, although it also had the greatest ALU due to the cultivation of alfalfa from which it is sourced, followed by YPC and insect meal. The ALU of the YPC could be almost entirely attributed to the cultivation of wheat, whilst 94% of the ALU of the insect meal was attributed to insect feed procurement. Unsurprisingly, the aquatic novel ingredients (i.e. microalgae, macroalgae and duckweed) had the lowest ALU. The GWP and ALU of the conventional ingredients considered in this study were presented in Chapter 3 (Table 3.1). The novel ingredients with the highest crude protein content and crude protein to amino acid ratio, e.g. YPC, resulted in the highest N in the excreta. Similarly, ingredients which had the highest total P content and had the lowest available P to total P ratio, resulted in the highest P in the excreta. Macroalgae was the novel ingredient with lowest total P content, whilst insect meal had the highest available P to total P ratio.

**Table 5.3**: The environmental burdens of soymeal and each novel ingredient included in this study as alternative protein sources. The global warming potential (GWP) emissions and agricultural land use (ALU) associated with the production of 1 kg of each ingredient are presented. The Nitrogen (N) and Phosphorus (P) content of the ingredients are also shown.

| Ingredient | GWP ($CO_2$ equiv; kg $kg^{-1}$) | ALU ($m^2$ $kg^{-1}$) | Total N content (kg $kg^{-1}$) | Total P content (kg $kg^{-1}$) |
|---|---|---|---|---|
| Soymeal | 3.05 | 3.11 | 0.075 | 0.006 |
| Microalgae | 2.31 | 0.034 | 0.093 | 0.014 |
| Macroalgae | 2.10 | 0.021 | 0.037 | 0.002 |
| Duckweed | 1.03 | 0.004 | 0.048 | 0.004 |
| Yeast protein concentrate | 1.08 | 1.26 | 0.108 | 0.013 |
| Bacterial protein meal | 1.49 | 0.026 | 0.117 | 0.015 |
| Leaf protein concentrate | 0.611 | 1.98 | 0.093 | 0.005 |
| Insect meal | 2.91 | 1.06 | 0.084 | 0.008 |

The environmental burdens of producing the total feed required by a chicken, of a fast-growing line and raised to a LW of 2.2 kg on a conventional diet formulation, were 4.96 kg $CO_2$ equiv, 8.84 $m^2$, 0.045 kg and 0.011 kg for GWP, ALU, N and P respectively. The environmental burdens of producing the total feed required by a chicken, of a slow-growing line and raised to a LW of 2.2 kg on a conventional diet formulation, were 5.90 kg $CO_2$ equiv, 11.2 $m^2$, 0.068 kg and 0.016 kg for GWP, ALU, N and P respectively. The percentage inclusion of each ingredient in each diet formulated for this study have been presented in Tables 5.4 and 5.5. The trend in the environmental burdens shown between diet formulations was similar for both chicken meat-producing lines that were considered (Figures 5.2 and 5.3). Slow-growing birds have a lower protein requirement for protein per kg of feed than birds of the fast-growing line (Appendix A, Table A3 and A4), hence the slow-growing birds' diets consistently contained less soybeans and soybean derivatives (where incorporated) to meet the bird growth requirements. Thus, per kg of feed, diets formulated for the slow-growing line had a lower GWP and ALU, than the diets formulated with the same objectives for the fast-growing line. Despite this, rearing a slow-growing bird resulted in an increase of every environmental burden considered in this study compared with rearing a fast-growing bird to the same LW, for every diet formulation. This was due to the increase in the total feed required by the slow-growing line to reach slaughter weight (4.39 kg) when compared with the fast-growing line (3.49 kg) (Tallentire et al., 2018a).

For every alternative diet formulated with a fixed inclusion of one novel ingredient, at least two burdens were reduced when compared with the Conventional diets (Figures 5.2 and 5.3). With the exception of the Insect meal diets, the total P in the excreta was the environmental burden that was least affected in each diet with a fixed inclusion of one novel ingredient, when compared with the Conventional diets. The Insect meal diets were also the only diets to reduce three burdens when compared with the Conventional diets. With the exception of the Macroalgae diet, the total N excretion was the environmental burden most affected in each diet with a fixed inclusion of one novel ingredient, compared with the Conventional diets. The total N excretion was increased in every diet with a fixed inclusion of one novel ingredient compared with the conventional diets, but the increase was greater in the fast-growing line (Figure 5.2) than in the slow-growing line (Figure 5.3). ALU was the only environmental burden to be reduced in every diet with a fixed inclusion of one novel ingredient, compared with the Conventional diet.

The lowest value for each environmental burden was axiomatically achieved by the alternative diet formulated to reduce that burden specifically. For instance, in the Least GWP and Least ALU diets this was achieved by reducing the inclusion of soybeans and soybean derivatives to zero; this protein was replaced by incorporating the novel ingredients (Tables 5.4 and 5.5). The Least ALU diet was the only formulation that resulted in the increase in three burdens when compared with the Conventional diets (Fig 5.2 and 5.3). With the exception of the Least N excretion diets, the total N in the excreta was the environmental burden most affected by minimising a specific environmental burden, compared with the Conventional diets. Only the Least N excretion diets reduced the N excretion compared with the Conventional diets; this was also the only formulation that included soybean derived ingredients at a higher level than in the Conventional diets. Again, ALU was the only environmental burden to be reduced in every diet formulated to reduce specific environmental burdens, compared with the Conventional diets.

**Table 5.4**: Percentage inclusion of each ingredient in each diet formulated for the fast-growing meat-producing chicken line.

| Ingredient | Conventional diet | Microalgae diet | Macroalgae diet | Duckweed diet | YPC diet | BPM diet | LPC diet | Insect meal diet | Least GHG diet | Least ALU diet | Least N excretion diet | Least P excretion diet |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wheat | 48.6 | 48.4 | 35.7 | 39.6 | 39.5 | 55.7 | 51.6 | 45.4 | 61.6 | 10.7 | 39.5 | 31.5 |
| Maize (Corn) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maize gluten meal | 0.0 | 0.0 | 4.7 | 4.7 | 0.0 | 0.0 | 0.0 | 0.0 | 4.8 | 4.8 | 0.0 | 0.3 |
| Rapeseed (Whole) | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 | 0.5 | 0.5 | 6.5 | 0.0 | 6.5 | 0.0 |
| Rapeseed meal | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 |
| Barley | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 11.7 | 0.0 | 0.0 | 0.0 | 0.0 |
| Sunflower meal | 0.0 | 0.0 | 0.0 | 0.0 | 3.7 | 0.6 | 0.0 | 2.0 | 0.3 | 0.0 | 0.0 | 8.7 |
| Soybeans | 0.0 | 0.0 | 8.6 | 11.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 7.8 | 0.0 |
| Soymeal | 24.6 | 11.7 | 14.2 | 9.5 | 10.9 | 9.6 | 2.2 | 2.5 | 0.0 | 0.0 | 23.2 | 2.3 |
| Field peas | 12.0 | 12.0 | 4.1 | 0.5 | 12.0 | 12.0 | 0.5 | 5.9 | 0.5 | 0.0 | 0.0 | 0.0 |
| Oats | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 12.0 | 0.0 |
| Fishmeal | 0.5 | 0.5 | 0.7 | 3.0 | 0.5 | 0.5 | 0.5 | 0.5 | 5.0 | 5.0 | 0.5 | 0.5 |
| Vegetable oil* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.0 | 0.0 |
| Soy oil | 4.2 | 0.9 | 5.0 | 5.0 | 4.5 | 2.3 | 3.6 | 0.1 | 0.0 | 0.0 | 5.0 | 5.0 |
| Limestone | 1.1 | 1.5 | 1.0 | 1.0 | 1.4 | 1.3 | 1.0 | 1.5 | 1.0 | 1.0 | 2.0 | 1.8 |
| Mono Calcium Phosphate | 1.3 | 0.7 | 1.3 | 0.9 | 0.7 | 1.0 | 1.5 | 0.5 | 0.8 | 0.1 | 2.0 | 0.5 |
| NaHCO3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.8 | 0.7 |
| Salt | 0.4 | 0.4 | 0.4 | 0.3 | 0.4 | 0.4 | 0.3 | 0.4 | 0.2 | 0.3 | 0.0 | 0.0 |
| Lysine HCl | 0.2 | 0.0 | 0.3 | 0.4 | 0.4 | 0.2 | 0.0 | 0.0 | 0.1 | 0.0 | 0.2 | 0.5 |
| DL-Methionine | 0.2 | 0.0 | 0.1 | 0.2 | 0.1 | 0.1 | 0.0 | 0.1 | 0.0 | 0.5 | 0.2 | 0.5 |
| L-Threonine | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.0 | 0.1 | 0.0 | 0.5 | 0.1 | 0.5 |
| Valine | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 |
| Premix | 0.2 | 0.2 | 0.3 | 0.2 | 0.2 | 0.3 | 0.3 | 0.2 | 0.3 | 0.3 | 0.3 | 0.2 |
| Microalgae | 0.0 | 17.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | 17.1 | 0.0 | 0.0 |
| Macroalgae | 0.0 | 0.0 | 17.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 17.1 | 0.0 | 17.1 |
| Duckweed | 0.0 | 0.0 | 0.0 | 17.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.4 | 0.0 | 0.8 |
| Yeast protein concentrate | 0.0 | 0.0 | 0.0 | 0.0 | 19.0 | 0.0 | 0.0 | 0.0 | 0.4 | 0.0 | 0.0 | 0.0 |
| Bacterial protein meal | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 9.5 | 0.0 | 0.0 | 0.5 | 9.5 | 0.0 | 0.0 |
| Leaf protein concentrate | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 38.0 | 0.0 | 16.4 | 1.2 | 0.0 | 0.0 |
| Insect meal | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 28.5 | 0.0 | 28.5 | 0.0 | 28.5 |

*50% palm oil, 50% Sunflower oil

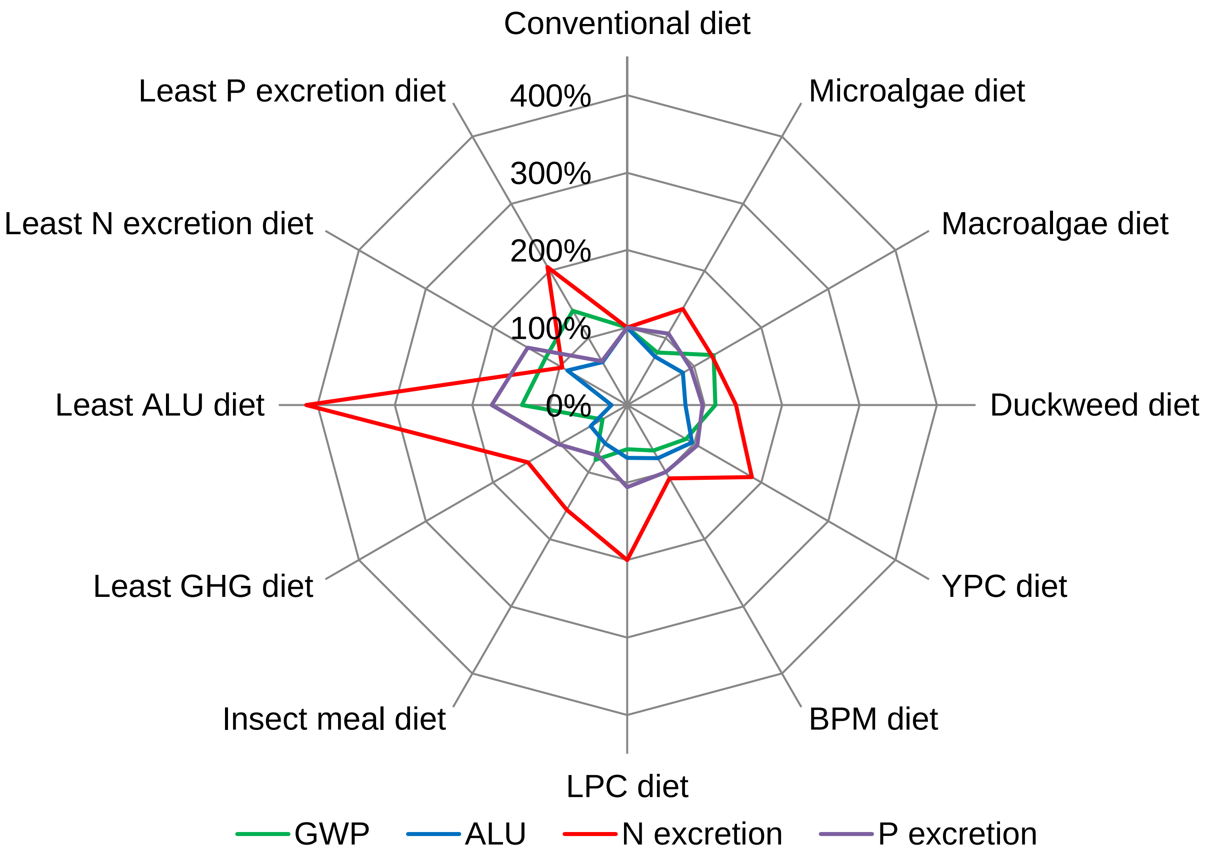

**Figure 5.2**: The burdens of producing the total feed required by fast-growing line chicken. The environmental burdens of the Microalgae, Macroalgae, Duckweed, Yeast protein concentrate (YPC), Bacterial protein meal (BPM), Leaf protein concentrate (LPC), Insect meal, Least Global warming potential (GWP), Least Agricultural land use (ALU), Least N excretion and Least P excretion diets are represented as a percentage of the Conventional diets (also displayed). The environmental burdens displayed are greenhouse gas (GWP; $CO_2$ equiv), agricultural land use (ALU; $m^2$), nitrogen excretion (N; kg) and phosphorus excretion (P; kg).

**Table 5.5**: Percentage inclusion of each ingredient in each diet formulated for the slow-growing meat-producing chicken line.

| Ingredient | Conventional diet | Microalgae diet | Macroalgae diet | Duckweed diet | YPC diet | BPM diet | LPC diet | Insect meal diet | Least GHG diet | Least ALU diet | Least N excretion diet | Least P excretion diet |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wheat | 50.3 | 50.0 | 40.8 | 41.0 | 43.0 | 57.9 | 53.0 | 47.8 | 65.5 | 11.4 | 39.9 | 32.4 |
| Maize (Corn) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maize gluten meal | 0.0 | 0.0 | 4.8 | 4.8 | 0.0 | 0.0 | 0.0 | 0.0 | 4.9 | 4.9 | 0.0 | 0.1 |
| Rapeseed (Whole) | 7.1 | 7.1 | 7.1 | 7.1 | 7.1 | 7.1 | 0.2 | 0.1 | 6.8 | 0.0 | 7.1 | 0.0 |
| Rapeseed meal | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Barley | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 15.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Sunflower meal | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | 0.0 | 0.0 | 0.0 | 9.2 |
| Soybeans | 0.0 | 0.0 | 8.2 | 12.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 9.6 | 0.0 |
| Soymeal | 21.7 | 8.5 | 11.7 | 5.7 | 9.9 | 6.6 | 0.4 | 0.6 | 0.0 | 0.0 | 19.3 | 0.4 |
| Field peas | 13.2 | 13.2 | 1.1 | 1.0 | 13.2 | 13.2 | 0.2 | 3.8 | 0.1 | 0.0 | 0.2 | 0.0 |
| Oats | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 13.2 | 0.0 |
| Fishmeal | 0.2 | 0.2 | 0.7 | 1.8 | 0.2 | 0.2 | 0.2 | 0.2 | 5.0 | 5.0 | 0.2 | 0.2 |
| Vegetable oil* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 0.0 | 0.0 | 0.0 |
| Soy oil | 4.2 | 0.8 | 4.9 | 5.0 | 4.0 | 2.2 | 4.0 | 0.0 | 0.0 | 0.0 | 5.0 | 5.0 |
| Limestone | 1.1 | 1.4 | 1.0 | 1.0 | 1.3 | 1.3 | 1.0 | 1.5 | 1.0 | 1.0 | 2.0 | 1.9 |
| Mono Calcium Phosphate | 1.1 | 0.5 | 1.1 | 0.9 | 0.6 | 0.8 | 1.3 | 0.3 | 0.7 | 0.0 | 1.9 | 0.3 |
| NaHCO3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.8 | 0.8 |
| Salt | 0.4 | 0.4 | 0.4 | 0.3 | 0.4 | 0.4 | 0.3 | 0.4 | 0.3 | 0.3 | 0.0 | 0.0 |
| Lysine HCl | 0.1 | 0.0 | 0.3 | 0.3 | 0.4 | 0.2 | 0.0 | 0.0 | 0.1 | 0.0 | 0.2 | 0.5 |
| DL-Methionine | 0.2 | 0.0 | 0.1 | 0.2 | 0.1 | 0.1 | 0.0 | 0.1 | 0.0 | 0.5 | 0.2 | 0.5 |
| L-Threonine | 0.1 | 0.0 | 0.0 | 0.6 | 0.1 | 0.1 | 0.0 | 0.1 | 0.0 | 0.5 | 0.1 | 0.5 |
| Valine | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 |
| Premix | 0.3 | 0.3 | 0.2 | 0.2 | 0.3 | 0.3 | 0.2 | 0.3 | 0.2 | 0.3 | 0.3 | 0.2 |
| Microalgae | 0.0 | 17.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 17.6 | 0.0 | 0.0 |
| Macroalgae | 0.0 | 0.0 | 17.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 17.6 | 0.0 | 17.6 |
| Duckweed | 0.0 | 0.0 | 0.0 | 17.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.9 | 0.0 | 0.4 |
| Yeast protein concentrate | 0.0 | 0.0 | 0.0 | 0.0 | 19.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Bacterial protein meal | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 9.8 | 0.0 | 0.0 | 0.2 | 9.8 | 0.0 | 0.0 |
| Leaf protein concentrate | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 39.0 | 0.0 | 14.2 | 0.0 | 0.0 | 0.0 |
| Insect meal | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 29.3 | 0.0 | 29.3 | 0.0 | 29.3 |

*50% palm oil, 50% Sunflower oil

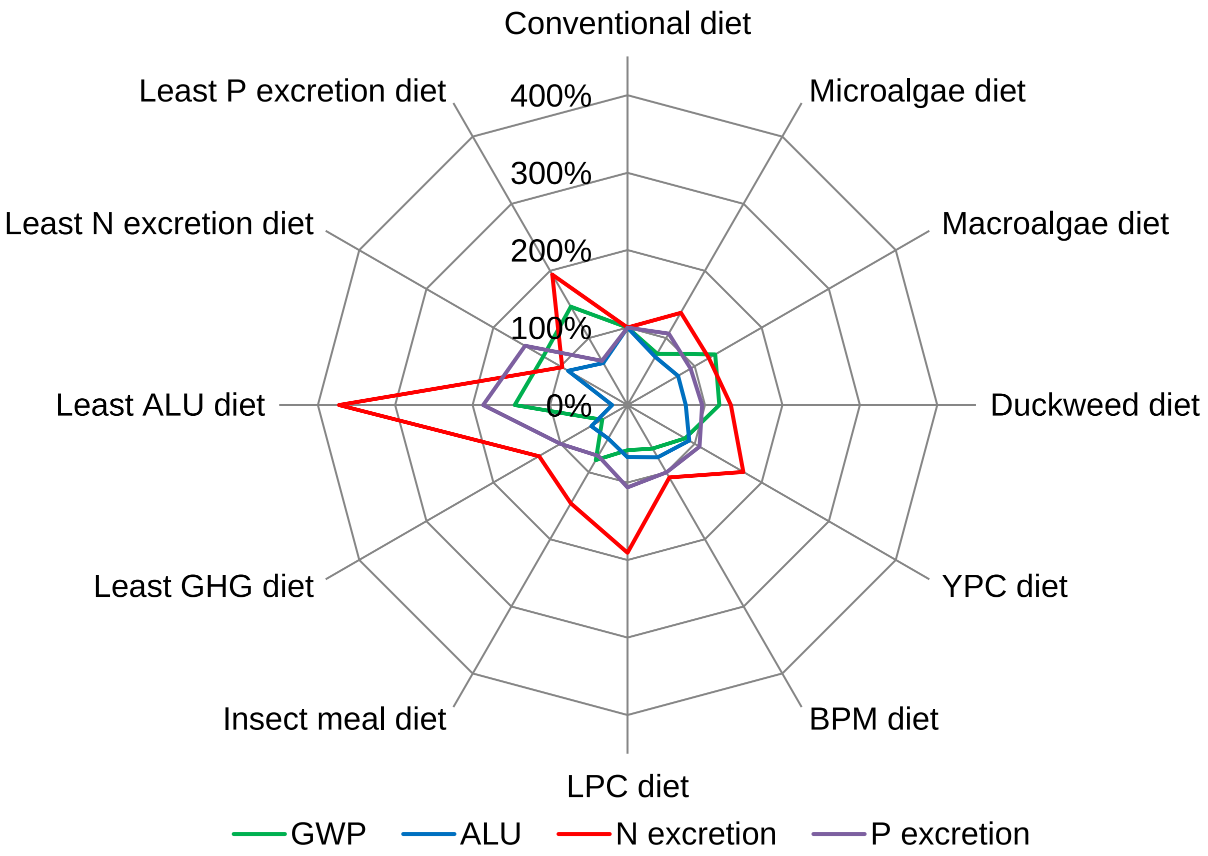

**Figure 5.3**: The burdens of producing the total feed required by slow-growing line chicken. The environmental burdens of the Microalgae, Macroalgae, Duckweed, Yeast protein concentrate (YPC), Bacterial protein meal (BPM), Leaf protein concentrate (LPC), Insect meal, Least Global warming potential (GWP), Least Agricultural land use (ALU), Least N excretion and Least P excretion diets are represented as a percentage of the Conventional diets (also displayed). The environmental burdens displayed are greenhouse gas (GWP; $CO_2$ equiv), agricultural land use (ALU; $m^2$), nitrogen excretion (N; kg) and phosphorus excretion (P; kg).

For both chicken meat-producing lines, each alternative diet formulation generated similar percentage changes for every environmental burden compared with the corresponding Conventional diet (Figures 5.2 and 5.3). When compared with the Conventional diet formulated for the fast-growing line, some environmental burdens of the alternative diets formulated for slow-growers were similar or reduced. For instance, the Least GWP diet formulated for the slow-growing line reduced the GWP and the ALU by 55% and 32% respectively, and increased the N and P in the excreta by 99% and 29% respectively, when compared with the Conventional diet formulated for and fed to the fast-growing line. In another example, the Insect meal diet formulated for the slow-growing line reduced the GWP and the ALU and P in the excreta by 3.1%, 37% and 17% respectively, and increased the N in the excreta by 108%, when compared with the Conventional diet formulated for and fed to the fast-growing line.

The output of the uncertainty analysis was the probability that the environmental burdens of each diet were larger or smaller than the Conventional diet for the GWP and the ALU only (Table 5.6). The excretions of N and P were not included in the uncertainty analysis; the reason for this was two-fold. Firstly, the potential distribution of each nutrient in the novel ingredients were in most cases not available. Secondly, the body composition of each line was determined for maximum energy use efficiency and presumed to be constant between lines and diets.

**Table 5.6**: Uncertainty analysis of the production of 1 kg of feed formulated for the Conventional diet vs 1 kg of feed of every other diet formulation. Percentages refer to how often the Conventional diet for each broiler line had a greater global warming potential (GWP) production value and greater agricultural land use (ALU) value than each of the other diets when the model was run 1000 times in parallel.

| | **Fast-growing line** | | **Slow-growing line** | |
|---|---|---|---|---|
| **Diets assessed** | **GWP** | **ALU** | **GWP** | **ALU** |
| Conventional diet > Microalgae diet | 99.6% | 99.6% | 99.9% | 99.9% |
| Conventional diet > Macroalgae diet | 0.50% | 98.3% | 0.30% | 98.0% |
| Conventional diet > Duckweed diet | 0.70% | 98.4% | 1.00% | 98.1% |
| Conventional diet > YPC diet | 99.8% | 97.1% | 99.9% | 99.9% |
| Conventional diet > BPM diet | 100% | 100% | 99.9% | 99.9% |
| Conventional diet > LPC diet | 99.2% | 98.1% | 99.4% | 98.2% |
| Conventional diet > Insect meal diet | 94.3% | 98.7% | 95.3% | 98.8% |
| Conventional diet > Least GWP diet | 99.7% | 97.5% | 99.6% | 99.2% |
| Conventional diet > Least ALU diet | 8.90% | 98.7% | 6.60% | 98.7% |
| Conventional diet > Least N excretion diet | 0.80% | 97.4% | 1.00% | 95.7% |
| Conventional diet > Least P excretion diet | 3.40% | 98.3% | 2.00% | 98.3% |

The uncertainty analysis showed only two cases of uncertainty in the results when comparing the environmental burdens of the alternative diets with the Conventional diet (i.e. the alternative diets had a greater or lower value than the Conventional diet for any one environmental burden in <95% of the parallel simulations). These were the Insect meal diet and the Least ALU diet, the commonality between these diets was that both incorporated insect meal. For all results the alternative diets had a consistently greater or consistently lower impact than the Conventional diet in >90% of the parallel simulations.

### *5.4.2 Sensitivity analysis*

The model was sensitive (i.e. change in at least one burden was ≥±5% the mean in at least one diet) to the coefficient of variation in the yield of microalgae, BPM, LPC and insect meal (Tables 5.7 and 5.8). The N and P excretion was only affected where the change in production yield led to an alternative diet formulation, e.g. when the LPC was reduced in the Least GWP diet. The N and P excretion was however not sensitive to the variation in the production yield (change <±5% the mean).

The GWP and ALU burdens of microalgae, macroalgae and LPC were sensitive to changing the economic allocation data that was applied to the base model (Table 5.9), hence the diets which incorporated these ingredients showed high sensitivity to this assumption, namely the Microalgae, Macroalgae, LPC, Least GWP, Least ALU and Least P excretion diets. The fast-growing line’s Least ALU diet was the only diet where the formulation was altered and the changes were small: the inclusion of wheat, monocalcium phosphate, duckweed and LPC were all reduced whilst YPC was increased by 0.99% of the total feed.

Finally, changing the maximum inclusion of each novel ingredient axiomatically affected the diet formulation of the Microalgae, Macroalgae, Duckweed, YPC, BPM, LPC and Insect meal diets. Lowering the maximum inclusion of some of the novel ingredients also affected the formulations of the diets that minimised GWP, ALU and P excretion (Table 5.10), however not the Least N excretion diets, since no novel ingredients were incorporated into these diets.

**Table 5.7**: Sensitivity analysis of the effect of low production yield on the environmental burdens of the diets. Each novel ingredient's production yield was reduced and increased on an individual basis. Results are presented as the percentage increase (+) or decrease (-) from the mean. Diets are presented where at least one burden was affected. The environmental burdens were greenhouse gas emissions (GWP), agricultural land use (ALU), N excretion and P excretion.

| | **Fast-growing line** | | | | **Slow-growing line** | | | |
|---|---|---|---|---|---|---|---|---|
| **Parameter** | **GWP** | **ALU** | **N excretion** | **P excretion** | **GWP** | **ALU** | **N excretion** | **P excretion** |
| Microalgae in Microalgae diet | +11.74 | +0.11 | 0.00 | 0.00 | +13.06 | +0.11 | 0.00 | 0.00 |
| Macroalgae in Macroalgae diet | +3.92 | +0.03 | 0.00 | 0.00 | +4.21 | +0.04 | 0.00 | 0.00 |
| Duckweed in Duckweed diet | +3.59 | +0.01 | 0.00 | 0.00 | +3.75 | +0.01 | 0.00 | 0.00 |
| YPC in YPC diet | +3.30 | +1.95 | 0.00 | 0.00 | +3.65 | +2.10 | 0.00 | 0.00 |
| BPM in BPM diet | +7.37 | +0.06 | 0.00 | 0.00 | +8.37 | +0.06 | 0.00 | 0.00 |
| LPC in LPC diet | +14.36 | +21.78 | 0.00 | 0.00 | +15.22 | +22.57 | 0.00 | 0.00 |
| Insect meal in Insect meal diet | +10.79 | +3.12 | 0.00 | 0.00 | +11.68 | +3.67 | 0.00 | 0.00 |
| Microalgae in Least GWP diet | +0.79 | +0.39 | +0.16 | -0.33 | 0.00 | 0.00 | 0.00 | 0.00 |
| YPC in Least GWP diet | +0.16 | +0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| BPM in Least GWP diet | +0.71 | 0.00 | 0.00 | 0.00 | +0.25 | +0.42 | -0.01 | +0.03 |
| LPC in Least GWP diet | +7.59 | -9.51 | +1.28 | +0.32 | +5.79 | -18.18 | +1.57 | +0.42 |
| Microalgae in Least ALU diet | +6.77 | +0.38 | 0.00 | 0.00 | +6.86 | +0.40 | 0.00 | 0.00 |
| Macroalgae in Least ALU diet | +3.73 | +0.14 | 0.00 | 0.00 | +3.78 | +0.14 | 0.00 | 0.00 |
| Duckweed in Least ALU diet | +0.59 | +0.01 | 0.00 | 0.00 | +0.33 | +0.00 | 0.00 | 0.00 |
| BPM in Least ALU diet | +3.68 | +0.24 | 0.00 | 0.00 | +3.73 | +0.25 | 0.00 | 0.00 |
| LPC in Least ALU diet | +0.39 | +1.64 | +1.06 | +0.28 | 0.00 | 0.00 | 0.00 | 0.00 |
| Insect meal in Least ALU diet | +6.46 | +8.87 | 0.00 | 0.00 | +6.55 | +9.24 | 0.00 | 0.00 |
| Macroalgae in Least P excretion diet | +3.61 | +0.04 | 0.00 | 0.00 | +3.76 | +0.05 | 0.00 | 0.00 |
| Duckweed in Least P excretion diet | +0.14 | 0.00 | 0.00 | 0.00 | +0.07 | 0.00 | 0.00 | 0.00 |
| Insect meal in Least P excretion diet | +6.25 | +2.80 | 0.00 | 0.00 | +6.51 | +2.91 | 0.00 | 0.00 |

**Table 5.8**: Sensitivity analysis of the effect of high production yield on the environmental burdens of the diets. Each novel ingredient's production yield was reduced and increased on an individual basis. Results are presented as the percentage increase (+) or decrease (-) from the mean. Diets are presented where at least one burden was affected. The environmental burdens were greenhouse gas emissions (GWP), agricultural land use (ALU), N excretion and P excretion.

| | **Fast-growing line** | | | | **Slow-growing line** | | | |
|---|---|---|---|---|---|---|---|---|
| **Parameter** | **GWP** | **ALU** | **N excretion** | **P excretion** | **GWP** | **ALU** | **N excretion** | **P excretion** |
| Microalgae in Microalgae diet | -11.74 | -0.11 | 0.00 | 0.00 | -13.06 | -0.11 | 0.00 | 0.00 |
| Macroalgae in Macroalgae diet | -3.92 | -0.03 | 0.00 | 0.00 | -4.21 | -0.04 | 0.00 | 0.00 |
| Duckweed in Duckweed diet | -3.48 | -0.01 | 0.00 | 0.00 | -3.64 | -0.01 | 0.00 | 0.00 |
| YPC in YPC diet | -3.30 | -1.95 | 0.00 | 0.00 | -3.65 | -2.10 | 0.00 | 0.00 |
| BPM in BPM diet | -7.37 | -0.06 | 0.00 | 0.00 | -8.37 | -0.06 | 0.00 | 0.00 |
| LPC in LPC diet | -14.36 | -21.78 | 0.00 | 0.00 | -15.22 | -22.57 | 0.00 | 0.00 |
| Insect meal in Insect meal diet | -10.79 | -3.12 | 0.00 | 0.00 | -11.68 | -3.67 | 0.00 | 0.00 |
| Microalgae in Least GWP diet | -1.28 | -12.23 | +1.69 | +0.81 | -0.33 | -14.20 | +1.48 | +0.94 |
| YPC in Least GWP diet | -0.20 | +0.30 | +0.16 | -0.33 | 0.00 | 0.00 | 0.00 | 0.00 |
| BPM in Least GWP diet | -8.39 | -19.19 | -2.87 | +0.56 | -9.31 | -22.01 | +0.68 | +0.46 |
| LPC in Least GWP diet | -9.62 | -11.76 | 0.00 | 0.00 | -8.57 | -10.19 | 0.00 | 0.00 |
| Microalgae in Least ALU diet | -6.77 | -0.38 | 0.00 | 0.00 | -6.86 | -0.40 | 0.00 | 0.00 |
| Macroalgae in Least ALU diet | -3.73 | -0.14 | 0.00 | 0.00 | -3.78 | -0.14 | 0.00 | 0.00 |
| Duckweed in Least ALU diet | -0.58 | -0.01 | 0.00 | 0.00 | -0.32 | 0.00 | 0.00 | 0.00 |
| YPC in Least ALU diet | 0.15 | -0.44 | +1.06 | +0.28 | 0.00 | 0.00 | 0.00 | 0.00 |
| BPM in Least ALU diet | -3.68 | -0.24 | 0.00 | 0.00 | -3.73 | -0.25 | 0.00 | 0.00 |
| LPC in Least ALU diet | -0.19 | -2.37 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Insect meal in Least ALU diet | -6.46 | -8.87 | 0.00 | 0.00 | -6.55 | -9.24 | 0.00 | 0.00 |
| Macroalgae in Least P excretion diet | -3.61 | -0.04 | 0.00 | 0.00 | -3.76 | -0.05 | 0.00 | 0.00 |
| Duckweed in Least P excretion diet | -0.13 | 0.00 | 0.00 | 0.00 | -0.07 | 0.00 | 0.00 | 0.00 |
| Insect meal in Least P excretion diet | -6.25 | -2.80 | 0.00 | 0.00 | -6.51 | -2.91 | 0.00 | 0.00 |

**Table 5.9**: Sensitivity analysis of the effect of adapting the economic allocation rule applied to the model on the environmental burdens of the diets. The price of the novel ingredients so that they were equal to soymeal per kg of lysine. Results are presented as the percentage increase (+) or decrease (-) from the mean. Diets are presented where at least one burden was affected. The environmental burdens were global warming potential (GWP), agricultural land use (ALU), N excretion and P excretion.

| | **Fast-growing line** | | | | **Slow-growing line** | | | |
|---|---|---|---|---|---|---|---|---|
| **Parameter** | **GWP** | **ALU** | **N excretion** | **P excretion** | **GWP** | **ALU** | **N excretion** | **P excretion** |
| Microalgae diet | -6.78 | -0.06 | 0.00 | 0.00 | -7.54 | -0.06 | 0.00 | 0.00 |
| Macroalgae diet | -13.87 | -0.12 | 0.00 | 0.00 | -14.89 | -0.13 | 0.00 | 0.00 |
| LPC diet | +8.32 | +12.54 | 0.00 | 0.00 | +8.82 | +12.99 | 0.00 | 0.00 |
| Least GWP diet | +5.05 | +6.77 | 0.00 | 0.00 | +4.97 | +5.87 | 0.00 | 0.00 |
| Least ALU diet | -16.76 | +0.26 | +1.06 | +0.28 | -17.33 | -0.73 | 0.00 | 0.00 |
| Least p excretion diet | -12.76 | -0.15 | 0.00 | 0.00 | -13.29 | -0.16 | 0.00 | 0.00 |

**Table 5.10**: Sensitivity analysis of the effect of reducing the maximum inclusion of each novel ingredient by 15% on the environmental burdens of the diets. Results are presented as the percentage increase (+) or decrease (-) from the mean. Diets are presented where at least one burden was affected. The environmental burdens were global warming potential (GWP), agricultural land use (ALU), N excretion and P excretion.

| | Fast-growing line | | | | Slow-growing line | | | |
|---|---|---|---|---|---|---|---|---|
| **Parameter** | **GWP** | **ALU** | **N excretion** | **P excretion** | **GWP** | **ALU** | **N excretion** | **P excretion** |
| Microalgae in Microalgae diet | +4.09 | +5.68 | -4.82 | -0.94 | +4.53 | +5.86 | -4.33 | -0.94 |
| Macroalgae in Macroalgae diet | -5.74 | +10.50 | -4.60 | +0.74 | -4.84 | +3.58 | -2.73 | +0.22 |
| Duckweed in Duckweed diet | -1.66 | +19.37 | -9.35 | +0.09 | -7.66 | +20.15 | -9.65 | +0.60 |
| YPC in YPC diet | +1.87 | -1.39 | -7.18 | +0.46 | +2.43 | +1.31 | -6.32 | -1.01 |
| BPM in BPM diet | +7.08 | +3.20 | -1.44 | +0.39 | +8.17 | +4.25 | -1.11 | -0.05 |
| LPC in LPC diet | -2.95 | -3.46 | -15.95 | -3.64 | -3.88 | -3.86 | -14.64 | -3.72 |
| Insect meal in Insect meal diet | -6.26 | +15.63 | -7.17 | +5.76 | -7.90 | +20.63 | -6.98 | +5.27 |
| LPC in Least GWP diet | +0.79 | -0.08 | +0.65 | +0.05 | +0.14 | +0.28 | +0.28 | +0.07 |
| Microalgae in Least ALU diet | -3.32 | +7.60 | -4.10 | -4.89 | -3.47 | +7.67 | -4.06 | -4.69 |
| Macroalgae in Least ALU diet | -1.67 | +1.21 | +0.16 | +0.72 | -1.70 | +1.28 | +0.16 | +0.70 |
| BPM in Least ALU diet | -0.92 | +3.29 | -2.65 | -3.06 | -0.94 | +3.20 | -2.65 | -2.97 |
| Insect meal in Least ALU diet | -7.18 | +4.65 | -6.26 | -3.88 | -7.53 | +4.58 | -6.18 | -3.77 |
| Macroalge in Least P excretion diet | -2.31 | +1.47 | -2.03 | +0.48 | -2.42 | +1.63 | -1.85 | +0.51 |
| Insect meal in Least P excretion diet | -4.42 | -0.56 | -5.84 | +6.09 | -5.33 | +0.04 | -8.51 | 0.00 |

### 5.5 Discussion

Europe faces increased pressure for feed protein supplies from a global population which is growing annually in size and appetite for animal products, especially in developing nations (van Krimpen et al., 2013). Non-ruminant livestock, such as pigs and poultry, consume the most soybean imports (≈85%), with the poultry collectively consuming the most soymeal that is processed in the EU (meat-producing chickens = 32%, laying hens = 10%) of any other livestock sector (van Gelder et al., 2008). Low self-sufficiency in the protein supply for the increasing production of chicken meat exposes Europe to food security risks, which may be related to market factors such as trade distortions, global price volatility and ingredient scarcity. Furthermore, feed provision represents the poultry industry's biggest environmental hotspot (Leinonen et al., 2012, Tallentire et al., 2017), exacerbated by the inclusion of imported soybeans from South America where they are grown in vast monocultures on land obtained via deforestation (van der Werf et al., 2009, Leinonen et al., 2012, de Visser et al., 2014, Kebreab et al., 2016). Meanwhile, the chicken meat industry is facing increasing pressure to improve animal welfare by reducing growth rates (EFSA Panel on Animal Health and Welfare, 2010, Jansen, 2014, RSPCA, 2015, Compassion in World Farming, 2017), which leads to increased feed intake (Tallentire et al., 2018a). Tackling these future challenges, whilst still meeting the demands of stakeholders and society in general, will continue to be a key objective of the poultry industry (The Poultry Site, 2014a). It is therefore highly relevant to investigate novel ingredients as an alternative protein source to imported soybeans for feeding future meat-producing chicken lines, in European livestock systems.

The Microalgae, YPC, BPM, LPC and Insect meal diets all had lower associated GWP than the Conventional diets, whilst incorporating macroalgae and duckweed into the diets resulted in greater GWP than the Conventional diets. Macroalgae and duckweed have low energy contents relative to conventional protein and energy sources (e.g. soymeal and wheat respectively), hence the energy deficit caused by the incorporation of these ingredients was largely counteracted by the increased incorporation of oil and maize gluten meal which increased the GWP of the diets. Insect meal replaced the most soybeans and soybean derivatives. This is due, in part, to its high maximum inclusion limit, but also due to its high energy content relative to (for example) BPM, which was the next best novel ingredient at replacing the need for soybeans and soybean derivatives. The Insect meal diet, therefore, had the lowest oil inclusion of all the alternative diets. Despite this, the BPM diet had a lower GWP due to BPM having the lowest associated GHG emission of all the novel ingredients included in this study.

Since the arable land in developed countries has declined in recent decades and this trend is expected to continue into the future, reducing the ALU burden of European livestock production is important in maximising the global carrying capacity (Alexandratos and Bruinsma, 2012). Every diet that included novel ingredients formulated in this study had an overall lower ALU burden than the Conventional diet corresponding to the requirements of each chicken meat-producing line. This is because the cultivation of the novel ingredients was intrinsically associated with low arable land requirements, especially the aquatic novel ingredients and BPM. LPC, YPC and insect meal all had a higher ALU burden due to the requirement of arable land to produce the feedstuff/feedstock used in these system processes, but all these novel ingredients had a lower ALU burden than soybeans and their derivatives.

In order to meet bird nutritional requirements whilst minimising a specific objective, some of the diets formulated using this model incorporated conventional ingredients that were not present in the Conventional diet formulation. For instance, barley, and to a lesser extent sunflower meal, was incorporated into the Insect meal diets. Including these ingredients ensured that the dietary threonine and arginine levels reached at least their minimum requirements, since these amino acids are low in insect meal relative to soymeal, for the least cost. Due to their low crude protein content, oats were only incorporated in the Least N excretion diets. The utilization of conventional yet less commonly used ingredients to meet bird nutritional requirements, alongside potential novel ingredients, highlights the advantages of performing a holistic approach to diet formulation such as what was carried out in this study. More generally, incorporating additional ingredients provides a market for a diversity of crops which in turn diversifies farming systems and leads to positive, indirect effects on soil quality, as well as insect and bird biodiversity.

No alternative diet formulated using the model presented in this study reduced all four environmental burdens simultaneously, when compared with the Conventional diets. GHG emissions are often prioritised when it comes to quantifying environmental burdens in literature, corporate social responsibility reports, policy or voluntary carbon labelling schemes (Garnett, 2009, Tan et al., 2014). However, targeting an individual environmental burden can have huge implications on other types of environmental impact caused by a production system in a phenomenon often referred to as “pollution swapping” (Stevens and Quinton, 2009). For instance, minimising ALU resulted in the greatest nutrient excretions (Figures 5.2 and 5.3); this is because of the high inclusion of novel ingredients which resulted in the oversupply of important nutrients in the diets. Formulating diets to reduce certain environmental burdens within specified economic and environmental constraints has been shown in previous studies (Castrodeza et al., 2005, Pomar et al., 2007, Dubeau et al., 2011, Moraes and Fadel, 2013, Mackenzie et al., 2016a, Tallentire et al., 2017), and can be applied in the future when incorporating novel ingredients such as the ones discussed here. This methodology could therefore allow nutritionists to integrate environmental objectives into system specific diet formulation. For instance, to reduce the GWP and ALU burdens of systems where manure can be managed sustainably, or to limit the excretion of N in nitrate vulnerable zones. In some cases, the novel ingredients themselves show huge potential for mitigating the negative impacts of these future chicken diets, such as by integrating duckweed ponds at the end of the livestock systems as a manure management option, thus contributing towards a circular economy (Cheng et al., 2002, Krishna and Polprasert, 2008, Xu and Shen, 2011). This gives nutritionists and livestock producers the option to integrate environmental objectives into diet formulation, facilitating bespoke feeding strategies and management choices specific to individual systems.

Whilst the total environmental burdens of feeding the birds each diet were greater for the slow-growing line than they were for the fast-growing line, in some cases the incorporation of novel ingredients led to the slow-growing line having at least some environmental burdens that were lower than those of the fast-growing line fed on a Conventional diet formulation. The GWP of the Microalgae, BMP, LPC, Insect meal and Least GWP diets formulated for the slow-growing birds were lower than that of the conventional diet formulated for the fast-growing birds. The ALU of the Microalgae, Macroalgae, Duckweed, BMP, LPC, Insect meal, Least GWP, Least ALU and Least P excretion diets formulated for slow-growing birds were lower than that of the conventional diet formulated for the fast-growing birds. All diets formulated for the slow-growing birds had a greater associated N excretion than the conventional diet formulated for the fast-growing birds. The P excretion associated with feeding the Insect meal and the Least P excretion diets to the slow-growing birds was lower than the P excretion associated with feeding the conventional diet to the fast-growing birds. These results show that the environmental burdens of feed associated with transitioning towards a slow-growing, high welfare chicken production system can be partially mitigated through carefully considered nutritional and manure management.

The sensitivity analysis revealed that the GWP and ALU were sensitive to the coefficient of variation in the yield of microalgae, BPM, LPC and insect meal. Further research into the production efficiency of these ingredients would strengthen the model. Sensitivity was shown to variation in the economic allocation input data, however only one diet formulation was changed by altering the economic value of the co-products; this revealed that the allocation method applied to the baseline model was sufficiently robust to allow the tool to generate diet formulations for specific sustainability objectives. At least one environmental burden was sensitive to reducing the maximum inclusion level of macroalgae, duckweed, LPC and insect meal in most diets where incorporation of these ingredients was fixed at that inclusion level. In addition, reducing the maximum inclusion level of microalgae, macroalgae, BPM, LPC and insect meal all affected the formulation of at least one diet designed to reduce an environmental burden. This demonstrates the importance of, where possible, not constraining the diet formulation process with overly conservative maximum inclusion limits, as to maximise the potential sustainability of the industry (Mackenzie et al., 2016a).

Attributional LCA was applied in the study described in this chapter. However, would it have been more appropriate to use a consequential approach when modelling the environmental impact implications of future feed ingredient choices? If using a specific ingredient in chicken diets is shown to increase some environmental impacts, nutritionists may wonder what the fate of this ingredient would be if not used in animal feed. For instance, consequential LCA could address what would happen to the soybean production in South America if there were to be a reduction in demand for soymeal in Europe. There are, however, issues with using such an approach and these were highlighted in Chapter 1 (section 1.3.1). For instance, when utilising co-products such as YPC in feed, there are a multitude of pathways for such a material to be used, if not included in the diets of the livestock system modelled. Expanding the model to include future scenarios to predict the replacement pathway for an ingredient, when this cannot be predicted with any confidence, means the modelling exercise would stray further away from being evidence based (Heijungs and Guinée, 2007).

Whilst the use of imported soybeans in European livestock feed is unsustainable, thus far only a few studies have addressed the implications of using alternative proteins for system level environmental impacts (e.g. Leinonen et al., 2013, de Boer et al., 2014, Van Zanten et al., 2015). This is the first study to investigate the potential of several novel ingredients simultaneously to reduce the total required soybeans in future chicken diets, by combining linear programming feed formulation and LCA methodology with horizon scanning. By applying this to two potential future meat-producing chicken lines, it enables nutritionists, livestock producers, breeders and policy makers to integrate environmental objectives into future feeding and breeding strategies. Comparing the environmental implications of each novel ingredient in this way is an important step when considering which novel technologies could produce the most sustainable outcomes.

## 5.6 Conclusion and implications

In this chapter a holistic diet formulation methodology which accounts for both environmental burdens and future livestock requirements was presented. Novel ingredients were incorporated into these diets, which display enormous potential for use as an alternative to soybeans in livestock feed in the future. However, the technologies being developed to produce these novel ingredients are still in their infancy; much work is required to viably upscale these system processes so that production is efficient and competitive with imported soybeans. Additional research is still required in the characterisation of these ingredients and their effects on specific livestock before they can become viable feed alternatives. In some cases, their incorporation into livestock diets face technical challenges and legislative barriers e.g. inclusion of insects in EU poultry diets (Brookes, 2001, Józefiak and Engberg, 2015). Nevertheless, it has been shown that increased environmental burdens associated with increasing animal welfare may be mitigated through carefully integrated nutrition and manure management systems. Most importantly in terms of Europe’s future food security, it was shown how imported soybeans can be replaced in non-ruminant livestock diets. Such work is crucial in efforts to improve the sustainability of livestock systems moving forward.

# Chapter 6. Incorporating animal welfare in a social life cycle assessment model of European chicken production

## 6.1 Abstract

The majority of sustainability studies of livestock have thus far focused on environmental performance and profitability. Where social analysis has been carried out, there has yet to be a consistent methodology developed that incorporates animal welfare into the SLCA. The aim of this study was to put forward an alternative methodology on how this may be achieved successfully, using chicken meat production in Europe as a case in point. A framework was developed to assess animal welfare that is congruous with already established methods for SLCA that have gained traction amongst practitioners. The quantitative risk of each social indicator was characterised based on farm data collected from continental Europe. Thus, an individual associated risk level for each welfare indicator could be determined for each farm based on best to worst practice; these risk levels received progressively higher weighting factors. The overall animal welfare was then assessed using a weighted sum methodology to aggregate the quantitative datasets for each welfare indicator and the estimated time the animal will be exposed to a specific risk level. Farms that keep more birds per building had an increased overall animal welfare impact. The trend over recent years appears to have been to increase the number of birds that are reared together. This suggests that animal welfare, determined by negative welfare indicators, is worse in more recently established farm buildings. Livestock farming is under increasing pressure to become more efficient and more sustainably intensive to meet the demands of a growing global population within the carrying capacity of the planet. Meanwhile, there is increasing public concern over standards of farm animal welfare. Hence, the development of a scalable impact category for assessing animal welfare within a SLCA framework, that is related to welfare assessment frameworks such as the “Five Freedoms”, is important to the sustainability of livestock industries. The study presented in this chapter provides a springboard for further development of SLCA, animal welfare assessment and, ultimately, improved animal welfare in livestock systems.

## 6.2 Introduction

For a production system to be sustainable it should be economically viable, contribute to the equitable management of resources, be embedded in its socio-cultural context and be respectful towards both humans and non-human animals (henceforth referred to in this chapter simply as “animals”) (Broom et al., 2013, Dolman et al., 2014). As a growing proportion of society is becoming sensitive to the way animals are reared, consumers are beginning to demand more humane treatment of livestock and, as a result, animal welfare is becoming a major concern in the agri-food sector (Appleby, 2003, European Commission, 2005, Hall and Sandilands, 2007, Carenzi and Verga, 2009, Bernués et al., 2011, de Jonge and van Trijp, 2013, Singer, 2013, 2017). Animal welfare is the health and well-being of animals and characterised by a concern that the way in which humans treat animals can cause the animals physical and mental suffering. In agricultural systems, where the environment is restricted, animals are often less able to carry out the actions that would reduce suffering (Dawkins, 1990). A widely used framework for the practical assessment of animal welfare is that of the “Five Freedoms”; these are: freedom from hunger and thirst; freedom from discomfort; freedom from pain, injury and disease; freedom to express normal behaviour and; freedom from fear and distress (FAWC, 1979, 2009).

Although chicken meat is expected to become the most consumed animal protein globally (Kearney, 2010, Alexandratos and Bruinsma, 2012, FAO, 2016c), it is often shown to be the animal protein with the highest associated animal welfare concerns (Matheny, 2003, Lamey, 2007, Clark et al., 2016, Scherer et al., 2017). There are concerns about the space in which the animals are raised, the enrichment of their environment or lack thereof, and their ability to express normal behaviour. Furthermore, production diseases associated with bird welfare (e.g. leg problems, contact dermatitis, ascites and sudden death syndrome) have been exacerbated by selection pressures for fast growth rate and increased feed efficiency placed on the birds over recent decades (EFSA Panel on Animal Health and Welfare, 2010). There are many important interactions between genotype and the environmental inputs, such as feeding regime and bird management, which can influence the animal welfare experienced in practice (Bessei, 2006, Buyse et al., 2007).

Much research has focused on the environmental impact of livestock production, and there is not a standard method for carrying out SLCA as there is for ELCA (i.e.

International Organisation for Standardisation, 2006). As a consequence, there have been relatively fewer studies thus far which have expanded life cycle assessment to encompass all dimensions of sustainability with regards to livestock production (Schoeneboom et al., 2014, Wu et al., 2014, Chen and Holden, 2017). Even fewer studies have considered animal welfare as a social dimension, despite its importance to sustainability (Broom, 2010); those that have included animal welfare indicators mainly focus on the dairy industry (Müller-Lindenlauf et al., 2010, Del Prado et al., 2011, Meul et al., 2012, van Asselt et al., 2015, Zucali et al., 2016), with only two studies having exclusively focused on broiler chicken systems (Bokkers and de Boer, 2009, Castellini et al., 2012).

Animal welfare encompasses scientific, ethical and political dimensions, and is a moral issue on which the progress of society can be judged (Lund et al., 2006). The absence of animal welfare as an impact category in SLCAs of the agri-food sector in its socio-cultural context excludes potentially significant issues from the assessment process (Neugebauer et al., 2014) and may be regarded as speciesism (Regan, 1987, Singer, 1995, 2013). Speciesism is a concept used to identify prejudice which references the physical or mental attributes of other species when it is arbitrary to do so, akin to intraspecies prejudices, such as sexism and racism. There is no reason to believe animals, such as chickens, are able to suffer less than humans; thus, animals should be accorded an impact category that represents their welfare alongside human social impact categories, such as Human Rights. The aim of this study was to address the methodological issues associated with incorporating animal welfare in SLCA and develop a framework for assessing animal welfare within a SLCA model, applying it to conventional chicken meat production systems in Europe as a case in point. Hence, several welfare-related indicators were applied to characterise the sector specific animal welfare risks on farms in Europe. Whilst the indicators outlined in this study are limited to only a part within the overall concept of animal welfare, the methodology developed here can accommodate other indicators in future assessments.

## 6.3 Methodological issues

### *6.3.1 Incorporating animal welfare into SLCA*

When carrying out SLCAs, most practitioners follow the guidelines that have been presented by the UNEP-SETAC (2009) Life Cycle Initiative. However, these guidelines are intrinsically anthropocentric, claiming that the ultimate goal of sustainable development is “human well-being” and making no mention of animals or their welfare. Instead, the guidelines focus on the following stakeholder groups: the workforce, the local community, the consumers, value chain actors and society. SLCA inventory data and impact assessment categories must be specified in relation to these different stakeholder groups and it is debatable how adequately each of these established stakeholder groups can represent the interests of the animals. Since animals have not been assigned an impact category or subcategory under any stakeholder group, nor have any assessment criteria been formally identified, animal welfare has been largely neglected in SLCA and life cycle sustainability assessment studies of agricultural systems (Notarnicola et al., 2017).

Although it is true that outside of captivity, animals fall victim to predators, disease and exposure, the conditions in which livestock are raised are under human control. Neugebauer et al. (2014) suggests this custodianship aligns livestock with the workforce as the most obvious stakeholder group. However, animals are not classed as workers per se, and combining human work hours and animal “work” hours when quantifying impact is not practicable. Furthermore, different species have different needs, including the needs of human workers and livestock, thus it is unlikely the animals will be sufficiently represented.

Other potential stakeholder groups that may feasibly represent animal interests are the consumers/citizens or value chain actors. Placing animals into the consumer stakeholder group follows the assumption that animal welfare is subjective and defined by the experience of the customer (Te Velde et al., 2002, Broom, 2010, de Jonge and van Trijp, 2013). However, as was the case with the first example, animals have a uniquely different relationship with the production system to consumers; the animals are the product. Animal welfare should be seen as independent of the empathy of individuals and therefore consumer judgment or value choices may not adequately represent the animal’s interests. The society stakeholder group has similar constraints and has only been proposed to cover ethical impacts at a societal level, e.g. conflict, legal system fragility and corruption.

Animals cannot express their concerns without the inputs of an invested third party (Compassion in World Farming, 2017); hence animal welfare may more easily fit in the value chain actors group, akin to promoting social responsibility. Alternatively, animals could be classified into their own stakeholder group. However, Neugebauer et al. (2014) argue that defining livestock in this way could lead to inconsistencies with existing stakeholder groups, pointing out the fact children are not defined as an own group, but as a subcategory.

It is crucial that a methodology be developed to allow the incorporation of animal welfare into simulation models at a farm level for comprehensive analysis of the agri-food sector to be achieved (Neugebauer et al., 2014, Llonch et al., 2015). However, it is at present unclear how practitioners should assess animal welfare alongside other impact categories when carrying out sustainability assessments. In this study, an individual social impact category was developed to assess animal welfare; this methodology can easily be adopted into any stakeholder group in the future should animals be acknowledged in an official framework.

### *6.3.2 Welfare assessment criteria*

Various assessment criteria have been proposed and used to assess animal welfare at the farm level and, in general, these are defined as being either resource- or animal-based indicators (Johnsen et al., 2001, Blokhuis et al., 2003). Traditionally, animal welfare has been assessed using resource-based indicators which involve measurement of the resources supplied, farm management practices and environmental conditions of a farm compared with the presumed needs of the animals (Bartussek, 1999, van Asselt et al., 2015). In a recent study, Scherer et al. (2017) considered chicken slaughter age and the stocking density; these are examples of resource-based indicators because they are affected by system management choices. Quality assurance schemes rely on resource-based indicators as a basis of their assessment of welfare (Assured Food Standards, 2017).

Although resource-based indicators have been shown to correlate with some animal-based indicators, e.g. behaviour (Mollenhorst et al., 2005), the provision of good management and resources alone does not guarantee that an animal has a high standard of welfare. For instance, due to continued intensive artificial selection, broiler chicken welfare may be increasingly influenced by genetics (EFSA Panel on Animal Health and Welfare, 2010, Fraser et al., 2013). Thus, the welfare assessment should include animal-based indicators where possible (Hewson, 2003, Whay et al., 2003, Munsterhjelm et al., 2015). Welfare assessment should also, where possible, account for the positive experiences afforded to the animals (FAWC, 2009, Wathes, 2010).

It is important to use welfare indicators that sufficiently reflect the scale of the issue. In their proposed framework, Scherer et al. (2017) considered stocking density, the number of animals affected, the slaughter age and “sentience level” (determined by calculating the cortical neurons an animal has relative to humans) as indicators of animal welfare. Using sentience level as an indicator is fundamentally flawed, as there is nothing to suggest an animal with lower “intellect” has any less ability to suffer; indeed, as pain is a primitive survival response, an animal with lower intellect may require more intense pain in order to learn. Furthermore, following this framework’s emphasis on the number of animals affected, insects have worse welfare than any other livestock despite their lower presumed sentience (Chan, 2011); this does not reflect present societal concerns (Varner, 2002). These indicators were thus ill-suited in the SLCA methodology.

Where animal welfare indicators have been incorporated into SLCA studies, the methodology by which animal welfare is assessed ranges from simply checking that employee training in good welfare practices is provided for farm workers (Revéret et al., 2015), to more sophisticated multicriteria decision analysis approaches that incorporate several animal-based indicators, such as kinetic activity level, animal injury and stress level (Castellini et al., 2012). Despite the superiority of animal-based indicators over resource-based indicators for assessing animal welfare, methodologies that rely on comprehensive animal-based indicators can require time-consuming data collection (Bokkers and de Boer, 2009, Castellini et al., 2012); these methodologies cannot easily be applied to an SLCA framework on a large scale. Thus, “iceberg indicators” may present a convenient compromise for evaluating the welfare performance of a farm (Wathes, 2010), especially when the data required are usually collected as standard practice, e.g. bird mortality or carcass condemnation (see section 6.4.3). Elsewhere the effects of changing farming practices for environmental impact reduction and animal welfare have simply been identified without a methodology being developed to assess the trade-offs between these impacts (De Vries et al., 2011, Leinonen et al., 2014). Hence, until now, no SLCA methodology has successfully included animal welfare in a way that is both scalable and related to welfare assessment frameworks.

The data collected in animal welfare assessments for each indicator are often expressed on an ordinal scale, which limits the use of weighted sums to aggregate them (Botreau et al., 2007). In SLCA, ranking systems that employ qualitative and semi-qualitative based assessment tools and relative scores may be applied (Müller-Lindenlauf et al., 2010, Del Prado et al., 2011, Head et al., 2014). These scores are based on previous literature or expert opinion and therefore may be subjective and, at worst, do not adhere to basic LCA requirements, such as by acting independently of the functional unit. For instance, when animal welfare is determined using an ordinal scale to rate a farm, and the number of animals or length of time the animals are affected on that farm is not considered, the animal welfare impact value associated with the product will always be the same regardless of the functional unit (e.g. Müller-Lindenlauf et al., 2010).

Although in most cases the authors of SLCA studies that consider animal welfare have attempted a logical characterisation methodology, e.g. determined by benchmarking farms via statistical analysis (Dolman et al., 2014) or by welfare protocols (Welfare Quality®, 2009, De Vries et al., 2011, Meul et al., 2012, Zucali et al., 2016, Scherer et al., 2017), no consistent methodology has been developed between studies. This can make it difficult to compare the animal welfare of different systems, especially when the systems are situated in different countries where social acceptability varies; as a social impact, animal welfare should not relate to cultural differences but to the biology of the species in question. To amend this, a framework was developed which has characterised the risk of several welfare indicators that can be applied as a framework for assessing (at least in part) the animal welfare of broiler chickens across Europe.

## 6.4 An alternative methodology

### *6.4.1 Goal, scope and system boundary of the SLCA*

The SLCA methodology developed in this study was applied to chicken production as a case in point. The goal of the SLCA was to evaluate the differences in animal welfare impact of meat chicken production between four European countries. In doing so the associations between farm characteristics and animal welfare implications in European chicken production systems could be identified. Data were collected from conventional chicken meat production farms, i.e. climate-controlled (e.g. fan-ventilated), artificially lit indoor systems, which is the predominant chicken meat production system in Europe (Compassion in World Farming, 2013). These data were used to: 1) inform the animal welfare assessment framework (section 6.4.4) that was applied in this study and; 2) assess the overall animal welfare impact associated with the functional unit of each farm.

The functional unit was the production of 1 kg of chicken meat. The system boundary of the study was limited to the chicken rearing and slaughter processes only; hence, all upstream processes associated with feed procurement, transportation and resource use were excluded for the purpose of this study, although it should be acknowledged that the boundary could be expanded to include upstream animal welfare issues in future SLCAs e.g. animal derived proteins in the feed, pest control, habitat destruction, roadkill etc. The research findings offer a context for developing options to improve the sustainability of chicken meat production systems and serve as a baseline for the future. Thus, the study presented in this chapter was aimed at a scientific audience, particularly LCA practitioners and animal welfare experts, with policy makers as a secondary interest group.

### *6.4.2 Data collection*

Data were collected from 358 conventional chicken meat production farms from across continental Europe, i.e. climate-controlled (e.g. fan-ventilated), artificially lit indoor systems, which is the predominant chicken meat production system in Europe (Compassion in World Farming, 2013). Information was provided on the characteristics of each farm, such as: the total number of birds on the farm at one time (henceforth referred to as “farm size”), the number of farm buildings in which birds are reared, the average age of the farm buildings (henceforth referred to as “farm age”) and the amount of space on the farm dedicated to rearing chickens. Farms sampled varied vastly in size (9000 - 405000 birds) and average building age (1 - 51 years). Further data were provided to determine the resource- and animal-based welfare indicators discussed in section 6.4.3. On the request of the participating poultry companies and as agreed by the PROHEALTH consortium who collected the data, the country from which each set of data was gathered was not disclosed and was instead assigned a code.

### *6.4.3 Animal welfare indicators*

To assess animal welfare within a SLCA framework, data were collected on stocking density, animal mortality and carcass condemnation in the slaughter house from broiler chicken production systems across Europe. These indicators are recorded routinely by broiler chicken producers and integrators; thus, they can readily be incorporated into sustainability assessments. Animal mortality was defined by the risk of three individual indicators: early mortality, late mortality and dead on arrival (DOA) at slaughter house. The indicators are more practical for use in future SLCAs than those used in other studies of chicken production (Bokkers and de Boer, 2009, Castellini et al., 2012). The indicators applied in this study were all negative, i.e. increased values relate to an increased animal welfare impact. Collectively, the animal welfare indicators reveal the farm animal welfare implications and at which part of the production process animal welfare may be improved, although other indicators could be included if data were available. The justification for each indicator and its relevance to animal welfare is discussed below.

Stocking density is defined by the total bird mass per square meter of rearing space at slaughter weight. Influencing welfare mainly via litter quality, air quality, pathogen transmission and thermal stress, high stocking density has been associated with the increased prevalence of foot pad dermatitis, hock burn, breast blisters, soiled plumage, restricted locomotion and panting (McLean et al., 2002, Bessei, 2006, Allain et al., 2009, EFSA Panel on Animal Health and Welfare, 2010). Thus, this indicator relates to the animals’ freedom from discomfort and freedom from pain, injury and disease (FAWC, 2009). Increased stocking density can also encroach on the animals’ freedom to express normal behaviour (FAWC, 2009); restricting the normal behaviours that the birds can perform may lead to other behaviours that can be presumed to indicate the space restriction is distressing, e.g. jostling, disturbance of resting birds, aggression etc. (Lewis et al., 1997, Hall, 2001, Bokkers et al., 2011, Buijs et al., 2011, Thomas et al., 2011). Of all the animal welfare indicators used in this study, stocking density was the only resource-based indicator. On its own, stocking density can be an important but insufficient proxy for quality of life. Scherer et al. (2017) used only stocking density as an indicator of the quality of life and disregarded superior animal-based indicators such as on-farm mortality, DOA and carcass condemnation. Collectively, these indicators build a much better picture of animal welfare, as management conditions such as litter quality, ambient temperature and humidity are more important than the stocking density (Dawkins et al., 2004); many welfare implications of increased stocking density can be mitigated to a certain extent through careful management.

Animal mortality included animals that had died without human intervention and those that were culled by farm workers and was comprised of three animal-based indicators: two on-farm indicators (early mortality and late mortality) and DOA. High percentage mortality is presumed to be related to poor flock health and thus associated with the animals’ freedom from pain, injury and disease (FAWC, 2009, Haslam et al., 2008, Welfare Quality®, 2009). The early mortality was the total percentage of birds that died or were culled in the first seven days. Late mortality included all on-farm fatalities that happened after the first week, but did not include the animals that died during transportation to the slaughter house. In many cases birds are culled due to performance issues that may or may not be related to poor welfare. Around half of the birds culled on the grounds of animal welfare can be attributed to lameness (Gocsik et al., 2017) and this was confirmed elsewhere (Applied Group; personal communication). The death of an individual bird is not necessarily a welfare problem; indeed, death may be seen as the ultimate welfare solution (Dawkins, 1990). However, the way an animal dies can cause undue suffering especially from disease or injury. In this light, timely culling can reflect good attention to the wellbeing of animals. On the other hand, culling underperforming but otherwise healthy birds may be seen as unethical on the grounds of welfare and respect for animals and will lead to increased lives lost; the ideal situation regarding welfare is when culling is not needed (EFSA Panel on Animal Health and Welfare, 2010, Gremmen et al., 2018). For practicality, the cause of death was not recorded in data utilised in this study.

DOA refers to the percentage of the flock that die in transit between the growing facility and the slaughterhouse and has been widely acknowledged as an important indicator of animal welfare in numerous studies (Nijdam et al., 2004, Warriss et al., 2005, 2006, Petracci et al., 2006, Haslam et al., 2008, Chauvin et al., 2011, Kittelsen et al., 2015, Jacobs et al., 2017). It reflects the conditions experienced during transport, in combination with previous life factors affecting the stress-susceptibility of individual birds. Transporting birds from the farm to the slaughterhouse subjects them to animal welfare issues related to each of the Five Freedoms (FAWC, 2009), due to: levels of handling which they have not previously experienced, noise, vibration, thermal challenges, feed and water withdrawal, high stocking density, social disruption and unfamiliar environments (EFSA Panel on Animal Health and Welfare, 2010). A high percentage of birds DOA has been associated with increased body temperature, soiled plumage and panting at the farm level (Jacobs et al., 2017); these are all indicators of animal stress that are not reported as standard by farms.

Finally, carcass condemnation refers to the number of birds that are rejected at the slaughter stage due to signs of disease or faecal contamination. Specifically, carcasses may be rejected due to evidence of tumours (e.g. in the liver), septicaemia infection, ascites, airsacculitis, cellulitis, synovitis or other signs of inflammation, bruising and haemorrhaging (Lupo et al., 2008, Allain et al., 2009, Gouveia et al., 2009). These conditions are associated with poor welfare related to the Five Freedoms and will result in increased animal mortality in most instances. However, where birds survive to the slaughter stage, these conditions may have caused undue suffering; in particular, stress caused by loading and transport may exacerbate the symptoms and enhance the expression of clinical signs in animals suffering from a disease (Huneau-Salaün et al., 2014). Animal-based indicators which can be measured post-mortem, and which are strongly correlated with the climatic conditions within the house during rearing, are seen by some as the most efficient way to organise controls and target potential problems with environmental conditions on farms (European Commission, 2018b).

Including carcass condemnation as a welfare indicator gives farms no incentive to keep birds alive that are experiencing welfare issues prior to slaughter. This is important, as the maximum stocking density a farm may achieve depends on mortality rate (European Commission, 2007); if the on-farm mortality is too high, the stocking density of subsequent flocks must be reduced, and this is often perceived by farmers as a penalty. To stay below the limit and avoid such a reduction, birds that might otherwise have been culled may instead be transported for slaughter, so they are not included as part of the on-farm mortality rates (European Commission, 2018b). Carcasses may also be condemned due to inadvertent incorrect slaughter that can have animal welfare implications (e.g. live bird scalding). However, the slaughtering method was not considered important in this methodology from an animal welfare perspective as, provided the process is humane, it is not intrinsic to welfare assessment frameworks (FAWC, 2009). Finally, increased carcass condemnation affects welfare via increasing the number of birds affected for the functional unit (Scherer et al., 2017).

### ***6.4.4 Assessment framework***

In this study, animal welfare was incorporated into the SHDB methodology for carrying out an SLCA developed by Benoît-Norris et al. (2012). The SHDB, built by New Earth in conjunction with an economic model derived from the Global Trade Analysis Project, is an overarching framework with a database designed to ease the data collection burden in sustainability assessment studies (Benoît-Norris et al., 2012, 2014, Pelletier et al., 2018). Following this methodology, each social indicator associated with a social impact category is assigned a quantified level of risk, which is then multiplied by the amount of time associated with the functional unit (Benoît-Norris et al., 2010, 2011).

The characterization of animal welfare risks for meat chickens in Europe was based on the quartiles of the data collected for each indicator: stocking density, early mortality, late mortality, DOA and carcass condemnation. This is consistent with the SLCA methodology developed by Benoît-Norris et al. (2015) where the risk levels assigned to the social indicators were based on the quartiles or obvious transitions of the data and defined as low, medium, high and very high risk (Table 6.1). Hence, an indicator would be determined as being low risk if it had a value in the lower quartile of the sample data for that indicator, medium risk if it was in the second quartile, high risk if it was in the third quartile and very high risk if it was in the upper quartile.

**Table 6.1**: Risk characterisation rules for animal welfare indicators at a sector level in Europe.

| Level of Risk | Early mortality (%) | Late mortality (%) | Dead on arrival (%) | Condemned carcasses (%) | Stocking density (kg/m$^2$) |
|---|---|---|---|---|---|
| Low | <0.56 | <2.18 | <0.09 | <0.61 | <33.74 |
| Medium | 0.56 - 0.91 | 2.18 - 2.75 | 0.09 - 0.14 | 0.61 - 1.00 | 33.74 - 39.59 |
| High | 0.92 - 1.23 | 2.76 - 3.34 | 0.15 - 0.21 | 1.01 - 1.60 | 39.60 - 45.25 |
| Very high | >1.23 | >3.34 | >0.21 | >1.60 | >45.25 |

The levels of risk were weighted by a factor of 0.1, 1, 5 and 10 for the low, medium, high and very high risk respectively (Benoît-Norris et al., 2015). These weightings were designed to represent the relative probability of an adverse situation to occur but may be changed in the future. Individual indictors may also receive different weightings depending on their importance, however every indicator was regarded as equally important in this study. The animal “work hours”, i.e. the collective hours (hrs) of life associated with the functional unit, were augmented depending on the level of risk throughout the system that was being assessed (Pelletier et al., 2018). To calculate the total hours associated with the functional unit, the birds that provided the meat, the birds that died in transit and the birds whose carcasses were rejected were associated with the total hours from hatch to slaughter weight. The on-farm mortalities were only associated with 50% of the time the birds were exposed to the risk of dying at each stage, because the exact time of death was not recorded. Since the weighted factor for medium risk had a value of 1, medium risk was used as the reference when calculating the weighted sum for animal welfare impact (Equation 3). This is consistent with the SHDB methodology, i.e. every social impact category can be expressed in terms of medium risk hour equivalent (mrh equiv).

Equation 3

$$Animal\ welfare\ impact\ [mrh\ eq.] = \sum_{i=1}^{n} (T[hrs] * \ R_i * W_i)$$

Where:

$i$ = indicator, e.g. of animal welfare

$n$ = number of indicators, e.g. of animal welfare

$T$ = Time, i.e. work hours

$R_i$ = risk weighting factor associated with indicator

$W_i$ = indicator weighting (all indicators had a weighting of 1 in this study)

Finally, a social hotspot index (SHI) may be calculated for the animal welfare impact (Benoît-Norris et al. 2012, 2015). This step is important, as the total value of the animal welfare impact (mrh equiv) will be changed if data for additional animal welfare indicators are collected and applied to the S-LCA. The value of the animal welfare impact also depends on the system efficiency; if birds grow faster but are slaughtered at the same age, and the risk level associated with every animal welfare indicator remains the same, then the system would have a lower animal welfare impact value associated with 1 kg of meat production despite the animal welfare being unchanged. The SHI for animal welfare impact resolves this, as the animal welfare of a system is calculated as a proportion of its maximum animal welfare impact, i.e. the potential weighted sum should the animals have been exposed to a very high risk for every animal welfare indicator (Equation 4). Whereby a SHI value of 1 would indicate the worst possible animal welfare for a given system. Each indictor may be also multiplied by an additional weighting factor $(W)$. As aforementioned, each indicator received an equal weighting in this study, but the methodology can easily be adapted to make individual indicators more or less important should the practitioner deem it appropriate to do so. Should no data be available for an indicator, e.g. for a specific farm or location, that indicator can be removed from the calculation (Benoît-Norris et al., 2015). This methodology can be used to assess any social impact category in the same way, and hence different social catergories can be combined to easily identify all the social hotspots within a system.

Equation 4

$$SHI = \sum_{i=1}^{n}(T[hrs] * R_i * W_i) / \sum_{i=1}^{n}(T[hrs] * R_{max} * W_i)$$

Where:

$SHI$ = Social hotspot index, e.g. for animal welfare

$R_{max}$ = maximum risk weighting, i.e. very high risk = 10

### *6.4.5 Data analysis*

All correlations between the welfare indicators were weak except between DOA and carcass condemnation (Table 6.2), highlighting the importance of including each indicator when calculating the animal welfare impact. Whilst no relationship was seen here between on-farm mortality and DOA, in previous studies a positive relationship between these two welfare indicators has been reported (Haslam et al., 2008, Chauvin et al., 2011). In contrast, a negative relationship was found by Jacobs et al. (2017); such an observation may indicate a greater emphasis on culling if animals are not “fit-for-transportation” (Jacobs et al., 2017). Culling birds in this way is arguably more humane than subjecting compromised animals to the ordeal of transit. This is reflected in the framework, as one consequence of the methodology presented here is that more birds overall may die at the farm stage (late mortality), than may die in transit (DOA), before a farm may be ranked a higher level of risk for these corresponding welfare indicators (Table 6.1). In addition, birds that die at the farm level are associated with half the “work hours” that a bird that dies in transit accumulates. A strong positive relationship was identified between DOA and carcass condemnation, which tentatively suggests birds are dying in transit due to predisposing conditions that would also result in carcass condemnation and not just poor handling. This justifies assigning the full lifetime to the DOA in the overall welfare calculation.

**Table 6.2**: Spearman correlation of animal welfare indicators.

| **Welfare indicator** | **Early mortality** | **Late mortality** | **Dead on Arrival** | **Carcass Condemnation** |
|---|---|---|---|---|
| Late mortality | 0.178* | - | - | - |
| Dead on Arrival | -0.118 | 0.296** | - | - |
| Carcass Condemnation | -0.140 | 0.218** | 0.657** | - |
| Stocking Density | -0.075 | 0.139 | 0.025 | 0.001 |

*Significant correlation (p=<0.05)

**Significant correlation (p=<0.01)

The farm characteristics (independent variables) were fitted in a univariate mixed model i.e. the farm age, farm size, number of farm buildings (in which birds are reared) and the average number of birds per building (henceforth referred to as “flock size”). This was to test the effect of each farm characteristic on each welfare indicator and the overall animal welfare value. Variables with a p-value of < 0.20 were retained for further analysis in a multivariable model (Van Limbergen et al., 2018). The correlations between the farm characteristics were assessed with bivariate Pearson correlation and were considered to be significant with a p-value < 0.05. The multivariable model was constructed by using a forward and backward stepwise selection procedure, also including testing of two-way interactions of potentially significant main effects. The country to which farms belong was always included as a fixed factor in the models to account for its effect. If more than one combination of independent variables were shown to have a significant effect on a dependent variable, the model with the best fit was reported. Normal probability tests and plots were examined to verify that the assumptions of normality and homoscedasticity of the residuals were fulfilled in the models. Finally, the differences between the countries for the overall welfare impact and the five indicators of welfare and the farm characteristics were analysed using analysis of variance (ANOVA) with Scheffé’s method for post hoc comparison.

## 6.5 Results of SLCA

### *6.5.1 Analysis of influence of farm characteristics on welfare indicators*

The farm age and farm size were both significantly correlated with flock size (r = -0.530 and 0.613 respectively) but were not significantly correlated with each other. The number of farm buildings was significantly correlated with farm size only (r = 0.814). For late mortality, carcass condemnation, stocking density and overall welfare, both farm age and flock size were retained in the multivariate model. Farm size was retained for stocking density and overall welfare. The number of farm buildings was retained for carcass condemnation and stocking density. Since farm size and the number of farm buildings was highly corelated, separate multivariate models were produced for stocking density to avoid issues of collinearity. No independent variable was retained for early mortality and DOA.

From the multivariate analysis, the farm age, the farm size and the number of farm buildings were not significantly associated with any welfare indictor in this study, although there was a tendency for farm age to be negatively associated with late mortality (Table 6.3). The flock size was significantly associated with both carcass condemnation and stocking density. Finally, there was a significant association between the overall welfare impact of a farm and that farm's flock size. Hence, the more birds kept per building, the greater the animal welfare impact in the systems considered (Figure 6.1).

**Table 6.3**: Final multivariate models, regarding broiler chicken welfare in Europe, for each dependent variable with at least one independent variable retained from the univariate analysis. The independent variables, their coefficients, standard errors, significance (sig.) and the model fit ($R^2$ and adjusted $R^2$ ($R^2$ adj.)) are shown. The country was included in all models as a fixed factor.

| **Welfare indicator (Dependent variable)** | **Farm characteristic (Independent variable)** | **Coefficient** | **Standard error** | **Sig. P value** | **Model fit $R^2$ ($R^2$ adj.)** |
|---|---|---|---|---|---|
| Late mortality | Farm age | -0.0149 | 0.00883 | 0.094 | 10.24% |
| | Country effect | | | 0.002 | (7.79%) |
| Carcass condemnation | Flock size | 5.6E-05 | 1.00E-05 | <0.001 | 36.75% |
| | Country effect | | | <0.001 | (35.03%) |
| Stocking density | Flock size | 0.00037 | 6.30E-05 | <0.001 | 36.88% |
| | Country effect | | | <0.001 | (35.14%) |
| Overall welfare | Flock size | 0.2464 | 0.0475 | <0.001 | 48.20% |
| | Country effect | | | <0.001 | (46.78%) |

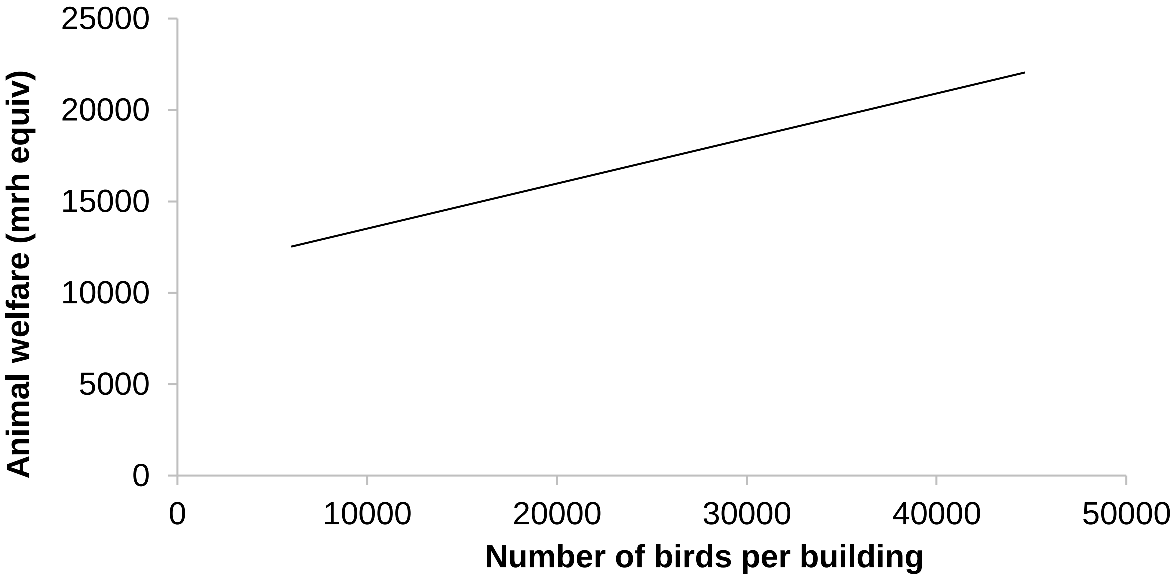

**Figure 6.1**: The relationship between number of birds reared in a building and the animal welfare measured in medium risk hour equivalents (mrh equiv) for 1 kg of chicken meat production. The regression was calculated from data taken from four countries, the country each farm belonged to was included in the model as a fixed factor.

### *6.5.2 Animal welfare impacts in four European countries*

The mean values of each animal welfare indicator and the overall welfare impact, along with the results of the analysis of the variance, of Country A, B, C and D are presented on Table 6.4. Country B had the lowest animal welfare impact per functional unit of the four countries, with a mean animal welfare impact of 3857 mrh equiv per 1kg production of chicken meat, giving Country B a mean SHI for animal welfare impact of 0.14. Country B had a high risk of early mortality, medium risk of late mortality and stocking density and a low risk of DOA and carcass condemnation.

Countries A and D had a SHI for animal welfare impact of 0.37 and 0.33 respectively. Country A had a mean animal welfare impact of 9905 and Country D had a mean animal welfare impact of 9056 mrh equiv per functional unit. Country A had a medium risk of early mortality and stocking density, a high risk of late mortality and DOA and a very high risk of carcass condemnation. Country D had high risk of early mortality, late mortality and stocking density, a medium risk of carcass condemnation and a low risk of DOA. Thus, although having relatively similar animal impact values, the higher risk levels were concentrated at different parts of the production systems in the two countries.

Country C had the highest mean overall welfare impact, with a value of 19894 mrh equiv, determined by a very high risk of early mortality, late mortality and DOA, a high risk of carcass condemnation and a medium risk of stocking density. Country C had a SHI for animal welfare impact of 0.72, which was also the highest amongst the countries considered. Thus, animal welfare in Country C was, on average, over 5 times worse than in Country B when stocking density, mortality and carcass condemnation were considered, and all indicators were of equal importance to animal welfare.

**Table 6.4**: Animal welfare indicators and overall animal welfare impact (mean values (standard deviation)) in broiler chicken farms in 4 countries (A, B, C and D). The animal welfare impact category was based on 1 kg of chicken meat production.

| Country | Early mortality (%) | Late mortality (%) | Dead on Arrival (%) | Carcass condemnations (%) | Stocking density kg/m$^2$ | Animal welfare (mrh equiv) |
|---|---|---|---|---|---|---|
| A | $0.69^{a}$ | $2.84^{a}$ | $0.17^{b}$ | $1.61^{a}$ | $36.6^{a}$ | $9905^{a}$ |
| (SD) | (0.49) | (1.59) | (0.07) | (1.07) | (6.68) | (4893) |
| B | $0.96^{a,b}$ | $2.47^{a,b}$ | $0.03^{a}$ | $0.18^{b}$ | $34.7^{a}$ | $3857^{b}$ |
| (SD) | (0.40) | (1.83) | (0.003) | (0.065) | (3.52) | (2660) |
| C | $1.52^{b}$ | $4.19^{b}$ | $0.46^{c}$ | $1.55^{a}$ | $35.8^{a}$ | $19894^{c}$ |
| (SD) | (0.43) | (1.04) | (0.18) | (0.28) | (3.13) | (2269) |
| D | $1.21^{b}$ | $2.79^{a}$ | $0.09^{a}$ | $0.76^{b}$ | $44.1^{b}$ | $9056^{a}$ |
| (SD) | (0.27) | (0.67) | (0.02) | (0.25) | (3.72) | (3110) |

Like-for-like superscript letters indicate no significant difference between countries for a given welfare indicator at the 0.05 level.

## 6.6 Discussion

The social acceptability of the agri-food sector is affected by issues such as food security, human health risks and animal welfare (Dolman et al., 2014). In this chapter, the latter was addressed by developing a framework to account for animal welfare as its own social impact category, which can be assessed in conjunction with the other social impacts outlined by Benoít-Norris et al. (2015) as part of a broader SLCA study.

Previous SLCA studies have sought to produce a scalable and representative framework for incorporating animal welfare using bespoke assessment criteria or have attempted to produce a general assessment framework for practitioners (e.g. Scherer et al., 2017). The novel risk-based approach to assessing animal welfare presented in this chapter achieved this as both resource- and animal-based indicators may be incorporated, characterised using values taken from many farms across several countries. These farms represent a broad range of management practices and thus reveal what constitutes the best and worst animal welfare performance values for each welfare indicator in European systems. Following this methodology, farms were assessed in comparison with other farms in Europe; removing the subjective nature of animal welfare within SLCA (Te Velde et al., 2002, de Jonge and van Trijp, 2013). The contribution of a social indicator to the social impact category to which it belongs is determined by the collective risk levels and work hours within the system processes. Hence, this methodology is consistent with efforts of the EU member states to support the livestock sector (Vavra et al., 2015) and, importantly, is intrinsically linked to the functional unit of interest.

Animal welfare is a multi-dimensional concept, and this is reflected in the assessment frameworks which have been widely used, such as the Five Freedoms (FAWC, 1979, Webster, 2001) or the Four Domains of Welfare Quality (Welfare Quality®, 2009). The indicators used in this study capture aspects of each of these dimensions but cannot be considered to comprehensively reflect every aspect of welfare. Nevertheless, the methodology developed has the capacity to encompass further indicators according to future availability. The indicators used in this study are all reflective of negative welfare. However, it is now widely accepted that animal welfare cannot simply be based on the absence of negative experiences, but must also encompass the presence of positive experiences, where life is worth living from the point of view of the animal (Boissy et al., 2007, Mellor, 2015). As a way of including positive welfare criteria, the assessment should extend to the measurement of environmental enrichment and behavioural expressions of the positive “emotions” of animals, including: play, interaction with enrichment (e.g. perches), exploration, affiliative behaviour, self-grooming and vocalizations (Fontana et al., 2015, Rodriguez-Aurrekoetxea et al., 2015, Bailie et al., 2018, Riber et al., 2018).

Unfortunately, research is still needed in this area of animal welfare and there are currently no feasible animal-based measures indicative of positive welfare that would easily be included in a large scale SLCA alongside the negative welfare indicators included in this study. However, the methodology presented here could easily accommodate such positive welfare indicators, if these were to be available to the practitioner. Just as the estimated time the animal was exposed to each negative welfare indicator was multiplied by the risk factor for that indicator, the estimated time the animal is exposed to a positive indicator may be multiplied by the “possibility” of the animal being exposed to that condition. The “possibility” would be the weight factor homologous to the risk level and would be calculated in the same way, based on best and worst practice in a population. In the case of positive welfare, best practice would receive the highest weighting and worst practice would receive the lowest weighting. The total positive welfare (mrh equiv) could then be subtracted from the overall welfare impact (mrh equiv) to determine the net welfare of the system. Impact offsetting is already commonplace in ELCA (Williams et al., 2006, Leinonen et al., 2012, Mackenzie et al., 2015). Thus, the closer the value of the SHI for animal welfare impact is to 1, the greater the animal welfare impact of the system; whilst a SHI value ≤ 0 would indicate that the animals’ positive welfare experiences completely compensate for the negative ones.

In the methodology presented in this chapter, the welfare indictors received equal weighting for a given risk level, which assumes one dimension of welfare is as important as another. Such a notion is unlikely to hold up to criticism (Fraser, 2003). Likewise, if positive welfare indicators were to be incorporated into the methodology, one dimension probably could not fully compensate for another (Botreau et al., 2007); for instance, good health may not fully compensate for behavioural deprivation. To amend this, scientific evidence, expert opinion and stakeholder approval of general principles could be sought to refine the weightings ($W_i$) in the model. The methodology could easily be modified to place greater emphasis on certain indicators over others in the future as understanding on such matters develops.

Human work hours are used to quantify time when determining the value of the social impact categories using the SHDB methodology. However, human work hours are largely irrelevant to the welfare of the livestock; for instance, a farm may employ a lot of staff and have identical values for the animal welfare indicators to another farm that employs fewer staff. The latter farm would seem to have better animal welfare based on the weighted sum methodology of the SHDB, where social impact categories rely on human work hours. To solve this, the animal welfare impact was calculated based on the collective animal work hours. Thus, the methodology presented in this paper acknowledges the fact that, where animals are at an increased risk of negative welfare implications, increased life hours can be worse from a welfare perspective, as it could lead to increased time spent suffering. On the contrary, if positive welfare indicators were to be considered, increased lifespan would improve animal welfare.

Increased flock size resulted in a higher animal welfare impact. There may be a number of contributing factors that account for this. The most obvious explanation is that keeping birds in larger flocks increases infection pressure and decreases the ability of farm workers to spot individual birds displaying signs of reduced welfare and applying appropriate measures to rectify this (Dawkins, 2017). The correlation between farm age and flock size suggests the trend has been to increase the number of birds reared in more recently established buildings compared with older ones. More recently constructed buildings may be more likely to employ technology to monitor animal well-being or other farm conditions. More research is needed to understand the pros and contras of handing more responsibility for animal welfare to machines as the agri-food sector moves towards greater application of precision livestock farming systems (Wathes et al., 2008, Wathes, 2009, Ben Sassi et al., 2016, Dawkins, 2017).

SLCA methodologies that include information on both performance assessment and on geographical contextualization, such as the one presented here, are considered better positioned to provide an assessment of the potential social impacts of corporate performance than other approaches highlighted in this study (Russo Garrido et al., 2018), e.g. expert input, stakeholder judgement or comparisons between alternative systems. Livestock farming is under increasing pressure to become more efficient and more sustainably intensive to meet the demands of a growing global population, whilst there is increasing public concern over standards of farm animal welfare. Hence, a novel and scalable impact category for assessing animal welfare within a SLCA framework was developed that aligns with this concern. Overall, this study paves the way for practitioners interested in assessing the sustainability of livestock industries holistically.

### 6.7 Conclusion and implications

A novel framework was presented for assessing animal welfare within an SLCA, specifically designed to be used in conjunction with the SHDB developed by Benoít-Norris et al. (2015), which characterises resource- and animal-based indicators using real farm data from across continental Europe. An aggregation of measures, although not exhaustive, was used to produce an overall assessment of animal welfare. The SHDB is also a useful methodology for identifying the social hotspots of a system; this was illustrated by the case study of four European countries (Table 6.4). Animal welfare is only one issue in a broad range of social issues that result from the agri-food sector but until recently it has received the least attention. Other social issues associated with the food supply chain include but are not limited to: labour rights and decent work, health and safety, human rights, governance and community infrastructure. The methodology presented here allows animal welfare to be measured alongside these other important social impact categories. Thus, this study provides a basis for discussion that will ultimately further the development of SLCA, animal welfare assessment and lead to the mitigation of animal welfare impact in future livestock systems.

# Chapter 7. General discussion

## 7.1 Introduction

The sustainability of the agri-food sector has come under greater scrutiny in recent years. This means that livestock systems are under increasing pressure to become more efficient, less environmentally impacting and more socially acceptable to meet the demands of a growing global population within the carrying capacity of the planet. Hence food production is at the heart of the 2030 Agenda for Sustainable Development (United Nations, 2015), with the objectives of ending world hunger, achieving food security, improving nutrition and promoting sustainable agriculture. The goal of the research that has been presented in this thesis was consistent with these aims.

Chicken meat is rapidly becoming the most consumed form of animal protein globally thanks to its affordability, convenience, short rearing time, low production costs, healthy image and an absence of religious guidelines limiting its consumption (European Commission, 2017b). Chickens also have a relatively “green image” compared with other livestock, with their meat having a lower GWP, EP, AP and NREU than beef, lamb and pork per unit of edible animal carcass weight (Williams et al., 2007). Despite this, chickens are associated with specific sustainability concerns that have been discussed throughout this thesis, from the resource inputs associated with the animal feed supply chain, to the contribution of environmentally important nutrients in the chicken litter and the animal welfare issues associated with fast growth rate.

Whilst the livestock sector has traditionally aimed to make continuous economic progress, there is now increasing public concern over standards of farm animal welfare in increasingly more intensive systems. This has led to an increased interest in quantifying the environmental and social burdens associated with the industry and identifying potential solutions to mitigate these using modelling techniques such as LCA. Over the last decade, the number of agricultural ELCAs, in particular, to be performed and reported in the literature has soared. In the studies reported in this thesis, LCA has been applied and methodologies have been developed to predict the input requirements of future chicken meat production systems, considering past trends and the apparent genetic potential, to inform future production strategies and advance towards increased system sustainability. In this final chapter, the implication of past and future genetic change of broilers on the sustainability of chicken meat production and the scope for future research on this topic have been discussed.

### 7.2 Genetic selection - how much further can we go?

How far we can take artificial selection is ultimately limited by biology. In Chapter 2, the genetic change in broilers, which has resulted from conventional artificial selection programmes, was explored; a detailed understanding of the interactions between the birds' genetic change and the observable performance trends was provided (Tallentire et al., 2016). The improved energy use efficiency is likely to be mainly the result of a lower total heat production resulting from increased growth rate. The reduction in the lipid content of the body has also resulted in increased energy use efficiency, but it is debateable how much this change in body composition was influenced by genetics and how much it was influenced by changes in nutrition. There may have also been some reduction in the energy consumption of the basal metabolism, which has freed up energy for deposition into growing tissues. Meanwhile, there seems to have been no change in the digestive efficiency (Mussini, 2012). Based on all available evidence, presented in Chapter 4, it was concluded that it is unlikely that continued artificial selection can improve the energy use efficiency of broiler production much further (Tallentire et al., 2018a). This conclusion contrasts with previous predictions (Defra, 2008, Leinonen et al., 2016), but is the only deduction in the literature to be drawn from the analysis of the apparent biological limits of broiler chickens.

Whilst the improvements in broiler efficiency have thus far been the result of the use of conventional breeding techniques, there is now much interest in the use of genomic selection which can be incorporated into molecular breeding strategies (Chen et al., 2011, Aviagen, 2013, Wang et al., 2013, Abdollahi-Arpanahi et al., 2014, Liu et al., 2014, Stainton et al., 2016). Whilst the chicken was the first livestock animal to have its genome fully sequenced (International Chicken Genome Sequencing Consortium, 2004), incorporating molecular breeding strategies into the poultry industry has unique challenges. The cost of incorporating genotyping into the current breeding process remains one of the greatest limiting factors (Wolc et al., 2016). However, the use of genomic data presents an opportunity to re-design breeding programmes, further reducing the risk of inbreeding through the implementation of cross-classified mating with parentage testing (Albers et al., 2006). With already very short generation intervals in broilers relative to other livestock, the major impact of molecular breeding will be on the accuracy of estimated breeding values, particularly for traits where this information is not conveyed by selection candidates at the point of selection. These include traits which contribute to reproductive performance, disease resistance and meat quality (Pampouille et al., 2018).

It may be expected that selection procedures based on genomic information will be an essential part of every poultry breeding programme within the next few years, and that will lead to the restructuring of the breeding process (Albers et al., 2006). This may lead to genetic progress via the avoidance of undesirable traits e.g. improved meat quality and increased liveability/robustness, ergo increased animal welfare. It remains to be seen whether these new technologies will allow geneticists to increase the efficiency of individual birds past the predictions made in this thesis, which were based on what is achievable through conventional breeding techniques i.e. index selection. Much research is yet to be done in order to fully understand gene structure, gene function, gene expression, cellular function and cellular communication. For instance, genes that affect the utilisation of different nutrients may be specifically targeted to improve feed efficiency related traits (Reyer et al., 2015). As highlighted in Chapter 4, genomics may unlock the potential of microbiota and lead to further improvement in digestive efficiency (Sergeant et al., 2014, Pourabedin and Zhao, 2015, Sell-Kubiak et al., 2017). It would be naive to underestimate what could be achieved once genetic power is unleashed; its exploitation through direct manipulation of gene structure and function is a natural next step, although commercial research into transgenics may gain little favour amongst consumers (Doran et al., 2016). The scenarios modelled in this thesis did not consider potential future genetically modified lines.

## 7.3 Modelling the impacts of chicken meat production

### *7.3.1 Current production systems*

The environmental impacts of conventional chicken meat production systems were modelled in an ELCA with multiple environmental impact categories, using broiler performance data from industry, system input data from literature and information available in databases. The purpose of the LCA in Chapter 3 (then again later in Chapter 5) was not to carry out a numerical exercise to determine the total impact of the system, although this was calculated, it was to identify the potential to mitigate the impacts through diet formulation. The algorithm developed formulated diets for specific objectives and considered multiple environmental impact categories related to production, including nutrient excretion, allowing for flexibility in the nutritional specification of the diets for the first time in broiler production systems. Environmental impact statements, such as those made in this thesis specifically, have been described as more sophisticated than their early predecessors (Peng, 2018); considering cost-effectiveness in addition to other more traditional impact measurements.

The results for the overall levels of environmental impact presented in this thesis cannot be compared in any meaningful way to the numerous ELCA studies of chicken meat production. The reason for this is that there are too many differences in the background system of an ELCA when comparing production systems in different continents, as well as the use of different LCA methods and different base assumptions. However, the results reported in Chapter 3 broadly agree with other Chicken LCA studies (Williams et al., 2006, Pelletier, 2008, Leinonen et al., 2012, Putman et al., 2017). Feed provision is consistently shown to be the biggest environmental hotspot and the data in this thesis agrees with this conclusion.

For the sake of this thesis, the LCA presented in Chapter 3 was expanded to incorporate social impacts (Tallentire et al., 2017). These too were concentrated in the feed provision section of the supply chain, although the consumers were not considered. Much more research is still needed to develop SLCA in order to incorporate each stakeholder group, including the consumers and the animals themselves. In Chapter 6 the challenge of incorporating animal welfare was addressed for current production systems in Europe. The mitigation of animal welfare impact in meat production is essential to the sustainability of the industry, thus it should be considered in future sustainability assessment studies of livestock systems. The methodology put forward for assessing animal welfare in this thesis offers a framework from which such assessments may be performed, although further development of this methodology may add value to these studies (see section 7.4.4).

### *7.3.2 Future Production systems*

Artificial selection to improve energy use efficiency in broilers has decreased the ALU requirement, the emissions of GHG and other wastes associated with the production system (Hume et al., 2011, Sell-Kubiak et al., 2017). In Chapters 4 and 5 the environmental burdens associated with feeding future broiler lines were investigated. Since the remaining genetic potential for reducing the environmental burdens was shown to be low, the focus turned to examining the potential for reducing the environmental burdens associated with feeding future broiler chicken lines. Demand for slow-growing birds is increasing with spending power and an increased awareness of animal welfare. This has been driven, in part, by welfare quality schemes: e.g. RSPCA Assured (previously known as Freedom Food) in the UK, Beter Leven and Kip van Morgen in the Netherlands, Initiative Tierwohl in Germany and Label Rouge in France (European Commission, 2017b). Consumer demand is supported by retailers striving to differentiate their products. Alternative production systems to conventional systems such as indoor systems with enriched environments and reduced stocking densities, free range and organic systems offer some of this differentiation (European Commission, 2017b).

As the understanding of animal welfare advances, farming practices will inevitably change to improve animal welfare as they have done so in the past (D'Silva and Webster, 2017). The LCAs reported in this thesis all focused on rearing birds in conventional broiler chicken production systems. Since the energy flow model relied on data from performance manuals (Aviagen, 2014c, 2016), the future growth potentials were based on a scenario where energy expenditure on behaviours was assumed to be consistent with current levels. The level of enrichment (e.g. whether the birds had access to perches) was not considered in these models. The slow-growing line represented birds reared with greater consideration of animal welfare, thus this market may deviate from the farming practices developed for the greatest efficiency (i.e. the conventional broiler production system), opting for something more similar to a free range system for instance. Such systems are likely to require welfare enhancing enrichment to meet consumer expectations. In Chapters 4 and 5 the difference in environmental burdens between future fast-growing and slow-growing lines, that would be due to genetics only, was determined. Thus, the environmental burdens calculated in this thesis may not reflect the reality of future production systems, especially for the slow-growing line. Models which can predict animal responses to potential feeding strategies based on genetic characteristics, or changes to production practices for enhanced welfare, may play an important role in identifying socially acceptable animal production systems which minimise environmental impact in the future.

There has been much interest in finding alternative feed ingredients for livestock that embody lower environmental burdens than conventional ingredients (Sala et al., 2017, Salemdeeb et al., 2017), this was the focus of Chapter 5 (Tallentire et al., 2018b). In addition, there is greater interest in developing the circular economy, through the development of “industrial ecology”, i.e. the rethinking of society using the natural world as an analogy (Andersen, 2007, Allenby, 2009, Li, 2018). Just as all materials are recycled in nature, industrial ecology emphasises the benefits of co-product utilisation and recycling residual waste materials. For instance, microbial biomass may be exploited to remove valuable nutrients from industrial wastewater and emissions so that they are available in the form of feed grade single cell protein (Rasouli et al., 2018). Some of the novel ingredients discussed in this thesis can be classed as co-products from already established industries, vegetable-based industrial residuals and former foodstuffs, or else they may simply rely on industrial waste streams, but all would contribute towards a circular economy e.g. having duckweed ponds on the end of livestock systems or feeding insects on food waste.

Price is a major market entry barrier that puts potential alternative feed ingredients under great pressure, since they need to be able to compete against the economy of scale that many of the mass-produced feeds have established over decades (European Commission, 2018a). More work is needed to develop a sustainable production strategy for each novel ingredient that is appropriate for the poultry industry. For instance, if the novel ingredient needs to be processed at the mill, what would be the capital investment required to achieve the minimum commercial volume requirement and earn the novel ingredient bin space? The Least GWP diet included BPM at a concentration of 0.5 and 0.2% for the fast-growing and slow-growing chicken feeds respectively. At such low inclusion rates, could BPM production be a viable industry? More work would be needed to determine whether it is economically viable to upscale the production of each novel ingredient.

Concerns regarding ingredient variability hinder increasing the inclusion levels of novel ingredients in animal diets. The effect of variability in the nutritional characteristics of the feed was limited in the diet formulation methodology presented in this thesis by restricting inclusion levels of highly variable ingredients. Further effort to account for the effects of ingredient nutrient variability on animal performance in animal growth models would enable the appropriate inclusion levels of the novel ingredients in livestock diets to be determined more systematically. Furthermore, the nutrient digestibility of the novel ingredients should be further evaluated for poultry (Salim et al., 2010, Veldkamp and Bosch, 2015). Finally, ingredient inclusion levels may be different when formulating diets for environmental impact objectives in comparison to commercial ones; a better understanding with regards to the effects of individual ingredients on bird growth would substantially improve the integrated LCA models.

### *7.3.3 Model limitations*

LCA is increasingly seen as an important tool for ensuring the transition towards more sustainable production systems, however the methodologies that are currently used have several limitations which require improvement. Some methodological challenges associated with performing LCAs and how they were resolved in this thesis, such as uncertainty and co-product allocation, were discussed in Chapter 1 and have been addressed elsewhere (e.g. Mackenzie, 2016). LCA modelling often requires large datasets, with the inventory of the system model consisting of many interconnected processes. Compared with other sectors, agri-food systems are inherently more complex, and thus more variability exists within the inventory data (Hauschild et al., 2013, Notarnicola et al., 2017). This variability, for instance, can result from different farm management practices, soil types, seasonality and weather conditions. These parameters are often difficult to estimate.

Specialised LCA modelling software packages, such as Simapro which was utilised in the studies reported in this thesis, incorporate large databases which ease the data collection burden when building background systems. However, it is not possible to integrate other modelling methodologies within Simapro, i.e. animal growth models or linear programming to formulate diets. Another drawback of the Simapro software package is the limited methodological choices provided for carrying out sensitivity analysis. In Chapters 3 and 5 a local sensitivity analysis to identify important sources of variance was employed; using this methodology, the effects of one factor was considered at a time. Global sensitivity analysis functions, which would be able to account for parameter correlations to identify the sources of variance in model simulations (Wei et al., 2015), are not available in the most popular LCA software tools. However, such functions could be easily installed in Simapro, as it is already able to perform underlying matrix-based LCA calculations, such as Monte Carlo simulations (Figure 3.2). As practitioners continue to address increasingly complex challenges, it is important that this modelling software be developed to discontinue the fragmentation of LCA models into sub-models that describe the important aspects of system behaviour.

Furthermore, there are many factors that are not captured in current LCA methods which are important to sustainability. One issue that is not encapsulated, which is related to the agri-food sector specifically, is that a large portion of food flows into the livestock industries despite widespread human hunger and malnutrition (Soussana, 2014). In the drive for greater efficiency, intensive systems of livestock production have developed that compete directly with humans for high-energy crops, particularly non-ruminant species such as poultry. The amount of human edible food used in animal feed is a major ethical concern (Steinfeld et al., 2006, Wilkinson, 2011, Di Paola et al., 2017), however a consistent methodology that defines food that is edible to humans and how to analyse how much of it is contained in common feedstuffs, is currently lacking. Mottet et al. (2017) have considered a FCR which specifically accounts for only human edible feed ingredients. Such methodological developments should enable researchers to provide quantitative analysis of exactly how much competition there is between the human and livestock food supply chains, enabling alternative feeding strategies to account for this and improve the sustainability of the agri-food sector in the future.

LCA studies typically miss out other important aspects of the production system critical for sustainable food production, e.g. decreased soil quality and fertility, increased erosion, reduced ecosystem services due to intensification and biodiversity loss (Geyer et al., 2010, Bateman et al., 2013, Schiefer et al., 2016, Chaplin-Kramer et al., 2017, Notarnicola et al., 2017). These were not considered in this thesis. Neglecting these facets of natural capital may lead to bias (Meier et al., 2015), making it difficult to adequately compare different systems. Studies where organic and conventional systems have been compared would have particularly benefited from expanding the analysis in this way, because these systems manage the landscape in completely different ways (e.g. Boggia et al., 2010, Leinonen et al., 2012). Water consumption is also an important environmental impact of livestock systems that was not included in this thesis (Mekonnen and Hoekstra, 2012), as it was not covered by LEAP guidelines (FAO, 2016a).

Finally, it should be acknowledged that the models in this thesis assess the relative impacts of the poultry industry opposed to its absolute impacts. In Chapter 1 and throughout the thesis, it has been assumed that the global demand for meat, particularly poultry meat, is rapidly increasing (Windhorst, 2006, 2011). This has been used as a justification for this research, as reducing the impacts associated with the functional unit (e.g. a bird grown to a specific slaughter weight or a certain amount of meat) will increase the sustainability of the industry compared with simply unscaling current practices. However, several studies claim future meat production is inherently unsustainable and imply the world's future protein supply can only be ensured by making a human dietary transition to 1) a diet containing less meat, and 2) a shift away from industrially produced meat (e.g. conventional chicken meat production systems) to extensive meat production (i.e. based on grazing livestock) that does not compete directly with humans for resources (de Boer and Aiking, 2014, Macdiarmid et al., 2016). Meat consumption is a complex and emotive issue, and one which fell outside the scope of this research. In terms of sustainability however, improving efficiency (via genetic change), making technological advances (e.g. incorporating novel ingredients into diets) and reducing waste in food production systems collectively only tackle part of the challenge; dietary habits will also need to change in order for meat production to be sustainable (Bajželj et al., 2014). Future models, which operate with a vision of absolute sustainability (e.g. using a cradle-to-cradle approach alongside LCA) may be employed in the future to identify potential solutions to this issue.

## 7.4 Scope for future research

### *7.4.1 Feeding trials*

In Chapters 4 and 5, the apparent limit of feed intake of broiler chickens was determined based on the best available evidence. However, the calculations used in the energy flow modelling approach applied here were based on only a small number of feeding trials, where the energy density of the feed was reduced so that the birds were forced to increase their feed intake. Feed intake was shown to increase as feed energy content was reduced, but only until growth rate was negatively affected. In no trial was the precise limit on feed intake determined. To improve the model reliability, it may be suggested that further trials be carried out in order to obtain more data on the feed intake capacity of the birds. Should commercial selection for increased energy use efficiency continue and breeders do increase bird energy use efficiency beyond the predictions made here, either via conventional or more likely molecular breeding methods, then the models in this thesis would have to be adapted accordingly in future LCA studies.

For the full potential of novel ingredients in livestock diets to be realised, further research into the digestibility of their nutrients and their effects on broiler chicken growth should be carried out. The digestibility values of each novel ingredient, applied in the integrated LCA model in Chapter 5, were gathered from various sources. In some cases, values for the digestibility of individual nutrients contained within the same novel ingredient had to be gathered from different sources (Table 5.2). This, paired with the often increased variability in the nutrient value of novel ingredients, reduced the reliability of the results in Chapter 5. To address this, an extensive literature search was performed, and experts were contacted, in order to determine the maximum inclusion levels for each novel ingredient. A sensitivity analysis on the inclusion levels was performed, however the birds' performance was assumed to be unaltered between diets. Hence, value can be added to the models when research has taken these novel ingredients to the point whereby they can be included alongside conventional ingredients in nutritional information lists, such as in Premier Nutrition (2014) where the nutritional information was sourced for the conventional ingredients.

### *7.4.2 Environmental life cycle assessment methodology development*

Progress towards sustainable systems requires improving the methods for quantitative, integrated assessment and promoting the use of these methods. As outlined in section 7.3.3, current LCA methods are incomplete, in that they fail to comprehensively assess critical aspects of sustainability and in doing so the conclusions from the LCA studies in this thesis may support less preferred policies and actions from a sustainability perspective. Important aspects were left out due to their complexity. For example, biodiversity is difficult to summarise in a single indicator as is done with other environmental impacts, due to the richness in the variety of ecosystems and species assemblages that must be considered. Therefore, there is considerable scope for determining a framework and compiling inventory data for such an issue so that it can be incorporated into future life cycle assessments.

Future LCA methodologies should seek to resolve the lack of information on the important landscape features and ecology (e.g. proximity to water bodies, habitat fragmentation etc.) associated with a system within the modelling approach, as to assess impacts on biodiversity and ecological services. For the broiler industry this is important in the feed production stage. Incorporating nonlinear relationships within the modelling approach may be a potential solution. This could accommodate important environmental conditions, such as soil quality or climate, as well as more accurately reflect the relationships between aspects of the agri-food sector e.g. between land use and species viability or crop yield.

### *7.4.3 Life cycle sustainability assessment of alternative diets*

In Chapter 5, the environmental implications of replacing imported soybeans with novel ingredients in chicken feed formulations were assessed. Seven novel ingredients were considered, each selected based on several criteria (see section 5.3.4), however in some cases there were several alternative ingredients which may have qualified. For instance, *Spirulina sp.*, is an alternative microalgae candidate (Bonos et al., 2016), and there are a number of insect genera with the potential to provide an alternative ingredient to the poultry industry other than mealworms, including: black soldier fly larvae, housefly larvae and pupae, crickets and silkworms (Wang et al., 2005, Adeyemo et al., 2008, Ijaiya and Eko, 2009, Pretorius, 2011, Makkar, 2014). In some cases, the ingredient that was assessed simply had the most data available in the literature which could be compiled in the system inventory. Similarly, the system processes that produced each novel ingredient were selected based on available data. With more time and resources, the LCA could have been broadened to include these other potential novel ingredients or the alternative novel technologies that can produce each novel ingredient. For instance, microalgae was assumed to be grown in raceway ponds in Chapter 5, however it may be grown in numerous other ways, such as: in large open ponds, in circular ponds with rotating mixing arms, in large plastic bags, or in closed photobioreactors (Kumar et al., 2015). The selection criteria filtered out conventional crops, such as European grown soybeans, which may be included in future assessments as yields are improved (Eriksson et al., 2018). This research would indicate which ingredients specifically have the most potential to reduce the environmental burdens associated with chicken feed production.

The social impacts of the novel ingredients were not outlined in this thesis as this is dependent on regional factors and working conditions once the systems are upscaled to economically feasible levels. Hence, to carry out a comprehensive sustainability assessment of incorporating the novel technologies alongside conventional cropping systems to formulate poultry diets would require considerable data collection efforts. Since most of these technologies are only in the early stages of development, most of the necessary data will not currently be available. However, such research would be required in the future in order to fully assess the sustainability of incorporating the novel ingredients into livestock systems. In addition, future work should seek to incorporate new methodologies (as discussed in section 7.4.2) and acknowledge the competition the ingredients may have between human food and animal feed requirements, in order to more comprehensively assess the system.

When performing the sustainability assessment on potential future diets, the practitioner may choose to apply a consequential LCA methodology as to address the changes that will occur elsewhere in the system as Europe acquires less soybeans from South America. This would require integration of market models and system/process models to properly understand the sustainability of broiler chicken production with different diet formulations. Such an approach would be more data intensive but could help better address the challenges associated with shifting the market towards European sourced protein sources.

### *7.4.4 Development of animal welfare within sustainability assessments*

Animal welfare has largely been neglected within the field of SLCA. The absence of a coherent methodology for assessing animal welfare as a social impact category excludes potentially significant issues from the assessment of the agri-food sector. In this thesis animal welfare was evaluated using the SHDB SLCA methodology for the first time. This included data that were available for five negative welfare indicators. There is reasonable scope to expand the negative welfare criteria included in such an assessment, such as by including an indicator for the pain induced by management procedures (Welfare Quality®, 2009), although these may be more difficult to quantify. Furthermore, it is now widely accepted that animal welfare cannot be based only on the absence of negative experiences but must also include the presence of positive experiences. Although the methodology for quantifying the animal welfare impact within an SLCA framework (developed in Chapter 6) could easily incorporate positive experiences, no positive welfare indicator was assessed in the case study that was presented here. This is because there is still no agreement on how to assess positive welfare in animals. Research is needed to identify feasible animal-based measures indicative of positive welfare that could be easily included in a large scale SLCA alongside the negative welfare indicators.

Once the indicators of positive chicken welfare have been identified, a large scale regional farm survey would have to be carried out to quantify the range of performance values for each indicator. To be included in the model developed in Chapter 6, this research should be carried out on European farming systems and follow the same characterisation method as has been applied to the negative welfare indicators. Thus, what constitutes a low, medium, high and very high “possibility” of good welfare may be objectively characterised within an SLCA framework and applied to a broader sustainability assessment of the broiler industry.

The animal welfare impact category, developed in Chapter 6, could easily be incorporated alongside other social impact categories applied in the SHDB methodological framework. Thus, animal welfare could be incorporated into a sustainability assessment of chicken production systems should the necessary data be collected from the production systems. Such an assessment should be carried out based on the prospective modelled scenarios presented in Chapter 5, as discussed in section 7.4.3. The consumer stakeholder group should be included within the boundaries of the model and to do this an appropriate functional unit should be defined. Whilst LW and the total weight of meat are conventionally used in the assessment of livestock systems, the nutritional value of the meat should be used in such a comprehensive assessment. The digestible protein mass, for instance, may be used to include human nutrition in the assessment as the function of the system (Heller et al., 2013, Sonesson et al., 2017). Thus, the sophistication of the sustainability assessments of the systems that produce fast-growing birds and slow-growing birds would be increased.

## 7.5 Concluding remarks

To contribute to the food security of a growing and richer world population, livestock production systems are challenged to increase production levels whilst reducing environmental impact, becoming more socially responsible and maintaining their economic viability. To be sustainable, the poultry industry must respond to the zeitgeist of modern society; shifting social acceptability and tolerance of animal welfare issues, for instance, is inconsistent with the performance objectives of fast-growing broiler lines. However, reducing growth rates increases the birds’ total feed requirement, leading to potential increases in the environmental impact and the financial cost associated with production. Holistic research methodologies for assessing the poultry industry, such as what was developed in the research presented in this thesis, are necessary to find potential solutions to these challenges.

Knowledge about the sustainability performance of current livestock production systems, and the potential performance of future production, can help to formulate strategies for future systems. Further improvements, that can be achieved in the environmental and economic performance of chicken meat production via continued artificial selection, was shown to be low relative to past progress. However, some environmental impacts may be reduced substantially further by exploring novel dietary input options; even mitigating some of the increased environmental burdens associated with transitioning towards a slow-growing, high welfare chicken production system. Such research should be important to nutritionists, livestock producers, breeders and policy makers.

Low self-sufficiency of the protein needed to rear livestock is inconsistent with sustainability objectives and exposes Europe to issues of food security, including but not limited to: trade distortions, price volatility on a global market, ingredient scarcity and increased environmental impacts. However, increasing consumer interest in sustainable and ethical food presents many opportunities to develop innovative business models that implement sustainable chicken meat production methods at the farm level.

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# Appendices

## Appendix A - Broiler chicken growth rates and nutritional requirements

**Table A1**: Growth rate and nutritional requirements at each phase of a current Ross 308 broiler line.

| **Growth and requirements** | **Starter phase (Day 0 - 10)** | **Grower phase (Day 11 - 24)** | **Finisher phase (Day 25 - slaughter)** |
|---|---|---|---|
| Size (kg) | 0.296 | 1.209 | 2.200 |
| Gain (kg) | 0.254 | 0.955 | 0.991 |
| Energy taken by animal (MJ $kg^{-1}$) | 12.55 | 12.97 | 13.39 |
| Crude Protein (%) | 23.00 | 21.50 | 19.50 |
| Lysine (%) | 1.28 | 1.15 | 1.03 |
| Methionine (%) | 0.51 | 0.47 | 0.43 |
| Methionine + Cystine (%) | 0.95 | 0.87 | 0.80 |
| Threonine (%) | 0.86 | 0.77 | 0.69 |
| Valine (%) | 0.96 | 0.87 | 0.78 |
| Isoleucine (%) | 0.86 | 0.78 | 0.71 |
| Arginine (%) | 1.37 | 1.23 | 1.10 |
| Tryptophan (%) | 0.20 | 0.18 | 0.16 |
| Leucine (%) | 1.41 | 1.27 | 1.13 |
| Available Phosphorus (%) | 0.48 | 0.44 | 0.40 |
| Potassium (%) | 0.40 | 0.40 | 0.40 |
| Calcium (%) | 0.96 | 0.87 | 0.78 |
| Chloride (%) | 0.16 | 0.16 | 0.16 |
| Magnesium (%) | 0.05 | 0.05 | 0.05 |
| Sodium (%) | 0.16 | 0.16 | 0.16 |

**Table A2**: Growth rate and nutritional requirements at each phase of a current Ross 708 broiler line.

| **Growth and requirements** | **Starter phase (Day 0 - 10)** | **Grower phase (Day 11 - 24)** | **Finisher phase (Day 25 - 39)** | **Withdrawal phase (Day 40 - slaughter)** |
|---|---|---|---|---|
| Size (kg) | 0.280 | 1.139 | 2.575 | 2.800 |
| Gain (kg) | 0.234 | 0.859 | 1.436 | 0.225 |
| Energy taken by animal (MJ kg$^{-1}$) | 12.55 | 12.97 | 13.39 | 13.39 |
| Crude Protein (%) | 23.00 | 21.50 | 19.50 | 18.30 |
| Lysine (%) | 1.28 | 1.15 | 1.03 | 0.96 |
| Methionine (%) | 0.51 | 0.47 | 0.43 | 0.40 |
| Methionine + Cystine (%) | 0.95 | 0.87 | 0.80 | 0.75 |
| Threonine (%) | 0.86 | 0.77 | 0.69 | 0.64 |
| Valine (%) | 0.96 | 0.87 | 0.78 | 0.73 |
| Isoleucine (%) | 0.86 | 0.78 | 0.71 | 0.66 |
| Arginine (%) | 1.37 | 1.23 | 1.10 | 1.03 |
| Tryptophan (%) | 0.20 | 0.18 | 0.16 | 0.15 |
| Leucine (%) | 1.41 | 1.27 | 1.13 | 1.06 |
| Available Phosphorus (%) | 0.48 | 0.44 | 0.40 | 0.38 |
| Potassium (%) | 0.40 | 0.40 | 0.40 | 0.40 |
| Calcium (%) | 0.96 | 0.87 | 0.78 | 0.75 |
| Chloride (%) | 0.16 | 0.16 | 0.16 | 0.16 |
| Magnesium (%) | 0.05 | 0.05 | 0.05 | 0.05 |
| Sodium (%) | 0.16 | 0.16 | 0.16 | 0.16 |

**Table A3**: Growth rate and nutritional requirements at each phase of a fast-growing line.

| **Growth and requirements** | **Starter phase (Day 0 - 10)** | **Grower phase (Day 11 - 24)** | **Finisher phase (Day 25 - slaughter)** |
|---|---|---|---|
| Size (kg) | 0.404 | 1.380 | 2.200 |
| Gain (kg) | 0.361 | 1.018 | 0.820 |
| Energy taken by animal (MJ kg$^{-1}$) | 12.55 | 12.97 | 13.39 |
| Crude Protein (%) | 28.66 | 21.02 | 18.55 |
| Lysine (%) | 1.60 | 1.12 | 0.98 |
| Methionine (%) | 0.64 | 0.46 | 0.41 |
| Methionine + Cystine (%) | 1.18 | 0.85 | 0.76 |
| Threonine (%) | 1.07 | 0.75 | 0.66 |
| Valine (%) | 1.20 | 0.85 | 0.74 |
| Isoleucine (%) | 1.07 | 0.76 | 0.68 |
| Arginine (%) | 1.71 | 1.20 | 1.05 |
| Tryptophan (%) | 0.25 | 0.18 | 0.15 |
| Leucine (%) | 1.76 | 1.24 | 1.07 |
| Available Phosphorus (%) | 0.60 | 0.43 | 0.38 |
| Potassium (%) | 0.50 | 0.39 | 0.38 |
| Calcium (%) | 1.20 | 0.85 | 0.74 |
| Chloride (%) | 0.20 | 0.16 | 0.15 |
| Magnesium (%) | 0.06 | 0.05 | 0.05 |
| Sodium (%) | 0.20 | 0.16 | 0.15 |

**Table A4**: Growth rate and nutritional requirements at each phase of a slow-growing line.

| **Growth and requirements** | **Starter phase (Day 0 - 10)** | **Grower phase (Day 11 - 20)** | **Grower phase 2 (day 21 - 30)** | **Finisher phase 1 (Days 31 - 40** | **Finisher phase 2 (Day 41 - slaughter)** |
|---|---|---|---|---|---|
| Size (kg) | 0.207 | 0.529 | 0.967 | 1.455 | 2.200 |
| Gain (kg) | 0.169 | 0.359 | 0.438 | 0.488 | 0.745 |
| Energy taken by animal (MJ kg$^{-1}$) | 12.55 | 12.97 | 13.18 | 13.39 | 13.39 |
| Crude Protein (%) | 22.50 | 20.46 | 19.43 | 18.41 | 17.94 |
| Lysine (%) | 1.28 | 1.15 | 1.06 | 1.00 | 0.96 |
| Methionine (%) | 0.51 | 0.47 | 0.45 | 0.42 | 0.40 |
| Methionine + Cystine (%) | 0.95 | 0.87 | 0.82 | 0.78 | 0.75 |
| Threonine (%) | 0.86 | 0.77 | 0.72 | 0.68 | 0.65 |
| Valine (%) | 0.96 | 0.87 | 0.82 | 0.78 | 0.75 |
| Isoleucine (%) | 0.86 | 0.78 | 0.74 | 0.70 | 0.67 |
| Arginine (%) | 1.32 | 1.19 | 1.11 | 1.05 | 1.02 |
| Tryptophan (%) | 0.20 | 0.18 | 0.17 | 0.16 | 0.15 |
| Leucine (%) | 1.41 | 1.26 | 1.17 | 1.10 | 1.06 |
| Available Phosphorus (%) | 0.49 | 0.43 | 0.40 | 0.37 | 0.35 |
| Potassium (%) | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 |
| Calcium (%) | 0.98 | 0.89 | 0.80 | 0.74 | 0.70 |
| Chloride (%) | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |
| Magnesium (%) | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| Sodium (%) | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |

## Appendix B - Ingredient inclusion levels

**Table B1**: Minimum and maximum inclusion values of each ingredient available to poultry diets.

| | Min | | | Max | | |
|---|---|---|---|---|---|---|
| **Ingredients** | **Starter (%)** | **Grower (%)** | **Finisher (%)** | **Starter (%)** | **Grower (%)** | **Finisher (%)** |
| Wheat | 0.00 | 0.00 | 0.00 | 100 | 100 | 100 |
| Maize (Corn) | 0.00 | 0.00 | 0.00 | 100 | 100 | 100 |
| Maize gluten meal | 0.00 | 0.00 | 0.00 | 3.00 | 5.00 | 5.00 |
| Rapeseed (Whole) | 0.00 | 0.00 | 0.00 | 5.00 | 5.00 | 8.00 |
| Rapeseed meal | 0.00 | 0.00 | 0.00 | 2.00 | 10.0 | 15.0 |
| Barley | 0.00 | 0.00 | 0.00 | 5.00 | 20.0 | 30.0 |
| Sunflower meal | 0.00 | 0.00 | 0.00 | 5.00 | 8.00 | 10.0 |
| Soybeans | 0.00 | 0.00 | 0.00 | 5.00 | 8.00 | 15.0 |
| Soymeal | 0.00 | 0.00 | 0.00 | 100 | 100 | 100 |
| Field peas | 0.00 | 0.00 | 0.00 | 5.00 | 10.00 | 15.0 |
| Oats | 0.00 | 0.00 | 0.00 | 5.00 | 10.00 | 15.0 |
| Vegetable oil | 0.00 | 0.00 | 0.00 | 0.00 | 5.00 | 5.00 |
| Soy oil | 0.00 | 0.00 | 0.00 | 5.00 | 5.00 | 5.00 |
| Limestone | 1.00 | 1.00 | 1.00 | 2.00 | 2.00 | 2.00 |
| Mono Calcium Phosphate | 0.00 | 0.00 | 0.00 | 2.00 | 2.00 | 2.00 |
| NaHCO3 | 0.00 | 0.00 | 0.00 | 2.00 | 2.00 | 2.00 |
| Salt | 0.00 | 0.00 | 0.00 | 2.00 | 2.00 | 2.00 |
| Lysine HCl | 0.00 | 0.00 | 0.00 | 0.500 | 0.500 | 0.500 |
| DL-Methionine | 0.00 | 0.00 | 0.00 | 0.500 | 0.500 | 0.500 |
| L-Threonine | 0.00 | 0.00 | 0.00 | 0.500 | 0.500 | 0.500 |
| Valine | 0.00 | 0.00 | 0.00 | 0.500 | 0.500 | 0.500 |
| Fishmeal | 5.00 | 0.00 | 0.00 | 5.00 | 5.00 | 5.00 |
| Meat and bone meal | 0.00 | 0.00 | 0.00 | 1.00 | 2.00 | 3.00 |
| Poultry offal | 0.00 | 0.00 | 0.00 | 2.00 | 3.00 | 4.00 |
| Wheat middlings | 0.00 | 0.00 | 0.00 | 10.0 | 10.0 | 10.0 |
| Wheat bran | 0.00 | 0.00 | 0.00 | 5.00 | 5.00 | 5.00 |
| DDGS (Corn) | 0.00 | 0.00 | 0.00 | 5.00 | 5.00 | 5.00 |
| Brewers grains | 0.00 | 0.00 | 0.00 | 5.00 | 5.00 | 5.00 |
| Premix | 0.250 | 0.250 | 0.250 | 0.250 | 0.250 | 0.250 |
| Enzymes (NSP$^2$/2*Phytase) | 0.0300 | 0.0300 | 0.0300 | 0.0300 | 0.0300 | 0.0300 |
| **Novel ingredients** | | | | | | |
| Microalgae | 0.00 | 0.00 | 0.00 | 9.00 | 18.0 | 18.0 |
| Macroalgae | 0.00 | 0.00 | 0.00 | 9.00 | 18.0 | 18.0 |
| Duckweed | 0.00 | 0.00 | 0.00 | 9.00 | 18.0 | 18.0 |
| YPC | 0.00 | 0.00 | 0.00 | 10.0 | 20.0 | 20.0 |
| BPM | 0.00 | 0.00 | 0.00 | 5.00 | 10.0 | 10.0 |
| LPC | 0.00 | 0.00 | 0.00 | 20.0 | 40.0 | 40.0 |
| Insect meal | 0.00 | 0.00 | 0.00 | 15.0 | 30.0 | 30.0 |

## Appendix C - Mean values and parameter ranges of conventional systems

**Table C1**: The normally distributed parameters and their coefficients of variation (CV) tested in the sensitivity analysis and used in the Monte Carlo simulations in Chapter 3.

| | UK | | USA | |
|---|---|---|---|---|
| **Variable** | **Value** | **CV*2** | **Value** | **CV*2** |
| Live weight achieved at slaughter | 2.20 kg | 8% | 2.80 kg | 8% |
| Overall feed intake /bird | 3.51 kg | 10% | 4.88 kg | 10% |
| Mortality | 3.50% | 30% | 4.50% | 30% |
| Feed spillage/bird | 0.07 kg | 10% | 0.09 kg | 10% |
| Wheat yield | 7.80 tonnes/ha | 12% | 3.01 tonnes/ha | 17% |
| Maize yield | 5.00 tonnes/ha | 17% | 13.00 tonnes/ha | 11% |
| Rapeseed yield | 3.50 tonnes/ha | 12% | 1.88 tonnes/ha | 14% |
| Soybean yield (USA production) | 3.12 tonnes/ha | 16% | 3.12 tonnes/ha | 16% |
| Soybean yield (Argentinian production) | 2.46 tonnes/ha | 10% | - | - |
| Soybean yield (Brazilian production) | 2.50 tonnes/ha | 10% | - | - |
| Barley yield | 6.00 tonnes/ha | 8% | 3.82 tonnes/ha | 7% |
| Oat yield | 5.62 tonnes/ha | 8% | - | - |
| Field pea yield | 5.1 tonnes/ha | 20% | - | - |
| Sunflower yield (Ukraine production) | 1.27 tonnes/ha | 10% | - | - |
| Palm yield (Southeast Asia production) | 4.00 tonnes/ha | 15% | 4.00 tonnes/ha | 15% |
| $NH_3$ lost at housing | 10.95% | 42% | 10.95% | 42% |
| $NH_3$ lost at storage | 13.95% | 37% | 13.95% | 37% |
| $NH_3$ lost at field | 15.86% | 11% | 16.15% | 26% |
| Total $N_2O$ emissions | 5.49% | 10% | 5.54% | 10% |
| Facility Electricity consumption/bird | 1.66 MJ | 28% | 0.94 MJ | 28% |
| Facility Gas consumption/bird | 10.81 MJ | 34% | 3.63 MJ | 34% |
| N retention | 0.062 kg | 12% | 0.078 kg | 12% |
| P retention | 0.011 kg | 10% | 0.014 kg | 10% |
| K retention | 0.004 kg | 10% | 0.006 kg | 10% |

**Table C2**: The mean, minimum and maximum values for the triangularly distributed parameters tested in the sensitivity analysis in Chapter 3. These distributions were used in the Monte Carlo simulations.

| Variable | Value | Minimum | Maximum |
|---|---|---|---|
| $NO_3$ (UK) | 19.7% | 12.8% | 20.7% |
| $NO_3$ (USA) | 21.3% | 13.8% | 22.4% |
| $PO_4$ (UK) | 5.00% | 2.00% | 15.0% |
| $PO_4$ (USA) | 6.67% | 2.00% | 15.0% |
| N replacement rate | 70.0% | 40.0% | 80.0% |
| P replacement rate | 80.0% | 60.0% | 100% |

**Table C3**: Emissions factors and their sources for each stage of the poultry manure model for the UK and the USA, expressed as a percentage of the total nutrients excreted in the litter (Chapter 3).

| Emission | Location | UK | USA |
|---|---|---|---|
| $NH_3$ | Housing | 11.0% | 33.7% |
| | Storage | 14.0% | 6.55% |
| | Field | 15.9% | 16.25% |
| $N_2O$ | Housing | 0.100% | 0.230% |
| | Storage | 4.73% | 2.44% |
| | Field | 0.660% | 0.710% |
| $NO_3$ | Field | 19.7% | 21.3% |
| $PO_4$ | Field | 5.00% | 6.67% |

## Appendix D - Additional inventory data (Chapter 5)

**Table D1**: Inputs and outputs of microalgae production.

| Process/stage | Inputs | Value | Unit |
|---|---|---|---|
| Cultivation (Pond) | Water | 530 | kg |
| | Flue gas | 7.00 | kg |
| | Urea | 0.09 | kg |
| | Diammonium phosphate | 0.08 | kg |
| | Electricity | 3.40 | kWh |
| Harvesting | Algal broth (from pond) | 226 | kg |
| | Flocculent | 0.26 | kg |
| | Electricity | 3.50 | kWh |
| Processing | Dry Algae (from harvest) | 4.60 | kg |
| | Hexane | 0.003 | kg |
| | Ethanol | 0.140 | kg |
| | Methanol | 0.132 | kg |
| | Sodium hydroxide | 0.011 | kg |
| | Sulfuric acid | 0.016 | kg |
| | Water | 0.140 | kg |
| | Electricity | 0.200 | kWh |
| | Heat | 9.40 | MJ |
| | Enzymes | 0.030 | kg |
| | **Outputs** | | |
| Product and co-products | Biodiesel (*36%) | 1.00 | kg |
| | Glycerol (*1%) | 0.113 | kg |
| | Animal feed (*63%) | 1.94 | kg |
| | Electricity | 1.82 | kWh |
| | Heat | 5.24 | MJ |
| *Economic allocation of environmental impact | | | |

**Table D2**: Inputs and outputs of macroalgae production.

| Process/stage | Inputs | Value | Unit |
|---|---|---|---|
| Cultivation | Electricity | 118.4 | kWh |
| Processing | Macroalgae biomass | 1000 | kg |
| | Electricity | 980 | kWh |
| | Heat | 3010 | MJ |
| | Sulphuric acid | 35.0 | kg |
| | Diammonium phosphate | 1.67 | kg |
| | Enzymes | 70.0 | kg |
| Drying | Heat | 3807 | MJ |
| Dehydration | Electricity | 8.05 | MJ |
| | **Output** | | |
| Product and co-product | Bioethanol (*29%) | 268.2 | kg |
| | Macroalgae meal (*71%) | 703.7 | kg |
| *Economic allocation of environmental impact | | | |

**Table D3**: Inputs and outputs of duckweed production.

| Process/stage | Inputs | Value | Unit |
|---|---|---|---|
| Cultivation | Pig slurry | 0.04 | $m^3$ |
| | Water | 215 | kg |
| | Electricity | 1.70 | kWh |
| Drying | heat | 4.80 | MJ |
| | **Output** | | |
| Product | Duckweed | 1.00 | kg |

**Table D4**: Inputs and outputs of yeast protein concentrate (YPC) production.

| Process/stage | Inputs | Value | Unit |
|---|---|---|---|
| Processing | Dry wheat grain | 3030 | kg |
| | Water | 10000 | kg |
| | Electricity | 1450 | MJ |
| | Heat | 5450 | MJ |
| | Sulphuric acid | 100 | kg |
| | Diammonium phosphate | 5.06 | kg |
| | Enzymes | 200 | kg |
| Dehydration | Electricity | 30.0 | MJ |
| Drying | Heat | 4272 | MJ |
| | **Outputs** | | |
| Product and co-products | Bioethanol (*82%) | 1000 | kg |
| | DDGS (*12%) | 988 | kg |
| | YPC (*6%) | 152 | kg |
| Waste | Water | 9942 | kg |

*Economic allocation of environmental impact

**Table D5**: Inputs and outputs of bacterial protein production.

| Process/stage | Inputs | Value | Unit |
|---|---|---|---|
| Processing | Water | 8.51 | kg |
| | Flue gas | 1700 | $m^3$ |
| | Oxygen | 2015 | $m^3$ |
| | Ammonia | 138 | kg |
| | Phosphoric acid | 42.0 | kg |
| | Magnesium sulphate | 18.0 | kg |
| | Iron sulphate | 1.00 | kg |
| | Copper sulphate | 1.00 | kg |
| | Potassium nitrate | 4.00 | kg |
| | Electricity | 1438 | kWh |
| Drying | Heat | 26.76 | MJ |
| | **Outputs** | | |
| Product | BPM | 1000 | kg |

**Table D6**: Inputs and outputs leaf protein concentrate production.

| Process/stage | Inputs | Value | Unit |
|---|---|---|---|
| Processing | Green biomas (Alfalfa) | 1000 | kg (dry |
| | Electricity | 160 | MJ |
| | Heat | 790 | MJ |
| | Water | 450 | kg |
| | Enzymes | 17.0 | kg |
| Drying | Heat | 96.0 | MJ |
| | **Outputs** | | |
| Product and co-product | Lactic acid (*87%) | 89.0 | kg |
| | LPC (*6%) | 26.0 | kg |
| | Fodder silage (*4%) | 261 | kg |
| | Residue for biogas (used on site) | 152 | kg |
| | Fertiliser (*3%) | 14.0 | kg |

*Economic allocation of environmental impact

**Table D7**: Inputs and outputs of insect meal production.

| Process/stage | Inputs | Value | Unit |
|---|---|---|---|
| Insect rearing and harvesting facility | Organic waste stream – cereals, pulses, vegetables and fruit (35:5:25:35) | 2.20 | kg |
| | Egg boxes | 0.01 | kg |
| | Water | 1.79 | kg |
| | Electricity | 5.30 | MJ |
| | Heat | 22.9 | MJ |
| Meal preparation | Mealworm biomass | 3.334 | kg |
| | Electricity | 0.04 | MJ |
| | Heat | 3.60 | MJ |
| | **Outputs** | | |
| Product and co-product | Insect meal | 1.00 | kg |
| | N in manure | 0.0047 | kg |
| | P in manure | 0.0014 | kg |