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Development and application of diverse modelling methods to evaluate management practices for sustainable beef finishing systems in Scotland

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Thesis presented for the degree of Doctor of Philosophy

The University of Edinburgh

School of Geosciences

2019

Declaration

I, Charalampos Kamilaris, hereby declare that this thesis is of my own composition, that the work contained herein is my own except where explicitly stated otherwise in the text. The work reported in this thesis contains no material previously submitted for the award of any other degree or professional qualification.

Charalampos Kamilaris

30 October 2019

Abstract

In Scotland, cattle production is considered the main agricultural activity, with beef farmers generating the highest proportion of all Scottish agricultural revenue, mainly from the sale of animals for meat production and breeding. In addition, Scotland has the highest ratio of beef to dairy cows among the countries of the UK and Europe. However, the cattle farming sector reports consistently low or negative margins and beef farming in Scotland remains highly dependent on Common Agricultural Policy (CAP) support payments to sustain its farming activities.

The beef production sector is currently faced with a volatile business environment and uncertain price conditions, which when combined with the recent global environmental concerns about the role livestock systems' play in climate change, further compromise the robustness and future viability of the existing beef production systems. Also, beef production is recognised as an important source of greenhouse gas (GHG) emissions linked to Climate Change. As a result, widespread pressure exists for beef production systems to increase the economic and emissions efficiency of production.

Various mathematical modelling attempts over the years have proven to be powerful tools tackling issues of beef production profitability and environmental concerns from numerous aspects. However, several issues impede their uptake, as the application of this knowledge to policy is hindered by the heterogeneity of agricultural systems. This thesis, therefore, set out to develop a model for the beef industry focused on the finishing stage to a) assess existing management practices to determine the drivers and limitations of profitability, b) to test scenarios to identify opportunities and alternative beef production systems in Scotland and c) to optimise these results for beef farms in Scotland.

The Grange Scottish Beef Model (GSBM) was developed and customized to simulate Scottish beef finishing enterprises using data related to beef studies and agricultural input and output price datasets. The model was used to determine the cost-effectiveness of alternative management practices and slaughter ages. Results highlight the small and often negative net margins of beef finishing systems in Scotland, as well as the superior financial returns of shorter duration systems. To improve the understanding of drivers behind profitability in beef finishing systems, scenarios simulating the genetic selection of stock for feed efficiency, financial aids and optimized inter-population performance were tested. Outcomes showed better net margins than the baseline systems for all systems examined, allowing some systems to become profitable. Monte Carlo simulation was also used to provide an estimate of the effects of uncertainty surrounding carcass prices.

The study also highlighted the pivotal role of management in the emissions intensity of production. Using Scotland again as a case study, the bio-economic simulation model GSBM was combined with AgRE Calc, a farm-level carbon footprinting tool, to investigate the environmental impact of a range of beef production scenarios, and trade-offs generated between mitigating emissions and increasing farm profitability. To measure the environmental impact of finishing duration, type and gender selection of beef fattening systems, emissions were grouped into five categories: (1) land and crops, (2) enteric emissions, (3) manure, (4) feed and bedding, and (5) fuel and electricity. Results suggest that more intensive shorter duration systems have the lowest environmental impact of all the systems investigated. However, medium duration pasture-based beef production systems in Scotland were found to achieve a balance between financial returns and environmental performance.

Finally, a new model was developed using real-world data obtained from Scottish farms to optimise between the systems already found to be more cost-effective with simulation modelling. While policy scenarios concerning the departure of the United Kingdom from the European Union were examined to assess the future impact of policy changes on beef finishing systems in Scotland. The impacts of three post–Brexit trade scenarios that were taken from the Agri-Food and Biosciences Institute (AFBI) report on post-Brexit trade scenarios on different Scottish beef farming systems were assessed. Scenarios include a free trade agreement with the EU (*FreeTrade*), a deal that assumes default World Trade Organisation tariff regimes (*WTO*) and the Unilateral Trade Liberalisation (*LibTrade*), with different tariffs and market specifications applied. Results showed that even though the *LibTrade* scenario generated the most adverse effect to farm profitability when compared to a baseline and other post-Brexit scenarios, the most decisive factor defining the economic viability of Scottish beef farms would be the abolition of EU's payment schemes.

Together, these assessments provide a framework for the development of tools for economic and environmental analysis of beef finishing systems, intending to increase their usability and relevance. Several areas in which further progress can be made are identified, and the thesis argues for the recognition of a demand for more regionalized modelling approaches by the developers on agriculture accounting methodologies. As such, the thesis as a whole provides a detailed blueprint for the advancement of modelling livestock systems, alongside a comprehensive synthesis of the state of the art.

Lay summary

The production of beef animals for meat is vitally important for Scottish agriculture, as it currently stands out as the largest single sector of the Scottish agricultural industry. Nevertheless, beef production is a practice that has been linked to low profitability for the most enterprises, since the majority of beef farms are not profitable at a level to reward the owners for their unpaid labour and risk capital invested in their business. Also, the sector has been associated with significant emission of greenhouse gases (GHGs) and has further negative impacts on the wider environment. Beef production is also becoming much more widespread because of increasing demand, as a result of both a rising global population and an increasing level of income in many developing nations. It is largely accepted that the global projected demand for beef is at a level that production is expected to continue growing for the near future. Besides, the pressing need for beef production systems to become economic and environmental efficient has been acknowledged; in essence, the global beef industry must increase production while reducing emissions.

However, efforts attempting to increase the cost-effectiveness and reduce the emissions intensity of beef production face a significant challenge. Mainly, because of beef production systems and practices can vary significantly. Differences occur not just between world sections or nations, but also over much lesser scales. This fact makes the systems complex and difficult to comprehend at a national level and so profitability and/or GHG mitigation strategies are difficult to legislate for. The nature of livestock farming implies numerous multi-variant factors that could affect an enterprise, for example, the soil type, grass

quality, altitude, breeds and animal performance. Consequently, various possible systems and feeding regimes could apply for the same situation in rearing or finishing cattle. In addition to being heterogeneous and naturally highly complex, GHG emissions could also be coming from many different sources. Hence, there is a need for accurate decision support tools based on mathematical models that should be flexible enough to deal with a diverse set of factors for the optimum system in a given situation to be correctly identified and applied.

A cost-effective and enlightening method for understanding the way real beef production physically perform, produce emissions, and how they can be made more efficient is to develop a mathematical model simulating the complex relationships found in these systems. Numerous different modelling approaches can be applied to agricultural processes, but a model must exhibit certain qualities to be considered 'fit-for-purpose'. A beef production model must be flexible enough to capture the wide variety of different practices, as well as delivering a broad framework to capture the full extent of production and avoid making false economies. Moreover, the input data required for the model should be simple and not complex or detailed, so that regular farms will be able to provide it. Finally, a satisfactory level of precision should be attained to make the outcomes useful to policy makers seeking to ensure the beef sector viability and reduce the emissions intensity. Given the challenges identified, this thesis aimed to develop a model focused on the finishing stage of beef production to fit these criteria. This model can be employed to assist farmers, researchers, policy makers, and relevant stakeholders to increase their understanding of how beef systems operate and respond to various fluctuations.

The first step taken in developing the model for beef finishing systems in the Scotland was to investigate the current situation, to highlight the importance of the sector in the context of Scottish economy and identify potential challenges that needed to be addressed. Afterwards, a review was conducted on other models for comparison, to analyse previous modelling styles and attempts, while recognising areas of strength and potential for further development.

Hence, the introduction (Chapter 2) presented a comprehensive review of different beef finishing systems practiced in Scotland and the UK in terms of physical performance and profitability. Economics of beef production at both regional and enterprise-level were analysed while acknowledging the upcoming changes and opportunities caused by the UK formally leaving the EU. It was identified that the profitability of the beef sector in Scotland was extremely low to non-existent and the sustainability of these enterprises was heavily dependent on the grants and schemes provided by the EU. Nevertheless, Scottish beef exports are high-value products and could grow outside the domestic and the EU market, if the sector makes efficient use of its resources and capitalises fully from the opportunities created. To achieve that goal, mathematical models will be valuable in informing agricultural policy and proposing ways to highlight the regions' unique assets and global market advantages.

As a result, Chapter 3 of this thesis incorporated a review of existing models and considered existing publications, which have attempted to do this. It was identified that there were two main modelling approaches on agricultural systems, namely, the simulation modelling and the optimisation modelling techniques. For each method, strengths and weaknesses were recognised and discussed. Afterwards, it was concluded that a mathematical bio-economic model that was designed to simulate grassland based dairy calf to beef systems in Ireland (Grange Dairy Beef Systems Model) would act as a basis for developing a model for the technical and economic evaluation of beef production systems in Scotland. This particular model would be re-parameterized and further developed, to depict accurately the current environment of beef finishing systems for Scotland.

Following these developments, in the subsequent Chapter 4 of the thesis, a detailed report was given of the exact process during the development and the steps followed for the Grange Dairy Beef Systems Model (GDBSM) to be used as a base for creating the Grange Scottish Beef Model (GSBM). Afterwards, the structure of the bio-economic Grange Scottish Beef Model (GSBM) was described and a list containing the various sources that were employed to inform the new model was compiled. The aim was to assemble information and data already available into one model that could support a decision-making process contributing to the development of novel farm-management systems that address low profitability. Consequently, the GSBM was implemented to examine scenarios concerning the effects of variation in market conditions, policy environment, and management practices on enterprise profitability. It was identified that:

a) The short and medium duration systems have proven more profitable for both steers and heifers. Also, the most cost-effective systems were the 18 and the 16-month slaughtering age for steers and heifers respectively.

b) For continental breeds in Scotland, steer systems were found to be more profitable than heifer systems.

c) Scenarios that involved selecting animals for feed efficiency or including farm subsidies, found all systems benefited from the positive influence, while some systems became profitable after the intervention.

d) Marginal returns increased remarkably for both steer and heifer systems, particularly for the longer duration heifer systems, when scenarios for within-herd variation in animal growth rates were tested.

e) By using stochastic analysis to examine the 24-month steer and heifer finishing systems, it became evident that these livestock systems were vulnerable to the experienced economic shocks.

For the study in Chapter 5, the attention was shifted to measuring the environmental impact of a range of beef finishing systems in Scotland. For this purpose, the Grange Scottish Beef Model was further modified and combined with an already established farm-level GHG footprinting tool (AgRE Calc) focused on temperate beef systems. The combination of those two models and the novel methodology produced was employed to examine environmental and economic scenarios of current systems and discover strategies to address both low profitability and potential GHG mitigation. The analysis encompassed possible trade-offs created between mitigating emissions and increasing farm profitability, using models developed for Scotland. It was identified that:

a) The bigger environmental impact can be attributed to the long extensive finishing systems when compared to both medium duration grazing-based approaches and short intensive housing systems.

b) At growth rates close to 1 kg per day, all the animals performed similarly in terms of emissions intensity, regardless of the finishing type and diet.

c) Systems finishing steers produced significantly lower emissions intensity than those with heifers.

d) Long-period grazing systems showed lower emissions per animal as well as low profitability with negative net margins for all systems. On the other hand, most of the medium and all of the short duration systems showed high emissions and high profitability when compared to long-duration grazing systems.

e) High input grazing medium duration systems could sustain high profitability and sustainable environmental performance.

A great amount of the research conducted up to this point in the thesis pointed the importance of the intensive short duration finishing systems and the medium period high input pasture-based grazing systems for the Scottish agriculture economy. For the study in Chapter 6 of this thesis, a simple optimization model (ScotBeefFarm) was developed to investigate the optimal profitable and environmentally friendly systems in Scotland, using real farm data and, hence; further progressing down the path of exploring alternative beef production systems. Therefore, this study was designed by employing the findings of the previous modelling exercises with bio-economic simulation GSBM and was focused on the systems that appear to be both profitable and emitting less GHGs. The policy scenarios examined were chosen to simulate various outcomes from the imminent Brexit that will have significant implications on the UK and Scottish agricultural commodity markets due to predicted changes to trade flows. For the analysis of the impacts of alternative trade agreements following Brexit on Scottish beef finishing systems, scenarios presented on the Agri-Food and Biosciences Institute (AFBI) report on post-Brexit trade were employed. These scenarios were formulated by using a partial equilibrium modelling framework, namely the FAPRI-UK model. The three different scenarios examined were the following:

a) Bespoke Free Trade Agreement (*FreeTrade*) with the EU
b) World Trade Organisation (*WTO*) default Most Favoured Nation (MFN) tariffs
c) Unilateral Trade Liberalisation (*LibTrade*)

It was identified that:

a) Domestic policy decisions and alternative trade deals will both influence the post-Brexit landscape of the beef production sector in Scotland. Possible outcomes like the *WTO* agreement resulted in increased farm net

profitability, while the scenario involving a *LibTrade* deal reduced farm gains.

b) The abolition of the EU financial support through direct payments will potentially have significantly more serious implications on farm profitability than alternative trade deals negotiated between the UK, the EU, and the countries from the rest of the world.

c) Low and in some cases non-existent profitability of beef farms projected in future post-Brexit Scotland is predicted to induce structural changes, forcing enterprises to search for alternative income sources. This may cause farms to diversify their current activities or increase levels of beef production efficiency, or even abandon the farming activity.

The thesis as a whole form a comprehensive evaluation of the current role and state of the beef production systems present in Scotland, with emphasis on the finishing phase, and sets out an agenda for how certain aspects can be improved and refined. The current and future role of simulation and optimisation modelling tools in the context of the global challenge of increasing profitability, while reducing beef emissions is defined and discussed. This study contributes several resources, databases, and methodologies, which can be meaningfully utilised for this purpose. The conclusion of the thesis provides a summary of current and gained knowledge for the farmers, the researchers, the users of modelling tools, their developers, and the related scientific community whose assembled knowledge forms the basis upon which models and decision-support tools rely.

Acknowledgements

First and foremost, I would like to express my sincere gratitude to my main supervisor; Professor Richard Dewhurst (SRUC) for his continuous support and motivation. I would also like to express my profound thanks to my supervisory team Dr Peter Alexander (University of Edinburgh), Dr Paul Crosson (Teagasc), Dr Bouda Vosough Ahmadi (SRUC), Dr Shailesh Shrestha (SRUC), Dr Ron Wilson (University of Edinburgh) and Dr Aidan Moloney (Teagasc), for their support, insightful comments, and feedback throughout the progress of my PhD.

I would also like to thank the staff of SRUC and SAC Consulting, particularly Dr Jimmy Hyslop, Dr Paul Hargreaves, Professor Alistair Stott, Dr Carol-Anne Duthie, and Robert Logan, for valuable contributions throughout the course of this PhD. My sincere thanks goes to my colleague and dear friend Dr Alasdair Sykes, for his friendly support throughout the duration of this project but also for his extensive input into the study conducted in Chapter 5 of this thesis. I would also like to thank the Scottish Government and the Agriculture and Horticulture Development Board (AHDB) for providing data and feedback during the development of this project.

I gratefully acknowledge the funding received towards my PhD from the Scottish Government through SRUC and Teagasc Walsh Fellowship. I appreciate every one's effort in The University of Edinburgh, Scotland's Rural College and Teagasc for the kind provision of support that made my working towards this PhD easier.

Finally, I would like to extend my deepest thanks to my parents Panagiotis Kamilaris and Andriani Pagona for supporting and encouraging me throughout my life and academic career. My thanks goes to my extended family and friends for the encouragement, moral support and their patience during the years of my studies.

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List of abbreviations used

AFV	Apparent fill value
AgRE Calc	Agricultural Resource Efficiency Calculator
CAP	Common Agricultural Policy
CFU	Cattle Fill Unit
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
DMI	Dry matter intake
EU	European Union
FAO	Food and Agriculture Organization
FBI	Farm Business Income
FBS	Farm Business Survey
GAMS	General Algebraic Modelling Systems
GDBSM	Grange Dairy Beef Systems Model
GHG	Greenhouse gas
GSBM	Grange Scottish Beef Model
INRA	Institut national de la recherché agronomique
IPCC	Intergovernmental Panel on Climate Change
LFA	Less-Favoured Area
LP	Linear Programming
LWG	Liveweight gain
MAW	Minimum Agricultural Wage
N	Nitrogen
N_2O	Nitrous oxide
OECD	Organisation for Economic Co-operation and Development
P	Phosphorus
RED	Ration energy density
SRUC	Scotland’s Rural College
t	Tonne
UFL	Feed Unit for lactation
UFV	Feed Unit for maintenance and meat production
UK	United Kingdom
VBA	Microsoft Visual Basic for Applications
WTO	World Trade Organization

List of publications

Work of the project that has been accepted for presentation through peer reviewed process and is available in conference proceedings:

Kamilaris, C., Dewhurst, R.J., Ahmadi, B.V., Crosson, P., Alexander, P. (2019). A bio-economic model for cost analysis of alternative management strategies in beef finishing systems. Agricultural Systems (in-press).

Kamilaris, C., Dewhurst, R.J., Sykes, A.J., Alexander, P. (2019). Modelling alternative management scenarios of economic and environmental sustainability of beef finishing systems. Journal of Cleaner Production (in-press).

Kamilaris, C., Dewhurst, R.J., Ahmadi, B.V., Crosson, P., Alexander, P. (2018). Bioeconomic Modelling of specialist beef finishing systems in Scotland. Book of Abstracts of the 69th Annual Meeting of the European Federation of Animal Science (EAAP). Dubrovnik, Croatia, 27-31 August 2018.

Chapter 1: Introduction

Agriculture business has great significance in Scotland manifesting the specific land's composition and capabilities, as about 79% of Scotland's total land area is dedicated to agricultural holdings and common grazing. Reflecting the large areas of grassland and rough grazing, the livestock sustains rural communities and supporting local economies. Beef production is at the core of Scottish agriculture and the largest single sector of the Scottish agricultural industry. Besides, producing beef is considered the most profitable activity for Scottish livestock. Consequently, the Scottish Government has recognised the strategic role of food and drink in the Scottish economy by adopting a Food and Drink Policy. The beef industry is currently regarded as a major contributor for the sector while holding the status of an iconic paradigm of high-quality Scottish food (ERSA, 2016; Quality Meat Scotland, 2018a).

Nevertheless, the beef sector in Scotland is found to be lacking several simple prerequisites for any production process, as the industry still produces in a highly speculative way. Most producers will not describe a specific market opportunity to justify the reason for engaging in beef enterprise on the farm. Also, the proportion of animals that are falling out of the preferred abattoir specification is supporting the apparent lack of connection and communication between the producers with the market. These facts come in direct contradiction with the prevalent reality in other livestock sectors (i.e. dairy, pig and chicken production), where the majority of producers tend to know exactly for which market they are producing, and consequently the specification and time of delivery of the required product. Moreover, the investing takes place at all levels of the production process, despite the price challenges and with little or no governmental support, while measuring and acting upon key performance indicators is a common practice (Scottish Government, 2014).

The reality is that on many occasions, farmers are reluctant to expand their business due to the adverse effects a possible increase in supply would have on the value of their total production. While, at the same time, processors could be hesitant to develop new demand or markets for beef worrying about increasing the cost of their raw material supply (Scottish Government, 2014). This complex chain of events that reinforce themselves and the current narrative regarding beef production in Scotland has led to forming this current vicious cycle. For the sector to grow, a higher degree of confidence and collaboration is required within the supply chain to allow the sector to develop and expand into new markets, while delivering the required supply to meet that increased demand.

Furthermore, the ruminant livestock production stands in the spotlight of every environmental agenda due to high greenhouse gas emissions, attracting the attention of policies related to mitigating Climate Change effects, also highlighting the need to drive efficiency in production while considering broader sustainability aspects. The fact that the global beef sector should reduce the emissions and promote overall sustainable solutions, brings attention to novel solutions that provide the Scottish industry with the opportunity to enhance both business profitability and environmental sustainability. While recent socio-political changes, like the unstable relationship between the United Kingdom and Scotland with the European Union, leaves the Scottish beef industry within a reality that presents both obstacles and opportunities (ERSA, 2016; Scottish Government, 2014).

However, apart from the challenges, Scotland's beef industry is also characterised by opportunity driven by a robust home market, growing demand for red meat and premium products around the world and a strong national reputation for food and drink from Scotland. To accomplish the vision of a market-driven grass-based cattle industry employing cutting-edge technologies capable of delivering profitably and high-quality products from sustainable systems, research should aim to better understand the interactions between beef systems' variable components and alleviating part of the uncertainty regarding production (Scottish Government, 2014).

Due to the interactions between various components such as animal gender, finishing age, and feed supply and demand, agricultural systems research is an important part of agricultural research and mathematical models can be used to analyse the complex interactions within the systems. There are two main types of mathematical models typically employed in agricultural systems: simulation and optimisation programming. Simulation models have been employed to model many aspects of beef farming systems including animal growth (Hoch and Agabriel, 2004; Jouven et al., 2008), grass growth and utilisation (Faverdin et al., 2011; Jouven et al., 2006) and whole-farm production systems (Guimarães et al., 2006; Romera et al., 2008). Optimisation models have been applied to examine the impact of policy restrictions (Acs et al., 2010), production and market changes

(Crosson et al., 2006b; Ramsden et al., 1999) and environmental restrictions (Gibbons et al., 2005).

For this study, it was decided to employ simulation and optimisation modelling to take advantage of the more flexible approach to modelling systems offered by simulation modelling, as well as reaping the benefits of handing complicated cases to achieve optimal solution offered by linear programming. Even though, these models have covered a wide variety of topics, this study identifies and addresses the need for designing novel livestock modelling approaches based on region-specific robust datasets (Antle et al., 2017a). Initially, a simulation model was developed to accurately portray the current Scottish beef production systems. Subsequently, this model was be linked with a well-recognised carbon footprint calculator to examine the environmental aspect of these systems, essentially through a framework that created an independent simulation model. As both simulation models grew in size and complexity, it became challenging to optimise solutions, as this would require to run and study simultaneously a great number of different scenarios. Therefore, we chose to build a simple optimisation model for beef production that would allow a more thorough examination of the policy implications stemming from the existing political landscape. This study attempts to develop a framework for modelling beef finishing systems that bring together and makes efficient use of information available aiming to inform the decision-making process on adopting alternative farm-management systems in Scotland.

Thus, the objectives of the study were to:

1. Develop a bio-economic simulation model for Scottish beef finishing enterprises using data from Scottish beef finishing studies, as well as agricultural input and output price datasets. For this purpose, an already existing model was used as a base, re-parameterized and adjusted to fit Scottish conditions.

2. Assess existing alternative management practices during the beef finishing phase to determine the drivers of profitability and test scenarios to identify limitations and opportunities for sustainable beef production in Scotland.

3. Combine the bio-economic simulation model and farm-level carbon footprinting tool to investigate the environmental impact of a range of beef production scenarios in Scotland, and identify trade-offs created from mitigating emissions and increasing farm profitability.

4. Develop an optimisation model for beef finishing systems, employ real farm data from Scotland, and determine an optimal solution both in terms of financial and environmental assessment.

5. Summarise the results of the study and identify areas of future research and implications for farmers, policy makers, researches, and relevant stakeholders.

Chapter 2 provides a summary of the economics of beef production systems and an overview of related government regulations of farming in Scotland. A brief description of beef production systems in Scotland is also provided. Successively, the economics of the sector is discussed at a regional and enterprise-level, while focusing on significant environmental and political parameters.

Chapter 3 presents a literature review on simulation and optimisation models. The advantages and disadvantages of both techniques are discussed along with the reasons for choosing the approach taken in this study.

Chapter 4 describes the process of re-parameterising further re-developing an already existing model, to construct the Grange Scottish Beef Model, a bio-economic simulation model for beef finishing systems. Subsequently, the model simulates numerous alternative beef production systems in Scotland and investigates their performance under different economic scenarios.

Chapter 5 describes the steps of combining the bio-economic model (Grange Scottish Beef Model) with a farm-level carbon footprinting tool (AgRE Calc) to simulate typical beef production systems in Scotland. Afterwards, the methodology of formulating scenarios is detailed, to determine the environmental impact of alternative beef finishing systems by examining factors such as finishing duration, type and diet, gender selection, as well as possible trade-offs between practices that promote environmental and financial sustainability.

Chapter 6 outlines the design process of developing an optimisation model for beef finishing systems in Scotland using General Algebraic Modeling System (GAMS), which is a high-level modelling system for solving linear, nonlinear, and mixed-integer optimization mathematical problems. The model employs real-world farm data generated in Scotland and examines several of the systems already identified as more cost-effective by the bio-economic simulation model, in an investigation towards the optimal system for the beef finishing phase in enterprises in Scotland.

Finally, Chapter 7 provides a synopsis of the most important findings of the study, discusses some limitations and strengths of the models developed and highlights potential areas for future research and implications.

Chapter 2: Beef production systems in Scotland

2.1 Introduction

In this chapter, the importance of the agri-food and agricultural sector to the Scottish economy is discussed followed by a focus on the beef sector of the region. The main agricultural policy changes over the last twenty years are described along with the environmental restrictions placed on farmers. Following, a comprehensive review of the beef sector in Scotland is discussed, along with references to general economic trends and the current state of beef imports and exports. For the next part of Chapter 2, the economics of beef production systems at the enterprise-level are analysed for the different beef finishing systems practiced in Scotland and the UK in terms of physical performance and profitability. Future changes and opportunities caused by the UK formally leaving the EU are argued in the next section. Finally, the issues identified in the course of this analysis that will be addressed in the next chapters will be presented.

2.2 Importance of agri-food sector to the Scottish economy

Agriculture is one of the most significant parts of the economy in Scotland, reflecting the land's composition and capabilities. Almost 79% of Scotland's total land area is dedicated to agricultural holdings and common grazing. About 60% of that land is considered rough grazing; including the hectares dedicated to common grazing, and over 85% of Scotland's agricultural area is classified as less favoured area (LFA) (ERSA, 2016). The LFA is an EU classification, which recognises natural and geographic disadvantage. Every region's agriculture activities are context-related, with a prime factor being land type. So, in the absence of other alternative agricultural uses, the livestock sector plays a pivotal role in sustaining the social fabric of rural communities and supporting local economies. The value of outputs produced from Scottish farms in 2016 was calculated to £2.82 billion, but that rose to an estimated £3.21 billion in 2017, with changes attributed to both volume and prices variation (The Scottish Government, 2018). The outputs from Scottish agriculture made up about 1% of the Scottish economy in terms of Gross Value Added (GVA) (ERSA, 2016).

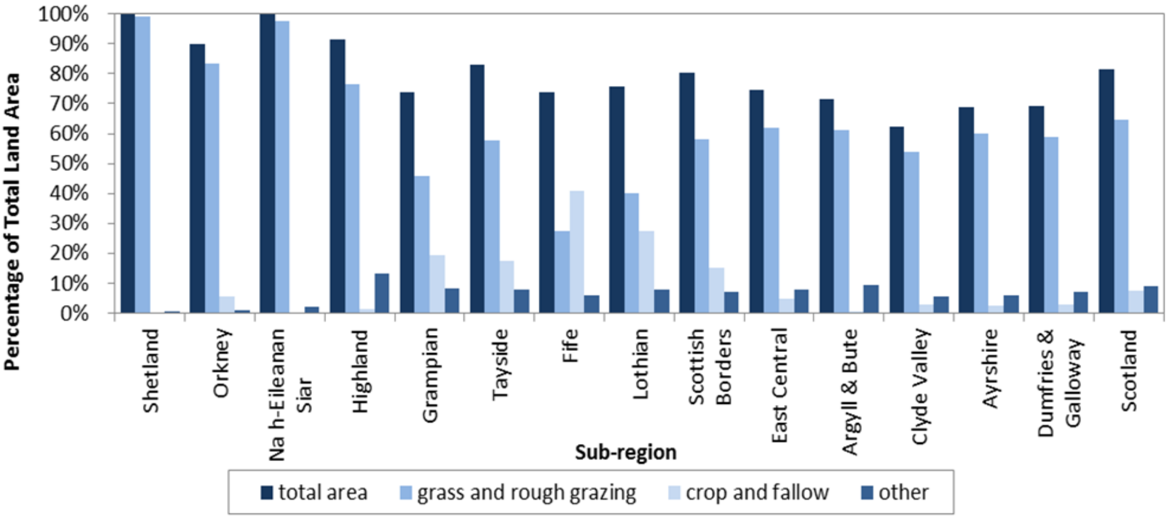

Figure 2. 1 *Percentage of Scotland's sub-region areas used for agriculture (ERSA, 2016).*

Agricultural holdings sustained employment for over 63,400 people in 2016, with the total working force consisting of working occupiers (58%), regular staff (32%) and casual and seasonal workers (10%) (ERSA, 2016). The National Farmers Union of Scotland reports that the agriculture sector employs 8% of the rural workforce, making agriculture the third largest employer in rural Scotland, after the service and public sector. Additionally, it was estimated that 1 in 10 of all Scottish jobs (360,000) are dependent on agriculture (NFU Scotland, 2018). Agricultural output is translated to products for the agri-food sector, one of Scotland's most commercial sectors. Overall, the region's exports were £29.8 billion in 2016, with much of the growth attributed to the lucrative agri-food and beverage sector, which contributed with nearly £5.5 billion for the same period. That establishes the manufacture of food and beverages the largest industry for exports in Scotland. These values indicate that the agricultural sector has an important role to play in the Scottish economy as a whole.

2.3 Agriculture policy context

The European Union Common Agricultural Policy (CAP) holds a fundamental role in steering livestock agriculture in Scotland, as it is the agreement that governs the agricultural policy of the European Union, by implementing a system of agricultural subsidies and other programmes. To consolidate the role of European agriculture for the future, the CAP has evolved over the years to meet changing economic circumstances and citizens' requirements and needs. After its foundation in 1962, the CAP has undergone frequent consecutive reforms. In 1992, the MacSharry reforms aimed at limiting the rising production while at the same time shifting the emphasis from previous market-based intervention towards direct (headage-based) subsidies to farmers, which consequently led to a more free agricultural market. In 1999, another notable change introduced with the 'Agenda 2000' that split the CAP into two pillars. Pillar One was for direct production support whereas Pillar Two was for rural development and agri-environmental schemes. This was the start of a transition away from direct production support (Pillar One). The ‘national envelope’ was also introduced under which member states were able to ‘top-slice’ their direct payments to create a national fund for specific purposes under member state control. Under Agenda 2000 reforms market support reduced but direct coupled payments increased (Swinbank, 1999).

Further reform of the CAP was instigated in 2005 when the Single Farm Payment (SFP) scheme was introduced, which decoupled subsidy payments from most sheep and cattle production, except for the Scottish Beef Calf Scheme. This CAP agreement allowed some flexibility for member states to choose payment structures with approaches ranging from the historic, flat rate per hectare or hybrid systems. Between 2004 and 2007, 12 new member states joined the European Union from Central and Eastern Europe. The Copenhagen Agreement (2002) was designed to allow the transition of these new member states into the CAP with most opting for a simplified area-based payment system and additional support for rural development (European Commission, 2013a). The Health Check in 2008 continued with the process of decoupling, agreed on the abolition of milk quotas in 2015 and allowed new member states to continue with the simplified area-based payment system until 2013. Further CAP reform occurred in 2013 and involved a move away from historical-based payments towards a more flat-rate system of payments. There was also the introduction of a Greening Payment with 30% of the national envelope linked to the provision of certain sustainable farming practices rewarding farmers for the provision of environmental public goods (European Commission, 2013a). The latest agreement in 2015 aims to ensure that the payments are better targeted by limiting support to those who are actively engaged with agricultural activities and environmentally sustainable agriculture. At the same time by acknowledging the issue of an ageing farming population, the CAP provides additional incentives for younger farmers entering the sector from 2015, while attempting to shield the smaller farmers and potentially vulnerable sectors (European Commission, 2013a).

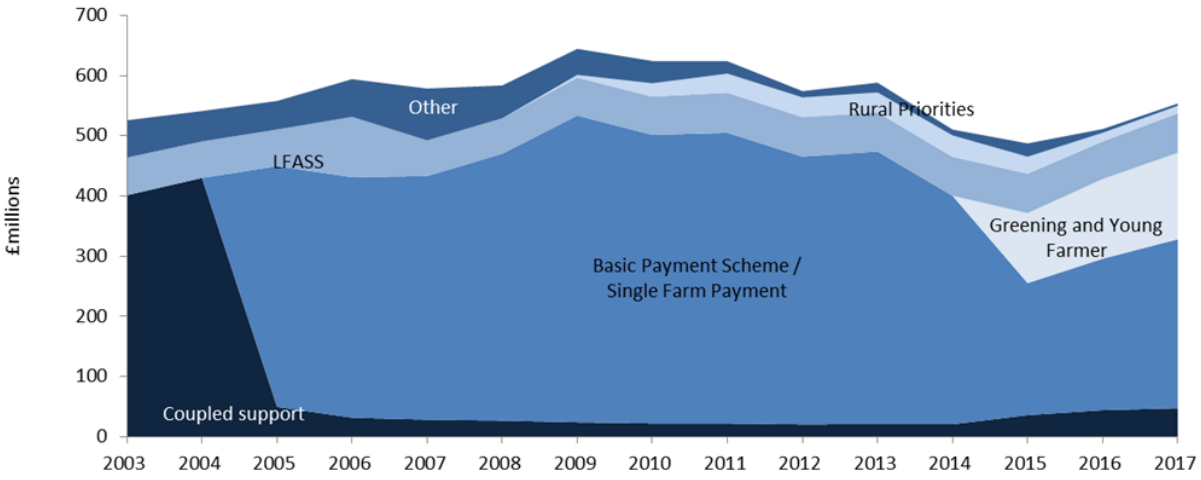

Figure 2. 2 *Grants and Subsidies 2003 to 2017 available for livestock farmers in Scotland (ERSA, 2016).*

The Nitrates Directive of the European Union (Directive 91/676/EEC) was implemented to ensure that the European Union standard of nitrates in potable water of 50 mg l^{-1} is not breached. Farmers can be penalised through loss of their SFP if found to be in breach of the Nitrates Directive regulations. The interpretation of these rules at the farm-level is that farmers must not exceed organic nitrogen (N) loading rates of 170 kg ha^{-1} and are also limited in the application of phosphorus (P) fertilisers. Still, farmers can apply for a nitrates derogation, which increases the legal organic nitrogen level to 250 kg ha^{-1} subject to the completion of a detailed nutrient management plan. There is also a closed period over the winter when no organic fertiliser can be spread and minimum requirements for storage of the organic fertiliser (Scottish Government, 2010).

2.4 Overview of the beef production sector in Scotland

Beef production in Scotland is considered a significant agricultural activity and reflects land composition and capability. A large percentage of the land in Scotland is considered suitable only for improved grassland or rough grazing, which suggest that it is only capable of supporting ruminant livestock production. As a result, when compared amongst other European Union member states, Scotland has the highest dependency on cattle production (Ashworth, 2009; Scottish Government, 2014). In contrast to various European countries, Scotland’s cattle sector is focused on producing meat as opposed to milk products (Vosough Ahmadi et al., 2015). Thus, reflecting the large areas of grassland and rough grazing, the livestock sector is one of special weight to Scottish agriculture, as it accounted for over 28% of all agricultural output on 2016 (ERSA, 2016). A number that indicates Scotland’s reliance on livestock sector to be far greater than it is either in the UK as a whole (15%) or, on average, in the EU (9%) (Quality Meat Scotland, 2017a).

In Scotland, livestock production is heavily subjected to the specific land type and cattle enterprises remained heavily concentrated in the South West and North East. As a result, in the North West, Tayside, the Borders and Argyll & Bute the cattle population is mostly beef. By contrast, in the South West, there is a heavier focus on finishing store cattle and dairy production. In the North East, producing beef calves and finishing beef cattle take place in relatively equal measure (Quality Meat Scotland, 2017a).

The livestock sector is highly dynamic and it's constantly evolving in response to demand for livestock products as well as environmental and ethical concerns. To provide meaningful insights and gain a deeper understanding of the current situation of the beef sector in Scotland, several different areas and variables should be considered. Cattle population including herd size, calf registrations and production were reported, to capture the output produced by the sector. Production indicators include the level of supply to the processing sector, seasonality of production, age at slaughter. Some drivers for the sector's economy would include the movements of producer and consumer prices, as well as the cost of various inputs. Additionally, consumption data, the sufficiency of production and trading figures, assist in calculating the demand for livestock products. The data presented has been collated from many sources and mostly covers the 2017 calendar year.

2.4.1 Cattle production

Historic data suggests a downward trend in the cattle population of Scotland since the 1970s that became more evident when cattle numbers fell by 9% between 1997 and 2007. A drop that could be largely attributed to a 6% decrease during the 2001 foot and mouth disease (FMD) crisis. After the crisis of 2001, a mild recovery in cattle numbers was noted up until 2005 and the introduction of the Single Farm Payment that led to a 3% reduction in cattle numbers, mainly due to the contraction of the national beef herd (Thomson, 2008). Current numbers show the cattle population in Scotland numbering 1.78 million animals in the 2017 census on around 12,000 agricultural holdings, which still represents a fall of 185,000 or 9% from 1.96 million in 2007. The cattle population experienced a drop of 5% over the four years from 2010 to 2014 and decreased by 22,500 animals or 1% over 2016. For female cattle aged one year and over, the beef population was estimated at 704,000 animals, which accounted for 40% of the total. A number that was almost two and a half times bigger than the equivalent of dairy cattle, where 275,000, animals accounted for 15% of the total. In both cases, the majority of cattle were those over two years old with offspring. As for the rest of the cattle population, male cattle aged one year and over made up 15% of the total, while 30% were calves under one year old.

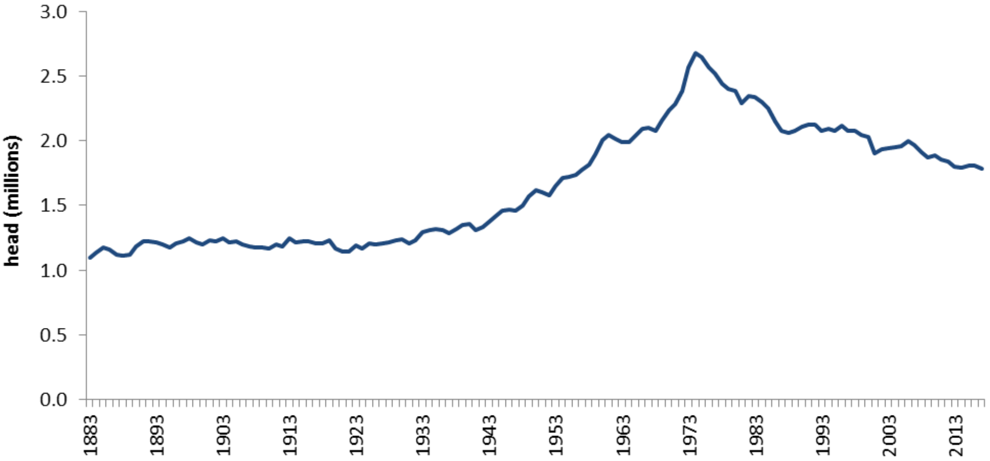

Figure 2. 3 *Historic data for cattle population in Scotland (ERSA, 2016).*

Differing trends can be observed between dairy and beef cattle over the same period. The number of dairy cattle decreased slightly between 2009 and 2013 but has been fairly stable since 2014. Beef cattle numbers, on the other hand, have been slowly declining over the period. Scotland's beef breeding herd has been dropping in numbers for the sixth time in seven years in 2017, losing 5,400 head to a total of 415,500 head. Breeding herd numbers are estimated 1% below their 2013–17 average and 10% below their 2006–10 average. In contrast, the dairy cow numbers showed a recovery in 2017, lifting 550 head to reach 175,200 head, nearly 1% above their five-year average but still below the average for 2006–10 (Ashworth, 2009).

Further analysis of trends between 2016 and 2017 reveal small decreases across all the main cattle categories between 2016 and 2017. The total number of cattle decreased by 22,500 to 1.78 million, the number of dairy cattle by 1,700 to 275,000, the number of beef cattle by 6,700 to 704,000, the number of dairy cows by 750 to 174,000, the number of beef cows by 3,800 to 433,000 and in the number of calves by 5,600 to 539,000. Nevertheless, calf registrations only edged lower in 2017 as a fourth consecutive annual rise in beef-sired calves was compensated by a decline in dairy-sired calves. The red meat industry is important to the UK as a whole, for approximately 18% of all cattle in the UK are in Scotland.

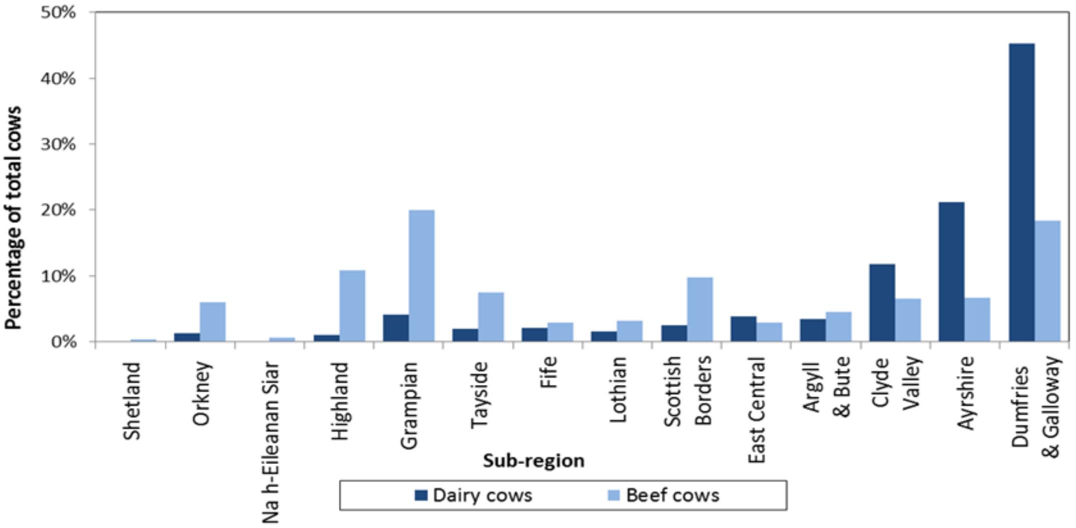

Figure 2. 4 *Dairy and Beef cows in Scotland presented by sub-region (ERSA, 2016).*

2.4.2 **Herd size**

The Scottish suckler beef herd size for 2017 increased to an average of 48 cows and was higher than the English average, which stood at 27 in 2015. Still, average herd sizes remain slightly lower across Scotland than before the decoupling of subsidy payments in 2005. Crofting is a traditional system of small-scale food production mainly in the Highland and the Islands of Scotland, characterized by lamb and beef rearing that are sold afterwards to lowland farmers for fattening and finishing since this is not cost-effective in the west due to climatic and soil quality constraints. This system keeps the number of the average herd size below the national average in the North West. For example, the average holding in Na h-Eileanan Siar and Shetland had just 7 and 11 cows respectively, while the largest average herd size was in the Scottish Borders (76 head), followed by Lothian (73), and Dumfries & Galloway (67). The beef sector in Scotland shows a high degree of concentration with many large cattle enterprises. Half of the beef herd was located on 14% of holdings with 100 or more cows in 2017. Nevertheless, the beef sector is less concentrated than sheep or pig farming (Quality Meat Scotland, 2018a).

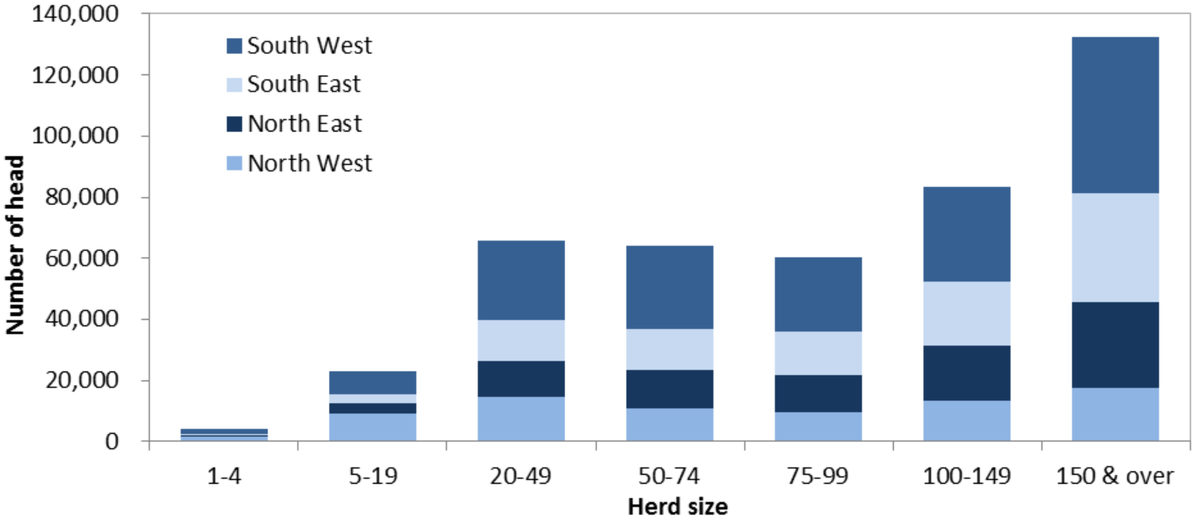

Figure 2. 5 *Herd Size in Scotland presented by region (ERSA, 2016).*

2.4.3 Calf registrations

In general, Scottish calf registrations provide a leading indicator of potential beef production in the following years. Currently, a downward trend is evident in calf registrations in Scotland, with the rate of growth slowing down for both 2016 and 2015, and consequently, the total number of calves dropping to 566,900 head in 2017. Yet, beef-sired registrations increased for the fourth consecutive year in 2017, recording a six-year high of 469,700 head in 2017. At the same time, dairy registrations reported losses of 5%, resulting in a nine-year low of 97,150 head. This led to an increased share of beef-sired calves in total registrations in Scotland to 83%. On a regional basis, differences were revealed in 2017, as registrations decreased in the North East (-2%) and the South West, while in the North West and South East slightly recovered. Beef registrations may have dropped in the North East, but they recovered in the North West, in the South East and in the South West. Especially, the South West accounted for 45% of beef registrations and 51% of total registrations in 2017. The apparent decline in total registrations in 2016 and 2017 indicates that steer and heifer slaughter availability may decrease in 2018 and 2019, with the further decline in dairy registrations in 2017 suggesting that young bull supplies may drop in 2018 (Quality Meat Scotland, 2018a).

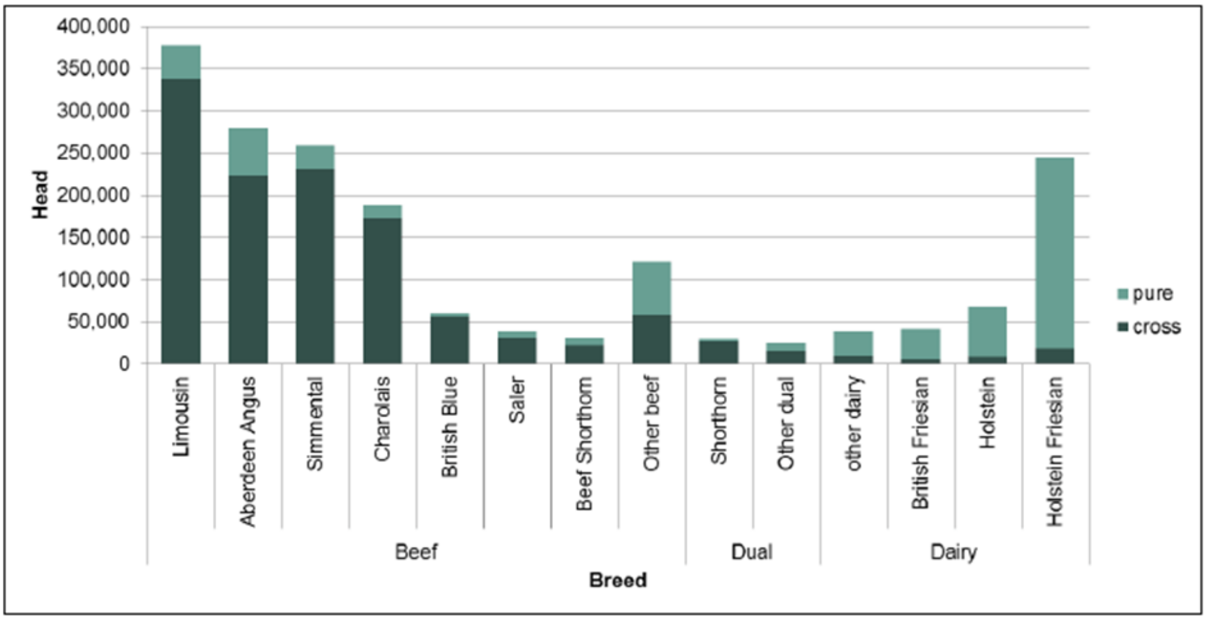

Figure 2. 6 *Beef breeds composition in Scotland (Scottish Government) (ERSA, 2016).*

Limousin sired cattle remained the most popular breed in Scotland for 2017, with 21% of the calves born in Scotland being sired by a Limousin bull, followed by Aberdeen Angus (17%), Friesian or Holstein (15%), Charolais (15%) and

Simmental (13%). A sharp decline has been reported for Limousin breed, with numbers falling by 3% in 2017 to 120,700 head, while at the same time the share of Aberdeen Angus-sired cattle has been rising for several years, resulting in registrations rising by 4% to 95,500 head in 2017. This trend may be attributed to the fact that producers can secure a premium from the marketplace for finished Aberdeen Angus-sired cattle. A decrease was noted in the registrations for Friesian or Holstein, Charolais and Simmental-sired calves in 2017 by 6%, 4%, and 1% fewer calves respectively. Sires that increased their shares in cattle registrations for 2017 in Scotland included native breeds, such as Shorthorn, Hereford, Luing and Highland, or other popular breeds like British Blue and Saler (Quality Meat Scotland, 2018a).

2.4.4 Output

In Scotland, the livestock sector has become more significant than it is either in the UK as a whole or on average in the EU. Beef production managed to recover gains after three years of declines, to reach a new record high of £851m. This represented an annual expansion of a nearly 7% for the largest sector of Scottish farming. Nonetheless, in terms of total agricultural output, the beef sector's share declined to the lowest value since 2013, down to 26% in 2017. Finished cattle and calves produced a turnout of £647m, an increase of 2%, as improved farm gate prices and coupled support payments overcompensated for the fall in production. In the meantime, the cross-border trade in store cattle and calves rose by 30% to reach £69m, while capital formation (the asset value of replacement breeding cattle) increased to £134m (Quality Meat Scotland, 2018a).

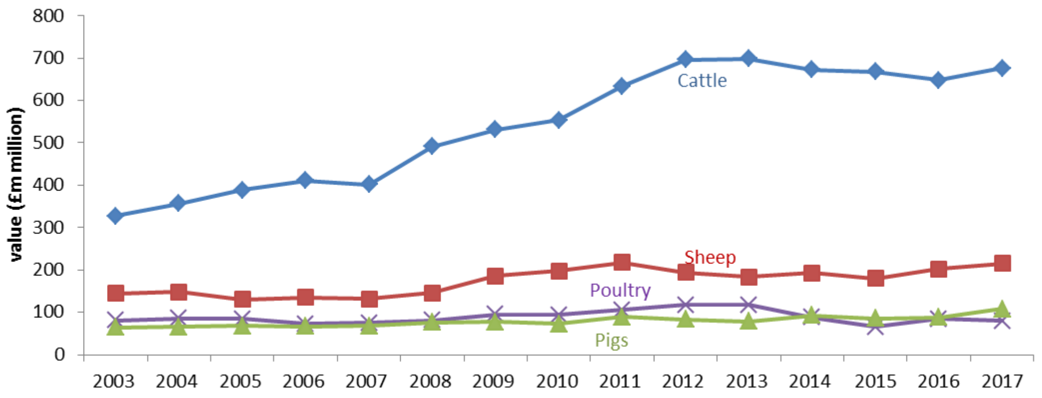

***Figure 2. 7** Output Value of Livestock (excluding subsidies) 2003 to 2017 in Scotland (ERSA, 2016).*

2.4.5 **Supply of livestock to the processing sector**

At Scottish abattoirs, the total number of cattle slaughtered in 2017 reduced by 2% to 462,400 head. Only 1% behind the average of 2013–17 and 11% below 2005–09. More specifically, prime cattle accounted for 388,700 head, which was 3% less than in 2016, and mature cattle for 73,550 head, a yearly increase of 4%. Another key point was that in 2017, the average carcase weight for both prime cattle and cow decreased to 365.8 and 338.2 kg respectively. Consequently, significant numbers of cattle, mainly steers, continued to exceed the target carcase weight range required to meet product specifications for prime cuts of beef sold by UK supermarkets. Pricing penalties for heavy carcases were imposed and have probably influenced the continued downward trend of carcase weights. Total beef production is estimated to have fallen by 3% at 167,250 t, while prime beef production declined by 4% to 142,200 t in 2017, mostly attributed to the reduction in prime cattle slaughter and carcase weights (Quality Meat Scotland, 2018a).

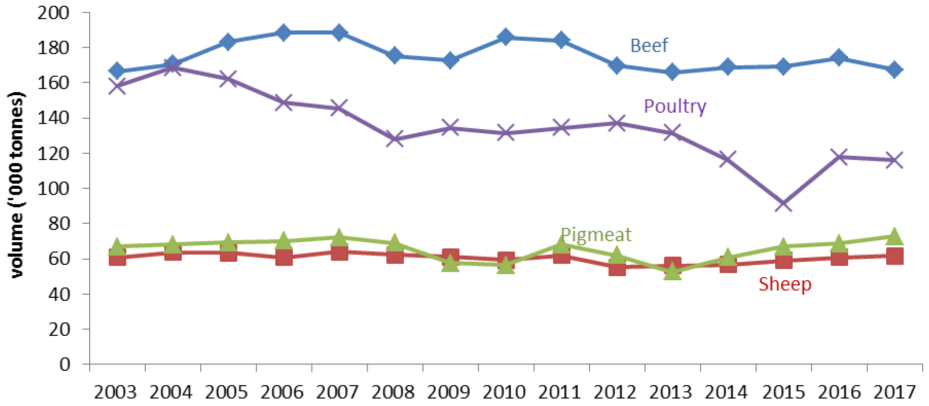

Figure 2. 8 *Output volume of Meat Production 2003 to 2017 in Scotland (ERSA, 2016).*

2.4.6 Seasonality of production

The calving season in Scotland depends greatly on the season, with carcase weights traditionally lower during the autumn, reflecting the dominance of spring calving. This has a major effect on the production systems, with steers and heifers tend to be slaughtered at around 18 months of age in the autumn, whereas those slaughtered in the springtime tend to be older, approximately two years old. Generally, steers and heifers tend to dominate cattle production, averaging nearly 78% of the total between them. There are examples of seasonal changes in the supply, as in the summer months, mainly in July and August, young bull production peaks, while cow culling reaches a peak in the autumn increasing their share between August and November. In 2017, beef production shifted from young bulls to cows. Steers accounted for 45% of the total, heifers increased slightly to 33%, cows increased to 16%, while the young bull share dropped to 6% (Quality Meat Scotland, 2018a).

2.4.7 Age of cattle at slaughter

In terms of the age of cattle at slaughter, there was a shift to a younger age profile in 2017, mainly for steers, and heifers. For male cattle, steers age profile moved away from 23–27 months, towards 18–22 months, while young bulls were mostly processed at 12–16 months. The most common age of slaughter for steers declined by a month to the 24th month, but the median age stayed at 23 months. Whereas, for female cattle, heifer age at death profile also moved younger, with the proportion slaughtered at 18–22 months rising to 36%. The 23rd month became the most common and the median age for a heifer to be slaughtered. Cows from the dairy herd appear to be culled mainly between four and seven years of age (48–84 months) while very few will live past the age of 14 years (168 months). As for beef cows, the profile remains stable from four years up to 13–14 years. Increased levels of female beef cattle slaughtered between 31 and 36 months of age usually reflect the slaughter of older heifers, including those that have been mated for the first time, but failed to conceive (Quality Meat Scotland, 2018a).

2.4.8 Price movements

Producers experienced higher annual average farm-gate prime cattle prices in 2017, after three years of decline, which followed a similar seasonal pattern as the previous years. This specific pattern begins with the festive period of January and February, where prices are kept low until market improving in March and until August supported by tight supplies. Then, after a relatively steady monthly period, prices dropped again in October and November before rising ahead of

Christmas. After the peak period of the festive season finishes, the prices drop once again. A significant proportion of prime cattle continued to exceed the level required meeting the product specifications of the multiple retailers despite the evident fall in carcase weights relative to 2016, thus; many producers faced price penalties. Consequently, for steers U grade was priced lower per kilo than R grade, while the opposite occurred for heifers. Average steer price was 375p/ kg dwt, an increase of 7% from 2016, but still 7% behind the 2013 peak. In general, deadweight prime cattle prices averaged around 6% higher in Scotland than they did in England & Wales in 2017. Moreover, Scottish abattoirs paid an average of £1,433 for a steer carcase and £896 for a cow carcase, while offering more for cull cows than their counterparts in England and Wales. The rise in producer prices in 2017 was adequate to translate into real terms prices increase of 4% in Scotland and of 4% in GB as a whole. Retail prices of beef and veal showed an increase at the beginning of 2017 and afterwards stabilised for the rest of the year, with minor differences compared to 2016. On average, beef retail prices were firm for extended periods in 2017; this resulted in the supply chain absorbing the significantly higher farm gate prices. Even though farm-gate and import prices for many agricultural products increased, heavy competition between UK retailers meant that much of this pressure was absorbed by the supply chain (Quality Meat Scotland, 2018a).

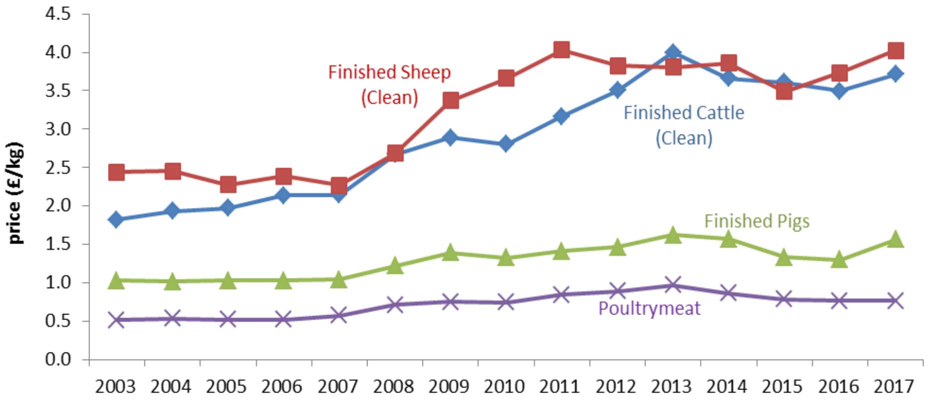

Figure 2. 9 *Output prices (£/kg) of finished livestock 2003 to 2017 in Scotland (ERSA, 2016).*

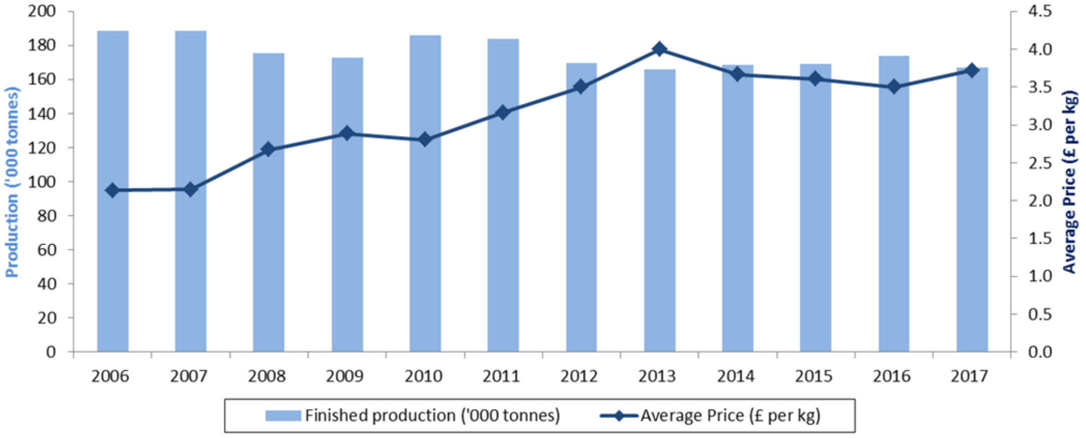

Figure 2. 10 *Finished cattle, production and average price from 2003 to 2017 in Scotland (ERSA, 2016).*

2.4.9 **Producer input costs**

A crucial element for beef production systems is store cattle prices, which mirrored a reoccurring historic seasonal trend again in 2017. The two main marketing periods that store cattle prices peak usually occur during spring and autumn, with the opposite effect taking place during summer and winter. After a sharp decline in 2016, average prices recovered in 2017, especially for steers where a 6–12 month steer sold for £865 and a 12–18 month steer traded at £979 in 2017 (Quality Meat Scotland, 2018). Another element that has an impact on beef production systems is the prices of the various inputs. The UK Agricultural Price Index for total inputs showed an increase of 5% in 2017, with the trend revealing relatively stable costs during the year, apart from a sharp decline in the summer. Energy costs recorded a decline from January till May, until steadying between May and July, to finally record an increase of 5% by the end of 2017. Electricity and gas prices were higher for most of the year, rising by 5–10% between January and December. Fuel costs exhibited a U-shaped cost trend, with similar prices recorded at the start and the end of the year and a drop by nearly 10% during the summer. In total, energy costs averaged 10% higher than in 2016 (Quality Meat Scotland, 2018a).

The evolution of overall energy costs reflects the seasonality of energy use and is heavily associated with fluctuations in the oil price. The fertiliser market followed a similar trend to energy costs in 2017, falling sharply in the first half of the year before rising in the second half to end the year higher than they had started it. This price trend is a manifestation of the global balance between supply and demand. During 2017, fertilisers averaged 8% higher than 2016, but in the long-term, this was their second lowest level since 2007. Feed costs appeared stable on average through 2017, with their monthly index showing a 5% difference between its minimum and maximum level. However, the prices were 7% higher than 2016 levels. A tendency that was evident since 2016, when the EU referendum initiated a downward trend in the value of the pound sterling. At the global level, rising grain production was sufficient to cover the demand, which increased for a fourth year, keeping the market to equilibrium (Quality Meat Scotland, 2018a).

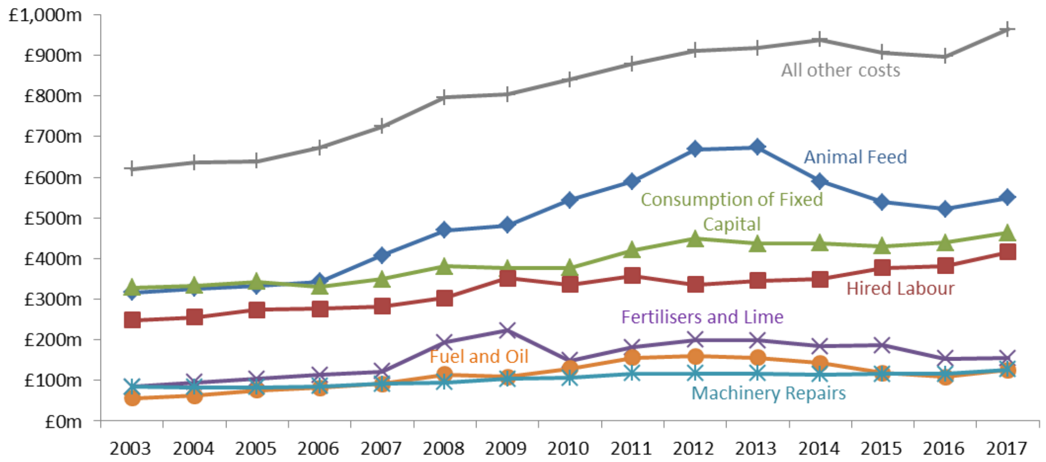

Figure 2. 11 *Total Agriculture Costs 2003 to 2017 in Scotland (ERSA, 2016).*

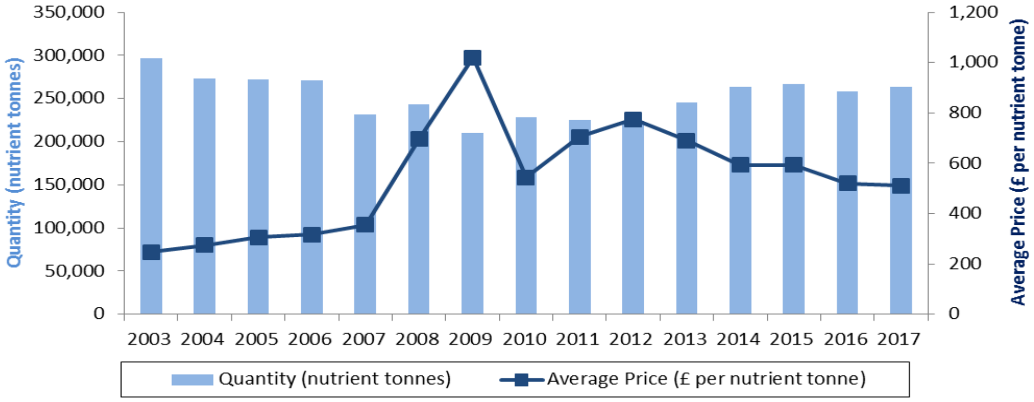

Figure 2. 12 *Quantity & Average Annual Price of Fertilisers Used 2003 to 2017 in Scotland (ERSA, 2016).*

2.4.10 **Livestock products consumption and self-sufficiency**

Domestic production coupled with imports makes up for the total volume of beef available for consumption in the UK, which reached a 30-year high of 1.11m tonnes in 2017. While domestic production fell by 11,800 t, the higher imports

(+12,900 t) and lower exports (-6,100 t) were able to compensate. Imported beef accounted for 31% of total supply, while, exports were equivalent to 15% of UK beef production, down from 15% in 2016. An estimated volume of 300,600 t of prime beef cuts (e.g. steaks, roasts and prime mince) was traded by multiple and independent retailers to UK households in 2017. While in Scotland, retail consumption increased by 2% to 29,300 t. Within the beef consumption, there was a shift away from roasts towards steaks (Quality Meat Scotland, 2018a).

Seasonal shifts exist for supply and demand and could lead to substantial variation in the region's self-sufficiency for beef, lamb and pork, and for different cuts. During 2017, Scottish self-sufficiency in beef is estimated to have fallen due to the combination of consumption growth and lower production. A rising Scottish population had a marginal downward impact on self-sufficiency estimates for the three categories. Still, for 2017, abattoir beef production was calculated at 149% of potential consumption in Scotland. UK beef production was equivalent to 81% of available supplies in 2017, down from 2016's 83%, but above its recent low point in 2015 (Quality Meat Scotland, 2018a).

2.4.11 United Kingdom overseas trade beef imports and exports

United Kingdom (UK) imported nearly 251,400 t of beef in 2017, a 3% increase since 2016, resulting in a three-year high that was 1% above the 2013 to 2017 average. Imports rose during the second half of the year by 7%, with a continued rebalancing between imports as frozen beef and deliveries of fresh beef product. Meanwhile, imports from EU countries increased by 6% in 2017 to reach 236,300t. This was 94% of total imports, up from 91% in 2015. The average value per tonne imported edged 1% higher to £3,700/t. Fresh boneless cuts accounted for 50% of beef imports from the EU, down from 53% in 2016. Meanwhile, frozen boneless cuts increased their share from 25% in 2016 to 27% in 2017, fresh carcases and half-carcases stabilised at 14%, and fresh bone-in cuts edged higher to 6%.

In terms of countries of origin, special mention should be made for Ireland, Ireland's share of the UK's beef imports boosted to 72%. Imports from the Netherlands fell by 4% to 16,600 t in 2017, shipments from Poland lifted by 28% to almost match Dutch volumes, while imports from Germany declined by 4% to 9,400t. The share of non-EU countries fell significantly for a fourth consecutive year in 2017, down 30% at 15,000 t. Deliveries from most of the main non-EU suppliers fell by 30-50%, including Brazil, Australia, Namibia, Uruguay, while Botswana shipped 3% less beef than in 2016. (Quality Meat Scotland, 2018a)

UK beef exports for 2017 were estimated at 105,150 t, which represents a fall by 3% from 2016. During 2017, 86% of the UK's beef exports were to the EU, a decline from 89% in the year before. The volume shipped to the EU declined by 6% to 90,900 t, but the average export price improved by 16% to £3,980/t, pushing up export revenues by 8%. Exports to the EU were 58% in the form of fresh boneless cuts, while frozen boneless cuts remained at 17%. Ireland remained the largest UK export market for beef in 2017. However, exports fell by 5% to 34,200t, leaving Ireland with a slightly smaller (32%) share of the total. In addition to product destined for retail, exports to the Irish Republic reflects cross border movements of beef between Northern Irish abattoirs and cutting plants in the Republic of Ireland for further processing. The Netherlands remained the UK's second largest export destination, but volumes dropped by nearly 10% to 23,400t, lowering its share to 22%. Concerning other significant European markets, exports to France and Italy declined, but sales to Belgium, Germany and Sweden grew. UK's beef exports to non- EU markets reached 14,200 t in 2017, with nearly over half of the product exported to Hong Kong, making it the UK's fourth largest export destination by volume (Quality Meat Scotland, 2018a).

2.5 Greenhouse gas emissions of the beef production sector in Scotland

Emissions from agriculture, including the associated land use, was the second largest contributor to the total in 2016 in Scotland. Agriculture accounted for over a quarter of Scotland's total emissions and was second only to the transport sector with emissions over 37% (Reid and Wainwrigh, 2018). The three main Greenhouse gases (GHGs) produced by an agricultural enterprise that contributes to the sectors' emissions are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Also, CH_4 and N_2O have a significantly higher total global warming impact than CO_2 over a set period. For CO_2, potential sources in a farm include burning fossil fuels like coal, oil and diesel, and via disposal of waste; it is also embedded in inputs such as feed, bedding, fertiliser and lime. For CH_4, the main pathways of production are as a natural by-product during ruminant digestion and from the management of organic manures. As for N_2O, it is released during the application of inorganic and organic fertilisers, from urine deposition by grazing animals and crop residues (Quality Meat Scotland, 2018b).

Consequently, out of the total agricultural sector emissions, livestock emissions stand out as they account for over 48% of the total in carbon dioxide equivalents (CO_2-eq), a common unit to measure emissions, of which cattle and sheep enterprises appear to be the biggest contributor. Agricultural land-use and emissions from soils account for a further 43% and a small contribution to emissions in made by farm machinery in the form of CO_2 (Reid and Wainwrigh, 2018).

In the years between 1990 and 2015, Scotland has experienced a reduction in emissions attributed to the agriculture and related land use sector. The emissions were reduced by 26%, from producing 3.8 Mt CO_2-eq in 1990 to emitting 10.8 Mt CO_2-eq in 2015 (Scottish Government, 2018a). This decrease is mostly attributable to factors like the improved efficiency in farming techniques (e.g. higher milk yields per cow and improved fertility), the drop in number of total cattle and sheep, the reduction in the amount of nitrogen fertiliser applied in land, and the reduction in grassland being cultivated for arable production (Scottish Government, 2018a). However, emissions from agriculture and related land use have been largely static for 8 years (Reid and Wainwrigh, 2018).

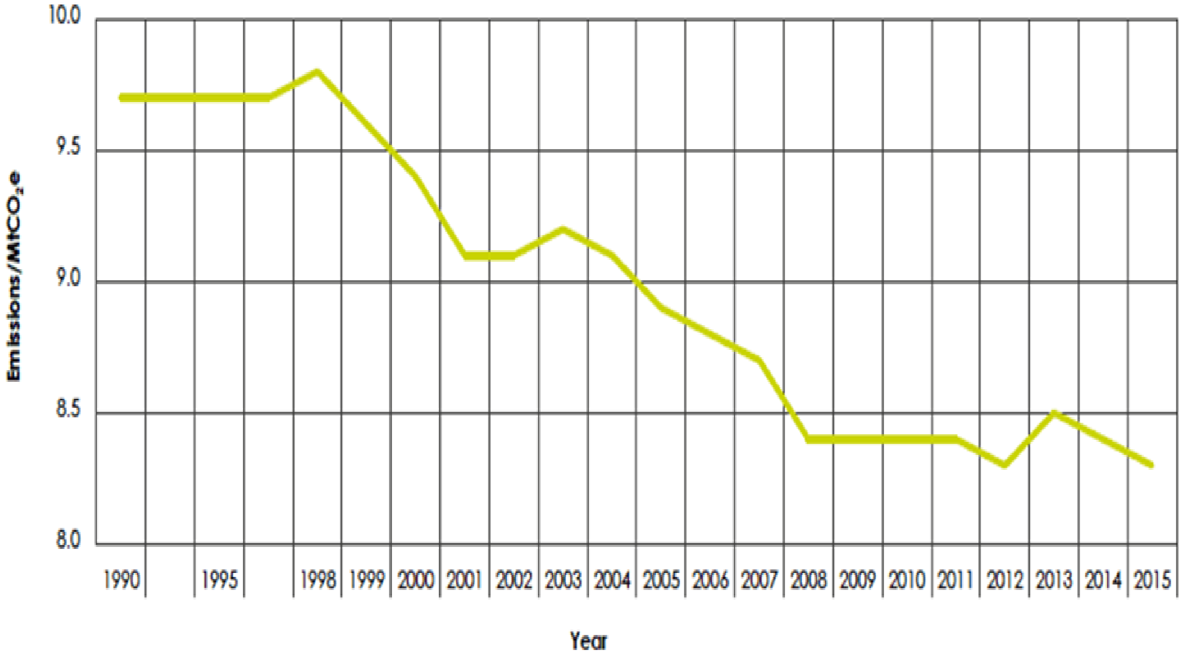

Figure 2. 13 *Historical Emissions of the Agricultural sector in Scotland from 1950 to 2015* (Scottish Government, 2018a).

GHG emissions in the food production chain are occurring naturally due to biological processes and chemical interactions in both livestock and plant growth. Methane and nitrous oxide are emitted in significant quantities by agriculture when compared to other sectors that the dominant GHG would be carbon dioxide. Therefore, the approach to mitigating emissions from agriculture differs from most other sectors. Moreover, as progress is made in reducing emissions in electricity or waste, the relative importance of agriculture in the total Scottish emissions budget grows. The tension between climate change mitigation and providing food security may increase in the future, considering uncertainties around the UK leaving the EU, the increased growing population rate, the growing pressures throughout the economy and the rising cost of living. Hence, mitigation strategies should be devised to ensure GHG reduction can take place while Scotland continues to produce secure and sustainable food (Scottish Government, 2018a).

As a response, the Scottish Government has revealed its position on climate change through the Climate Change Act (2009) and following secondary legislation. The Climate Change (Emissions Reduction Targets) (Scotland) Bill sets clear targets for greenhouse gas reductions in Scotland, as it introduces a legislative target to reduce greenhouse gas emissions by 90% by 2050 across the whole Scottish economy (Quality Meat Scotland, 2018b; Scottish Government, 2018a). The UK and Scottish Government's statutory advisers, the Committee on Climate Change (CCC), consider this reduction goal to be at the edge of feasibility. Furthermore, agriculture and livestock production is acknowledged as a key contributor to GHG emissions in Scotland, so all sectors of the industry and the wider community are anticipated to strive for emissions decrease (Reid and Wainwrigh, 2018; Scottish Government, 2018a). In addition, in a progress report published in February 2018, the Scottish Government sets a goal of a further 9% reduction in emissions from agriculture by 2032 (Quality Meat Scotland, 2018b).

However, several opportunities exist to reduce emissions arising on-farm. Most of these will necessitate shifts from business as usual behaviour, and include agroforestry, restoring peatlands, soil testing and management to increase carbon capture, changes to cattle feed to reduce enteric emissions, farming breeds and crop varieties that produce less methane, precision agriculture to reduce fertilizer and pesticide use, and dietary change (Scottish Government, 2018a).

2.6 Economics of beef production

The main measure for farm income employed in Scotland is the Farm Business Income (FBI). FBI is the business-level measure of farm incomes and is based on crop years. It provides an estimate of average incomes, outputs, costs and subsidies for different farm types. In Scotland, the average income of commercial farms was reduced by nearly 50% throughout a six year period to 2014/15. The measure of average FBI was introduced in 2009/10, and it has reported a steady yearly decline, from £51,000 to an average of £28,000 in 2015 and £26,400 in 2016-17.

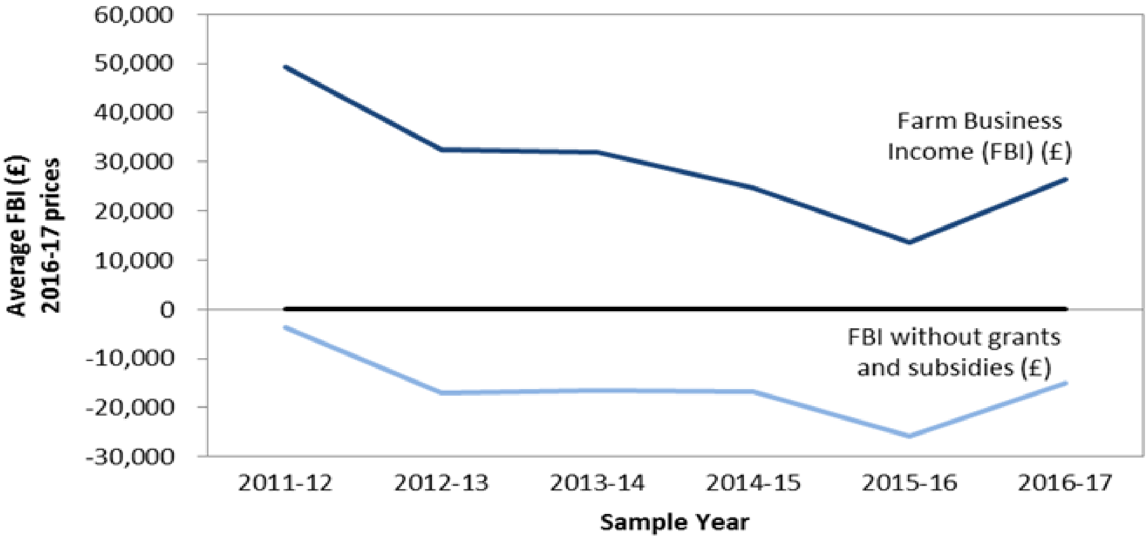

Figure 2. 14 *Average Farm Business Income (FBI) of Scottish Farms for the 2011-12 to 2016-17 periods (ERSA, 2016).*

The Estimated Total Income from Farming for 2015 was £667 million in Scotland, about £2,750 million in England, £183 million in Northern Ireland and

£175 million in Wales. Nevertheless, when the total of the agricultural area is taken into account, agriculture generated about £292 per hectare in England, £177 per hectare in Northern Ireland, £108 per hectare in Scotland and £95 per hectare in Wales. Furthermore, the estimated average Farm Business Income for UK nations at the same period, the highest average value for 2014-15 was reported in England at £39,700, followed by Wales (£29,400) and Northern Ireland (£24,900). Scotland had the lowest average FBI value at £23,000. While farm incomes in all countries fell in 2014-15, the decline in average income in Scotland was the steepest, with average incomes down by a quarter (ERSA, 2016).

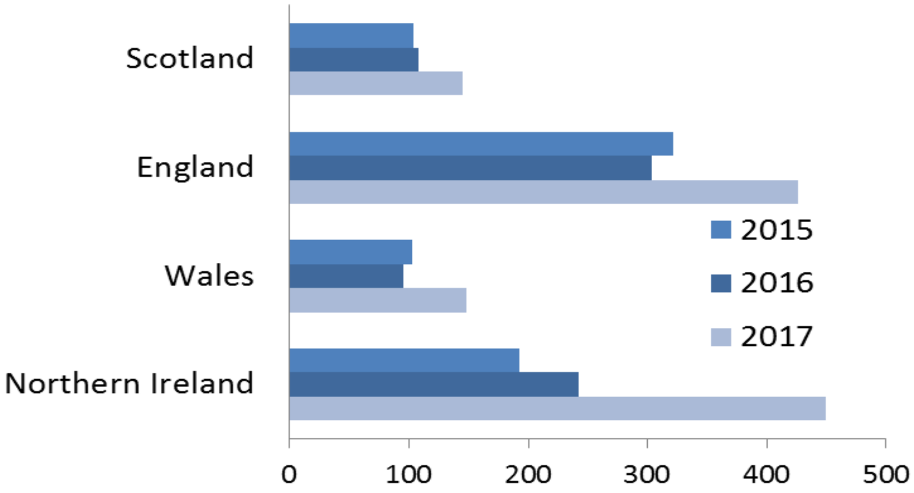

Figure 2. 15 *Total Income from Farming per hectare (£) for the different regions of the United Kingdom (2015-2107) (ERSA, 2016).*

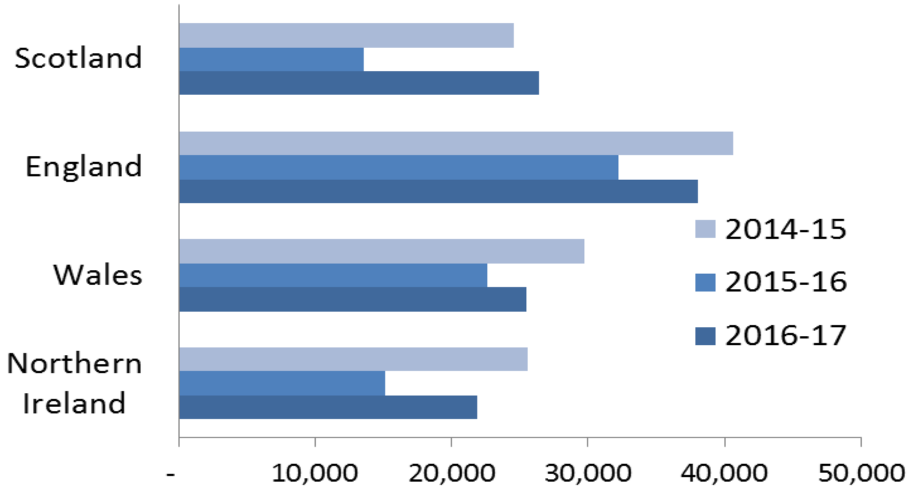

Figure 2. 16 *Average Farm Business Income (FBI) (£) for the different regions of the United Kingdom (2014-2107) (ERSA, 2016).*

Data from the Farm Accounts Survey (FAS) are employed to calculate the Farm Business Income and other relevant metrics for three categories relevant to beef production, namely the 'Specialist Cattle (LFA)', 'Specialist cattle and sheep (LFA)' and the 'Lowland Cattle and Sheep Farms' for Scotland. For the year 2016, the FBI value of specialist cattle (LFA) was calculated at £25,600 with around 44% of farms generating incomes equivalent to less than the minimum agricultural wage (MAW). Heavy losses were recorded when excluding subsidy payments that ranged from £15,800 in 2011-12 to their highest level of £31,300 in 2013-14. In 2016-17 losses of £21,100 were recorded when excluding subsidy payments from the FBI. Spending on inputs averaged £147,200, with the largest portion of the input costs was due to feed and "other inputs" such as machinery and land and buildings (Scottish Government, 2018). The FBI value of specialist cattle and sheep (LFA) farms was £35,300 in 2016-17 and decreased by 17% between 2012 and 2017, mainly due to a decrease in output value. Around 23% of specialist cattle and sheep (LFA) farms generated incomes equivalent to less than the MAW and losses were recorded in each year when excluding subsidy payments from the FBI calculation, which ranged from losses of £21,900 in 2011-12 to the highest loss of £37,900 in 2012-13. Spending on inputs averaged at £140,400. The largest portion of the input costs was due to livestock costs such as feed, as well as machinery and land and buildings costs (Scottish Government, 2018). For 'Lowland Cattle and Sheep Farms', the average FBI of lowland cattle and sheep farms decreased by 50% between 2011-12 and 2016-17. In the last year, both spending on inputs and outputs decreased. However as the drop in inputs decreased by a larger amount, the effect had been a 47% increase in the FBI value of lowland cattle and sheep farms to £18,300. The main decrease in output was a drop in livestock output. Around 55% of lowland cattle and sheep farms generated incomes equivalent to less than the MAW. FBI without subsidy payments has been a loss, ranging from a loss of £24,600 in 2012-13 to a loss of £10,400 in 2014-15. In 2016-17 the FBI without subsidy payments was a loss of £16,000. Spending on inputs averaged £151,000. The largest portion of the input costs was due to feed and other inputs such as machinery and land and buildings (Scottish Government, 2018).

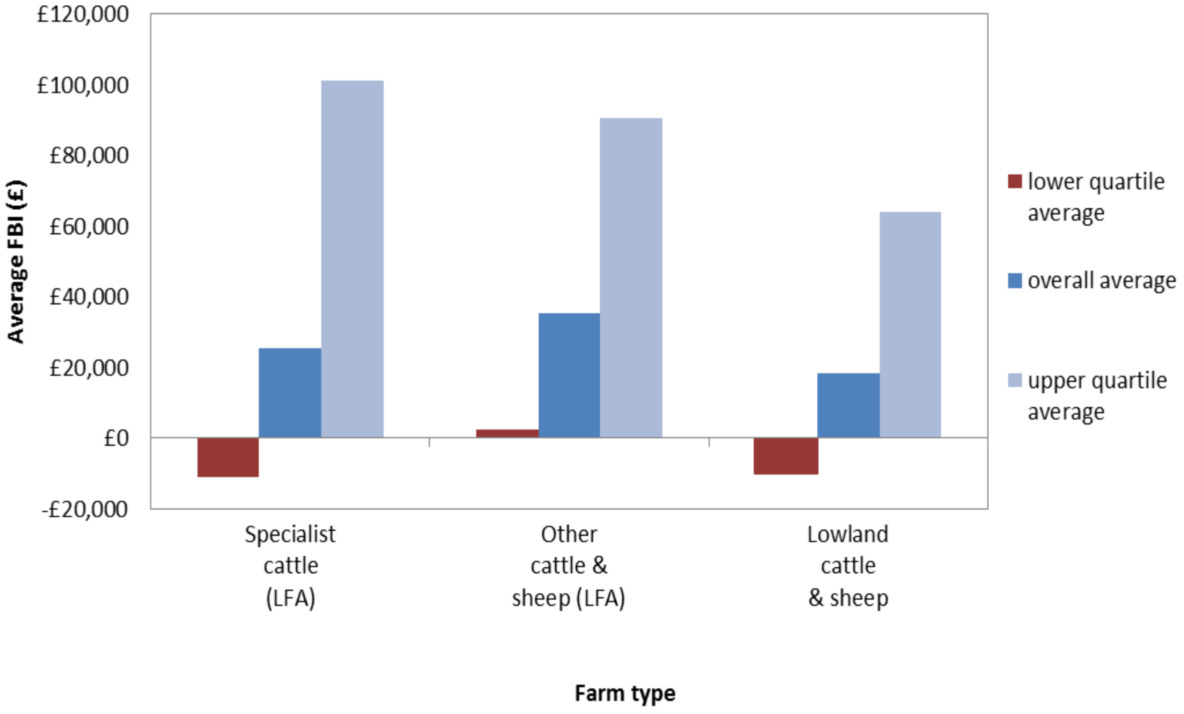

Figure 2. 17 *Farm Business Income (FBI) by farm type in Scotland for the 2011-12 to 2016-17 periods (ERSA, 2016)*

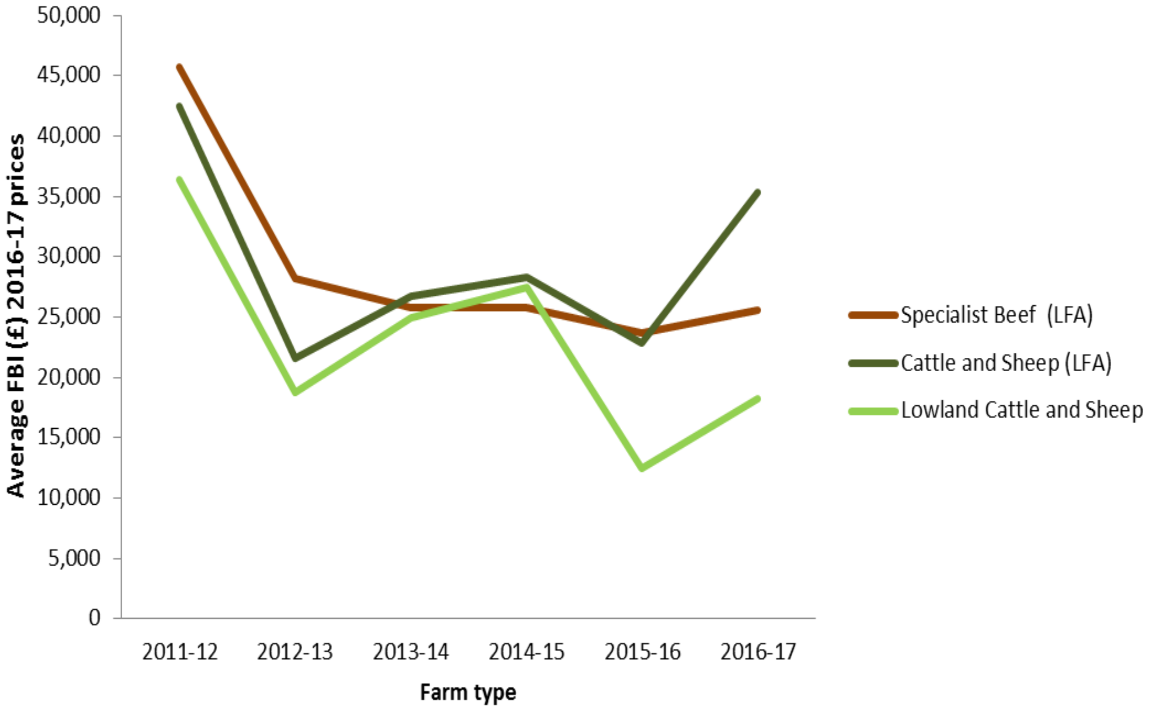

Figure 2. 18 *Average Farm Business Income (FBI), lower quartile and upper quartile: 2016-17 (ERSA, 2016).*

2.6.1 Enterprise-level in the United Kingdom and Scotland

Beef finishing enterprises have been sub-divided based on the average age of animals at sale, to represent the most common production systems that will allow comparisons. For the UK, information about the economic performance of beef enterprises comers from the Stocktake Report 2016, a reference document for the English beef industry against, which could be used as a benchmark for producers for their own performance and enterprise costs (AHDB, 2016a). The category of beef finishing enterprises identifies farm businesses that have sold the majority of animals as finished. In most cases, these animals have been transferred from a suckler herd and/or purchased as calves or stores at various ages. There are three age groups identified, finishing cattle up to 16 months, finishing at 16 to 24 months, or over 24 months. The age relates to the average age of the animals when they are slaughtered and sold as finished. Amongst the beef finishing producers, the top half of all beef finishing systems achieved positive cash-only net margins, mainly because they presented lower total variable costs than bottom half producers. Also, when examining beef systems finishing cattle over 16 months of age, it is evident that bottom half producers purchase older animals at a higher cost than top half producers, while in systems finishing cattle up to 16 months of age, top half producers achieved higher daily live-weight gains with a higher reliance on forage rather than concentrates, resulting in lower feed costs. Nevertheless, on average in the UK, beef producers finishing cattle performed poorly, achieving a negative net margin on a full investment basis (AHDB, 2016a).

On the other hand, data specifically describing Scottish beef enterprises were sourced from a report produced annually by Quality Meat Scotland. There are four types of beef finishing enterprises described. The first category describes the rearer-finisher enterprises, where, businesses produced an average gross margin per cow of £554, within a range from £320 to £755 per cow, and zero (£0) average net margins per cow. The top producers ranked by gross margin per cow achieved a net output £140 higher than the average, because they managed to produce 20% more output per cow despite a drop in the sale price below average. Cow replacement rates and mortality rates remained low, which contributed to lower herd maintenance charges that affected the net margins. Top producers achieved higher output with lower variable costs per cow, particularly lower concentrate feed volumes and cost. Fixed costs were £50 per cow higher than the average for the top producers, attributed to higher labour and property and machinery maintenance costs. Nonetheless, because of the higher physical output, fixed costs per kg of output were 10% lower than the average. Although fixed and variable costs were lower per cow among the bottom producers, lower physical output led to gross and net margins some £104 per cow lower than the average (Quality Meat Scotland, 2018b).

Cereal-based cattle finishing enterprises represent another type of beef enterprise in Scotland, where the producers managed a positive average gross margin of £145 per animal and a positive average net, at £40 per head that ranged from (-) 120 to 313 pounds per head. Top producers achieved a net output of £102 per animal above the average and £194 better than the bottom businesses. Some key points for the top producers were that they accomplished the heaviest carcass weights (380–400 kg) and the best growth rates, while they started with the lightest cattle and fed them for the longest period. Nevertheless, they used the least amount of home-grown and purchased concentrates, which indicates high levels of feeding efficiency. Output was boosted by the fact of having the lowest mortality during the finishing period and the best sale prices. On the contrary, the farms with the bottom performance turned their cattle over the quickest but carried the highest concentrate use and highest mortality rates. These farms failed to benefit from the high prime heifer sale prices, and also received lowest per kg prices for steers and young bulls. The survey showed that bottom producers in terms of financial performance sold heavier steers carcasses over 420kg, which contributed to receiving lower selling prices. In contrast, they received the best prices for heifers through lower carcase weights but had the lowest proportion of heifers in their mix of sales (Quality Meat Scotland, 2018b).

The forage-based cattle finishing enterprises have been split into two groups based on the age at which the majority of the cattle were sold. The average age at which Scottish prime cattle are slaughtered is around 22 months of age. This has been taken as the age for splitting the business surveyed. Thus, the two groups are those selling finished cattle under 22 months of age and those selling finished cattle at over 22 months of age. Those selling younger cattle reported a gross margin of £164 per animal sold, falling to a net margin of (-) 74 pounds per animal sold, while their counterparts selling older cattle reported a gross margin of £155 per head and a net margin of (-) 105 pounds. Those selling younger cattle finished them around 14 weeks more quickly than those selling older cattle, but they sold heavier cattle. From the four different types of beef finishing farms that were previously described for Scotland, three were considered appropriate for comparison, as they correspond with the systems found in the UK report. The following table presents some physical and financial performance data for the three types of finishing systems in terms of intensity farming (Quality Meat Scotland, 2018b).

Table 2. 1 *Physical and financial performance finishing systems in various farming intensities**

£ per head	AHDB	QMS	AHDB	QMS	AHDB	QMS
	Finishing up to 16 months	Cereal-based finishing	Finishing 16 to 24 months	Forage-based finishing <22 months	Finishing 24 months and over	Forage-based finishing >22 months
Stock Sales	1,171	1,281	1,190	1,223	1,065	1,286
Stock purchases	691	767	536	777	578	838
Total feed & forage Costs	290	285	233	195	189	204
Total Variable Costs	384	368	318	279	256	292
Total Fixed Costs	230	105	421	241	270	260
Gross Margin	113	146	354	166	231	155
Net Margin	- 117	40	- 67	- 74	- 39	- 105
Feeding period (days)	207	232	419	307	259	408
Start weight (kg lwt)	329	324	234	338	383	365
Finish weight (kg lwt)	624	639	607	642	636	629

*Adopted from Quality Meat Scotland, (2017c) and AHDB, (2016).

2.6.2 Economics of greenhouse gas emissions on a cattle enterprise

Agriculture and livestock production has been identified as a significant contributor to greenhouse gas (GHG) emissions in Scotland. The Agricultural Resource Efficiency Calculator (AgRE Calc) was employed to evaluate the type, source and extent of the GHG emissions attributed to cattle production systems in Scotland. The GHGs examined was carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Carbon dioxide is generated from burning fossil fuels such as coal, oil and diesel, and the disposal of waste; it is also embedded in inputs like feed, bedding, fertiliser and lime. Moreover, methane is produced as a natural by-product during ruminant digestion and from the management of organic manures, while nitrous oxide is released during the application of inorganic and organic fertilisers, from urine deposition by grazing animals and from crop residues (Quality Meat Scotland, 2018b).

Carbon emissions comparisons for different Scottish cattle farms reveal that lower emissions tend to be associated with higher margins. The outcomes highlight the wide range of emissions within and between cattle enterprise types and the correlation between emissions and financial performance. This can be attributed to the fact that for livestock enterprises, the productivity of the system and the technical efficiency of that system are common drivers for both improved margins and reduced emissions (Quality Meat Scotland, 2018b). Moreover, total GHG emissions and cattle farm profitability are also influenced by the physical environment in which the enterprise is based. For example, the levels of rainfall, sunshine hours and temperature not only affect animal productivity and performance, but can also result in considerable seasonal change in input use. The amount of fertilisers and animal feeds, and the need for fuel and electricity for extended fieldwork and/or housing periods and feed preparation and delivery have a great impact on a farms' emission intensity (Quality Meat Scotland, 2018b).

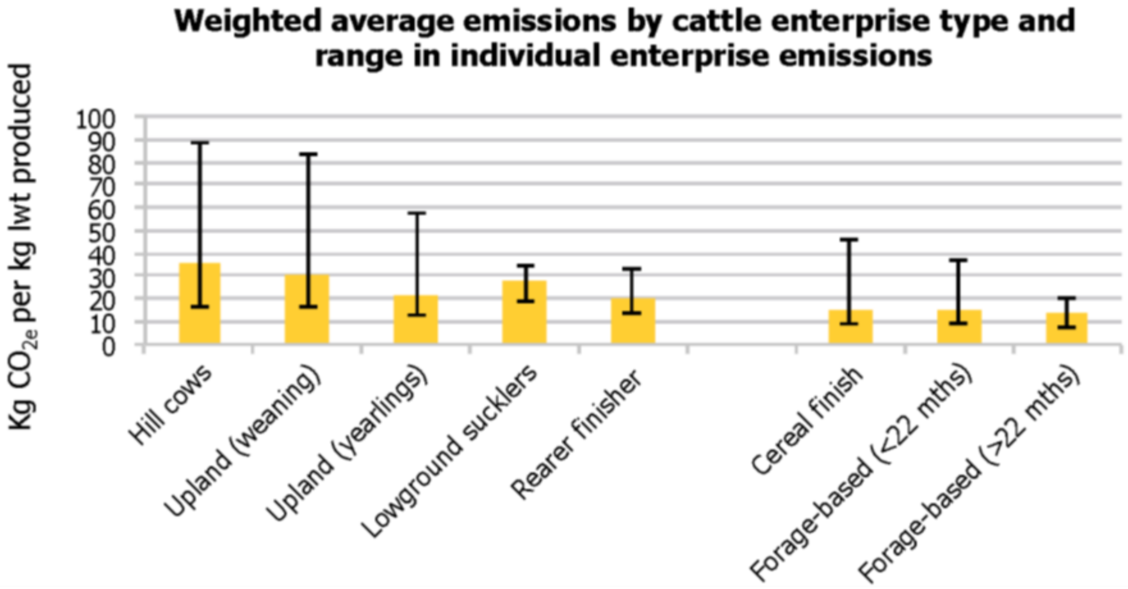

Figure 2. 19 *Average Emission by cattle enterprise type in Scotland (2017) (Quality Meat Scotland, 2018a).*

Emissions from cattle enterprises show great variation in terms of the GHG emissions associated with the output, or production, of these enterprises. The type, source and extent of the GHG emissions produced from the cattle production systems common in Scotland were reported for the years 2015, 2016 and 2017. Cattle finishing systems are ranked by gross margin per animal sold, with results highlighting the wide diversity of emissions within and between enterprise types, as well as the correlation between emissions and financial performance. They also demonstrate the opportunities that exist to regulate GHG while maintaining or improving financial sustainability (Quality Meat Scotland, 2018b).

Table 2. 2 *Cattle finishing systems ranked by gross margin (£) per animal sold (2015-2016)**

	Bottom Third		Average		Top Third	
	Kg output per cow	CO_2-eq / kg output	Kg output per cow	CO_2-eq / kg output	Kg output per cow	CO_2-eq / kg output
Cereal-based finishing						
2015	290	12.6	313	11.4	333	10.8
2016	283	14.3	315	12.7	345	10.1
2017	292	20.3	334	15.8	367	10.4
Forage-based finishing under 22 months						
2015	276	14.1	295	12.9	309	12.3
2016	290	15.5	304	13.6	365	11.1
2017	285	14.3	272	14.3	304	14.0
Forage-based finishing over 22 months						
2015	255	14.6	289	13.0	309	11.4
2016	230	14.3	264	13.8	316	11.9
2017	252	13.9	270	13.2	363	10.1

*Adopted from (Quality Meat Scotland, 2018b).

2.6.3 The United Kingdom leaving the European Union

In a referendum held in 2016, the majority of the UK electorate voted to leave the European Union. This led to formally triggering Article 50 and thus began the two-year countdown to the UK formally leaving the EU, commonly known as the "Brexit" (Walker, 2018). The substantial reliance of the Scottish agricultural sector on subsidies brings forward the issue of the approaching departure of the UK from the EU and hence, the multidimensional policy changes that will follow. In the light of these recent developments, the future direction of agricultural policies in Scotland stands in question (AHDB, 2016b).

The impending departure of the UK from the EU means that Common Agricultural Policy (CAP) will not be further implemented in the UK and Scotland as well. The post-Brexit agriculture policy that UK is going to adopt will have to address the absence of subsidies and determine how farmers will be supported. The new Agricultural Bill that will replace CAP will likely be constrained by the World Trade Organization (WTO) rules on agricultural subsidies, but this is still on a theoretical level (Potton and Webb, 2017). Previous reforms of the CAP on several occasions had brought changes in beef production systems. Thus, a transformation of a larger magnitude will likely have more multifarious impacts on the sector's ability to be profitable (Thomson et al., 2011)

Furthermore, trade arrangements that were in place through the Single market will certainly shift, as well as external tariffs and provision of labour for Scottish farms. The prospects remain unclear as to the post-Brexit trading agreements that UK will pursue with the EU and the rest of the world. It is possible that the UK could pursue a Free Trade Agreement (FTA) with the EU, or there may be a provisional deals allowing free trade to continue, or it is even possible for the UK to revert to trading with the EU on the same basis as other WTO members, with UK exports subject to EU import tariffs. Moreover, with the UK outside of the EU Customs Union, it would be free to negotiate FTAs with trading partners of its choosing. The position of agricultural goods in these types of negotiations would likely be complex and time-consuming (AHDB, 2016b).

In terms of beef production, although Scotland in more than self-sufficient, the UK as a whole was only 76% self-sufficient in 2016, with exports playing a key role in managing seasonal supply and demand. The UK is considered mainly a net importer of beef products, with its main supplier being the EU, providing approximately 90% of beef imports, with Ireland alone supplying around two-thirds of all the beef imports. In the face of uncertainty regarding the trade agreements and new tariffs to be applied to imports, the beef supply is projected to tighten on the UK market until the production catches up. Another topic to be considered, as far as the imports are concerned, is the competition the local farmers will face from low-cost producing beef exporting countries such as South America, the US and Australia (Agriculture and Horticulture Development Board, 2017). Especially in Scotland, where most of the beef production is focused on the domestic market and beef producing prices are higher than the rest of the UK, the consequences will be far greater (Quality Meat Scotland, 2017b). Another subject that causes further ambiguity in the Scottish beef sector is whether the EU scheme, where certain agricultural products associated with a particular region are given protected status, known as geographical indications (GIs) (e.g. Scotch Beef),will hold the same status after UK leaves EU (Potton and Webb, 2017).

2.7 Identified issues and opportunities for the Scottish beef sector

The post-Brexit landscape of the beef sector in Scotland apart from the issues of the heavy reliance on the grants and schemes provided by CAP that needs to be addressed could hold opportunities as well for reshaping the region's agricultural sector and putting forward novel policies, based on its unique assets and global market advantages. Scottish beef exports are high-value products and could look for opportunities for growth outside the domestic and the EU market. Scotland is far from a powerful exporter, as the current non-EU markets are estimated to have accounted for just over 5% of total export revenues in 2016 (Quality Meat Scotland, 2017a). However, the forage-based nature of Scottish beef production systems indicates that there might be good prospects in niche lucrative premium markets for grass-fed organic beef.

The Organisation for Economic Co-operation and Development (OECD) in association with the United Nations Food and Agriculture Organization (FAO) produced a forecast for the next years, where beef consumption is set to increase by almost 6% in developed countries and by approximately 17% the next ten years (OECD/FAO, 2017). Among the main drivers influencing world consumer demand are population growth, income per capita and income distribution. The world population is growing faster, because of a larger population base with the projection of a population increase by 2.5 billion people, with 90% of this growth in the developing countries. Distribution of income is vital as well, with the latest reports indicating a trend of an emergent global middle class, where consumers have more disposable income to purchase consumer goods, and are open to a western type of diet with higher levels of protein intake, promoting the meat sector (Agriculture and Horticulture Development Board, 2017). More specifically, high population numbers in Asia, along with the positive view of Chinese buyers' that bovine meat is healthier and disease-free will result in an expected 44% increase in beef consumed in Asia over the next decade (OECD/FAO, 2017).

This demand for western goods, along with the ability to purchase high-value products, determines high-end opportunities in Asian markets like Hong Kong, China, Japan and South Korea for the UK and Scotland. Besides, the freedom to negotiate new agreements should present more opportunities for exporting markets for beef offal shipments to markets like in West Africa and emerging Asian economies such as the Philippines (Agriculture and Horticulture Development Board, 2017).

Nevertheless, for the Scottish beef sector to deal with low profitability and fully capitalize on the aforementioned opportunities, the challenge is to make optimum use of resources and discover unlock the best combination of alternative management practices to improve its efficiency, productivity and profitability. Scottish forage-based beef production systems, could remain sustainable in environmental terms, but economic sustainability is still out of reach for most farms. By further enhancing the efficiency, the beef industry has the opportunity to boost both business profitability and environmental sustainability, despite the volatile business environment and uncertain future trends (Scottish Government, 2014). There is a need to investigate how adaptations, which are largely inside farmers' control, could counteract the effects of uncertainty amid the recent critical political and economic developments.

2.8 Conclusion

Chapter 2 provided a comprehensive analysis of the beef sector in Scotland while focusing more on the physical and technical aspects for the fattening stage of the cattle production cycle. Also, the economics of beef production systems at the enterprise level were presented for the most common beef finishing systems practiced in Scotland and the UK in terms of physical performance and profitability.

The issues of the beef production sector in Scotland that were identified in the course of this analysis and will later be the focus of the thesis were:

1. The low profitability, evident over the whole beef production sector in Scotland that leads is in most cases to negative net margins for the producers.
2. The declining animal numbers over the last years and the downward trend in terms of beef production's output.
3. The excessive fluctuation of the agricultural input prices over the last years.
4. The high reliance of the whole sector on financial support provided by the European Union in the form of various grants and subsidies (e.g. Basic Payment Scheme, Greening, etc.).
5. The high levels of uncertainty regarding the stability of the sector because the United Kingdom leaving the European Union, which is expected to introduce changes in the agriculture policy in Scotland with unpredictable impacts for the farmers, the market and the consumers.
6. The need to further reduce the beef sectors Greenhouse gases emission and decrease the carbon footprint of the enterprises while maintaining high levels of profitability.

Furthermore, the analysis in Chapter 2 aimed to recognise economic trends driving the industry and identifying issues that could potentially be addressed using modelling tools that will be described in the following Chapter 3. Consequently, in Chapter 3, a detailed exploration of the available modelling tools will be presented, along with a review of the suitability and 'fit-for-purpose' for addressing the industry problems identified.

Chapter 3: Review of literature on models of agricultural and livestock systems

3.1 Introduction

Agricultural systems science is an interdisciplinary field that studies the behaviour of complex agricultural systems by focusing on understanding the structure, as well as the apparent relationships that govern a system (Swinton and Black, 2000). Agricultural systems research can generate knowledge that allows researchers to solve multifaceted problems or make informed agricultural decisions, by employing mathematical models to formulate and perform system analysis (Jones et al., 2017). Because of the large number of potential finishing ages, environmental conditions, input and output prices, there are many complex interactions within the beef finishing systems. Hence, mathematical modelling is often employed to understand the interactions within these systems.

This review outlines agricultural systems and mathematical modelling. Subsequently, a distinction between the two main methodologies of agricultural modelling is presented followed by several examples from the literature. The scope of this literature review is publications concerning livestock farming systems, with most examples coming from the beef industry. Finally, the farm models developed by Teagasc and the relevant papers available in the literature will be presented in detail. As these models provided the basis for designing the model that was applied to study Scottish beef finishing systems, they will be discussed separately from the rest of the models presented in this literature review.

3.2 Agricultural systems and Mathematical modelling

Agricultural Systems analysis is a discipline that advances knowledge of the way different components of a farm interact with each other and how these fit and interrelate with the wider financial, political, and environmental context. Systems research delivers a platform where experimental data from several studies and disciples can be integrated to generate scientific recommendations regarding the profitability of alternative management options (Davis et al., 1994).

Agricultural systems can refer to different scales, from micro-nutrient level to single plants or animals, whole-farms, and on to larger scales like environmental zones. Another element that differs in systems research is time; as systems can be viewed either as static, meaning that time does not affect the system, or as dynamic, where the evolution of a system over a period of time is studied (Swinton and Black, 2000). Systems are also classified as open, responding to external stimuli, or closed, when systems do not have any interaction with the external environment (Sanders and Cartwright, 1979).

A mathematical model is a quantitative illustration of a system designed by applying the formal logic of mathematics to a conceptual model; essentially this corresponds to a set of equations that represent how a system behaves (Thornley et al., 2007). The mathematical expression of a model provides a natural framework for organising information in a meaningful way (Thornley et al., 2007). A chief notion in modelling agricultural systems is that a system’s components interact with each other over-time and that such interaction is the main determinant of system behaviour (Cacho, 1997).

The origins of mathematical modelling in agriculture can be traced in early attempts to model the economics of agricultural production and spatial dimension. The mathematical format (i.e. process or activity analysis) is particularly suitable for implementation in agriculture (Preckel et al., 1987). Essentially because the consensus between farmers, agronomists and other agriculture specialists involved thinking of inputs and outputs in terms of an annual crop cycle and of relevant coefficients were already measured per acre or hectare or other unit of land (e.g. yields are conceived of in tons per land unit, fertiliser applications in kilograms per hectare etc.). That particular way of quantifying and visualising agriculture production lead to translating inputs and outputs to column vectors, which is the pillar of a programming model. Additionally, perceiving problems in terms of inequality constraints, such as upper bounds on seasonal resource availability, is the type of thinking suitable for analysis via programming models (Preckel et al., 1987). Hence, mathematical modelling is suitable for applying knowledge and indispensable for science and societies, especially agriculture (Dumas et al., 2008). Another advantage is that farm-level modelling can facilitate simultaneous processing of production, price and policy information (van Calker et al., 2004).

3.3 Types of models

Models can be employed in research and management of production systems for a great range of purposes. Models can be used among other for (1) identifying gaps in research, (2) integrating prevailing data and concepts, (3) understanding and assessing experimental results, (4) generating and testing hypotheses, (5) screening of potential experiments, (6) designing efficient production systems, (7) determining optimal operating conditions for a production system , or (8) evaluating current and future policy (Bywater and Cacho, 1994).

Models can be classified according to multiple criteria, depending on the phenomenon or system they describe and the mode in which they are defined, implemented and used. Mainly, models can be categorised depending the level of complexity (simplistic and holistic), the way model equations are derived (mechanistic and empirical), in relation to the way time is treated (static and dynamic), whether random events are included (deterministic and stochastic), and whether optimum behaviour is assumed (simulation and optimisation) (Cacho, 1997). Holistic models often attempt to describe a system in detail as opposed to a limited number of assumptions used in simplistic models. Empirical models are based on observed relationships aiming to "predict", while mechanistic models embrace an element of understanding of the system and aim to "describe" (Thornley et al., 2007). Static models do not contain time as a variable and usually describe equilibrium conditions, whereas dynamic models include the factor of time, using differential equation or set of differential equations to illustrate changes in the system over a period of time (Jalvingh, 1992). Deterministic models predict a definitive outcome, while stochastic models encompass random elements or probability distributions, reflecting the uncertainty in the real world. Finally, models can be categorised according to whether they simply indicate/simulate possible outcomes that will result from alternative decisions (simulation), or provide information that leads to an optimisation of a particular criterion (optimisation) (Cacho, 1997).

Methodologically, in this review, the models included were divided initially into optimisation and simulation models (Figure 3.1). Simulation models are mainly developed to improve the current level of knowledge of systems by analysing their behaviour under various varying conditions. To perform this task, the models usually calculate the expected utility under a given set of parameters and decision rules. Frequently, this type of modelling is employed to determine strategies that aim to use the best set of decision rules in the current knowledge of the parameters. On the other hand, optimisation models include the design and use of an objective function of expected utility or a function of profit that is maximised according to production alternatives (i.e. prices and resources availability), to determine the optimal solutions (Plà, 2007; Stygar and Makulska, 2010).

Furthermore, two additional classes, namely deterministic and stochastic, can be outlined within optimisation and simulation models. In terms of assumptions, deterministic models operate under the basis that there the real system has no random variation while in stochastic models the variation of variables and parameters is represented through appropriate probability distributions (Stygar and Makulska, 2010). After a certain level of confidence is achieved regarding the performance and outputs of a deterministic model, commonly the next step would be inserting a stochastic element. Typical methods employed to introduce stochastic behaviour into models include allowing either input prices in economic models or environmental conditions to vary randomly according to specified probability distributions. Another technique of including stochastic behaviour in growth models is by considering a probability distribution to the growth potential of the plant or animal population (Scott and Cacho, 2000).

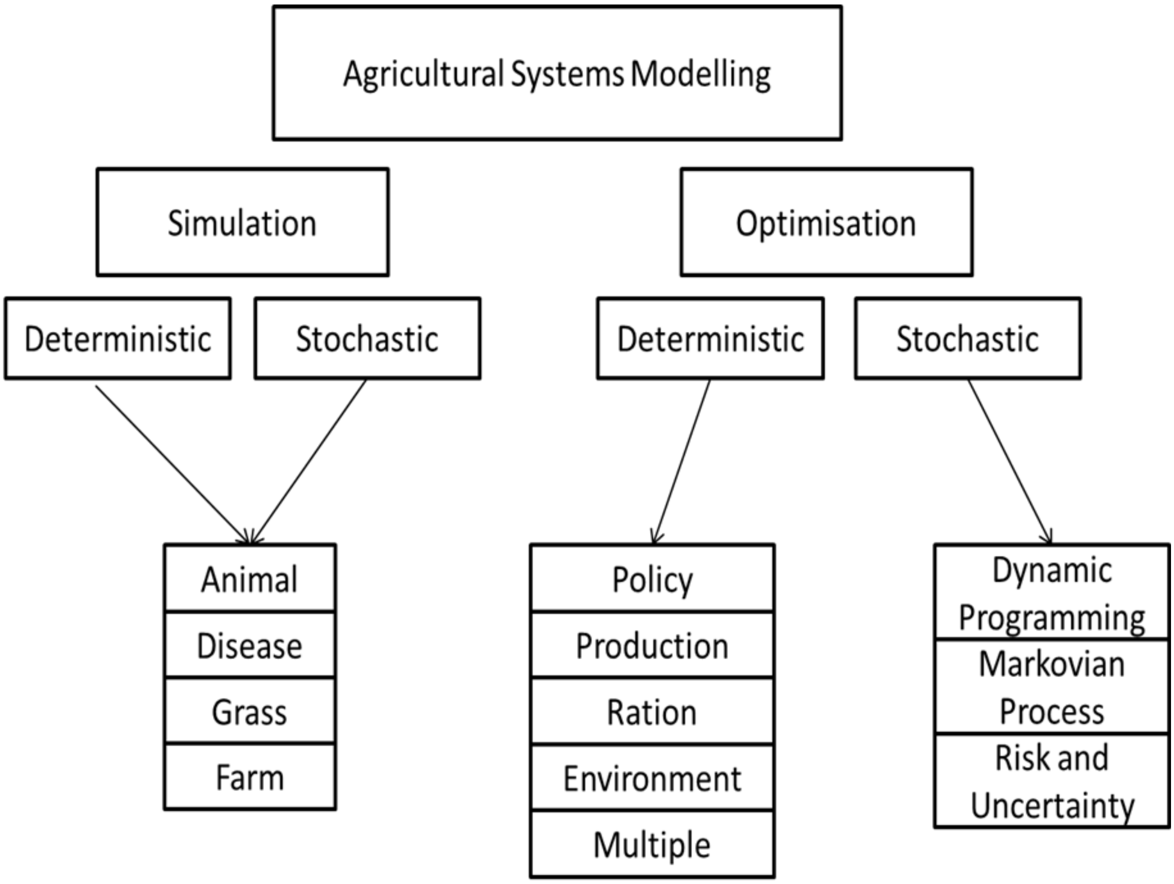

Figure 3. 1 *Illustration of the different categories of agriculture systems models included in this review.*

3.4 Simulation modelling

Simulation modelling can describe the state of a system at any given time, providing valuable graphical and predictive tools for scientists, farm managers and policy makers (Swinton and Black, 2000). Given the fact that there usually no universal optimum solutions to a problem due to the fact that the efficacy of a solution depends on the restraints and the subjective judgement of the farmer, this particular type of models can be employed to support a “trial and error” learning process by swiftly and cost-effectively exploring alternative management strategies (Cros et al., 2004). Simulation models make this type of virtual experimentation under repeatable conditions possible in cases that the sample size that would be required for physical experiments to consider variability and explore the efficiency of strategies would be immense (Cros et al., 2004). Moreover, agricultural and beef production systems are generally considered to be highly complex, so addressing these problems with optimisation models seeking a single and narrow solution would not be effective since these models are based on a series of assumptions difficult to closely meet in practice (Cros et al., 2004; Joandet and Cartwright, 1975).

Simulation modelling has a number of advantages; for example allowing the estimation of the performance of an existing system under a predictable set of operating conditions, proposing novel systems that best meet a required outcome, achieving control over experimental conditions that would not be attainable in the real world, and studying a system with a long time frame in compressed time (Dent et al., 1979; Law and Kelton, 1991). Furthermore, simulation is often the only type of investigation available as various stochastic real-world elements would be impossible to evaluate analytically by a mathematical model, while the process of designing a model sanctions critical and objective review of knowledge concerning the system (Dent et al., 1979; Law and Kelton, 1991). Among the disadvantages of simulation models stated by Dent and Blackie, (1979) and Law and Kelton (1991) are the time-consuming development process, the risk of misguided assumptions affecting the model's accuracy, and the complication of the validating process, as it would never be possible to prove a simulation model completely precise and accurate.

3.4.1 Simulation deterministic models

3.4.1.1 Animal production models

Simulation models are capable of dealing with the variability and complexity found in animal production. Simulations are often simplified by ignoring variability beyond that generated by the models' deterministic equations, simulating lower levels of variability typically found in the real-world (Shafer et al., 2007). However, numerous examples of studies employing simulation deterministic models can be found in the literature (Stygar and Makulska, 2010).

Simulation deterministic models could be focused on the animal level attempting to simulate animal growth, predicting animal responses to feeding practices and evaluating economic impacts of management decisions (Tobias et al., 2006). These models aim to accurately predict the energy content of growth and are important in formulating diets to meet requirements and predicting the rate of gain, costs and time required to meet specific target weight and body composition (Tedeschi et al., 2004).

One of these models named CompoCow was developed by Garcia and Agabriel, (2008) to predict energy requirements for growth and finishing for cull cows of Charolais, Limousin and Holstein breeds, by summing up the energy requirements for maintenance and liveweight gain. The model considered the effects of age, liveweight, body condition and level of growth on the composition of gain while excluding variations in energy intake, utilisation for maintenance or energy retained in gain efficiency. Following, A deterministic model that could predict the performance of growing steers grazing tropical pastures was developed by combining the effects of protein and energy intake from forages and supplements (Tobias et al., 2006). This model generally underestimated gain, but it was concluded that there was room for upgrading by improving intake prediction when grazing and energy and protein elements of the feedstuff.

Another model consisting of daily intake and performance module was developed to predict the dynamics of intake and performance of suckler cows with calves (Jouven et al., 2008). A dynamic computer model was adapted by Oltjen et al., (1986) to simulate the empty body weight and chemical composition of growing steers, while growth could be adjusted according to the effects of body composition and nutrition. ECOWEIGHT is a bio-economic deterministic model simulating life-cycle production of both beef and dairy cow herds was built, to assess utilisation of bulls in various production systems in the Czech Republic (Wolfová et al., 2005a, 2005b). Herd dynamics were defined in terms of animals' different states and possible transitions among specific states at various stages. The algorithms developed served as a foundation to develop the computer model ECOWEIGHT, which could estimate economic values for sixteen different traits under four different beef bull management systems. The same model was applied to calculate economic values of traits for Slovakian cattle under different marketing strategies (Krupa et al., 2005), and economic weights of production along with functional traits in Slovak dairy production system under a direct subsidy regime (Krupová et al., 2009).

An alternative methodology was adopted by Vetharaniam et al., (2001), where simulation of animal growth was based on anabolism and catabolism rather than a growth curve and maintenance requirements. Animal's energy demand was formulated by its state, age and genetics, while actual intake, subject to energy demand and supply, determined the final performance. The model could be employed to investigate the effects of management and breeding decisions and was validated by data on sheep. Next, INRAtion uses a database comprised of available forages and concentrates for feeding animals, to calculate diets for suckler cows, dairy cows, growing animals and sheep on either an individual or group basis over a period of time (Sauvant et al., 2018). The model could account for animals fed to achieve a specific level of production or a required energy level while calculating nitrogen excretion as well for all systems.

In addition, the Cornell Value Discovery System was developed to predict feed requirements, carcass composition, performance and costs of individual animals fed in groups (Tedeschi et al., 2004). The model simulates daily feed intake and daily gain to calculate the weight and feed required. Profit was determined by collecting weight, composition and market prices along with the break-even price for each animal. Animals of different size and breed were compared in terms of feed efficiency and cost of production. A deterministic computer model for simulating cow-calf-feedlot production systems involving five cattle breeds in the USA was developed by Lamb et al., (1993). The goal was to assess mating systems in terms of biological and economic efficiency, by taking into account variability in carcass weights and genetic trends.

Simulation modelling methods were also applied to develop models that examine animal growth and metabolism. Examples include two models developed to predict the composition of empty body gain of several breeds of beef cattle, while testing alternative nutritional levels, or at different maturity stages (Keele et al., 1992; Williams and Jenkins, 1998). Williams and Jenkins, (2003) designed a simulation model that partitioned energy for maintenance and support metabolism to predict the resulting heat production in growing and mature purebred and crossbred cattle.

Furthermore, a model was developed to simulate the influence of a range of feeding regimes on beef cattle growth and carcass composition of several different cattle breeds by Kilpatrick and Steen, (1999). The model provided information on the most cost-effective level of concentrate feeding, if relevant costs were provided, to achieve the animal growth and quality of carcass composition required. An extensive dataset of experiments conducted by the Department of Agriculture for Northern Ireland was mobilised to support the model, which resulted in a farm-level decision support system that could accurately describe performance variables across a wide range of feeding and animal-type options.

The model of Hoch and Agabriel (2004a, 2004b) was developed based on the variation of body protein and lipid contents, in which beef cattle growth and body composition were simulated for different animal types (sex, breed) under various nutritional conditions. In the model, proteins and lipids were distinguished for carcass and non-carcass tissues to capture different energy metabolism of these two body components. Rather than a model based on maintenance requirements, this model was based on anabolism and catabolism to increase accuracy when accounting for the restricted feeding patterns and compensatory growth that occurs in the systems being modelled.

3.4.1.2 **Disease modelling**

Several deterministic simulation models attempted to study the effects on diseases on agricultural management systems (Bush et al., 2008; Mateus-Pinilla et al., 2002; Sabatier et al., 2004; van Schaik et al., 2001). The model developed by Bush et al., (2008) estimates the potential cost of a Johne's disease outbreak in the region of New South Wales versus the benefits of vaccinating sheep flocks, though Mateus-Pinilla et al., (2002) built a deterministic dynamic computer simulation that assumed conditions of closed and equilibrium population size that investigated the transmission of Toxoplasma gondii in swine farms and evaluated the use of a feline vaccine. Sabatier et al., (2004) developed a herd-level model describing the disease pathway transmission of scrapie in a sheep flock, while an economic model exploring the impacts of a more-closed farming system as a measure of eradicating and controlling diseases in dairy farms was introduced by van Schaik et al., (2001).

3.4.1.3 **Grass management models**

Models for predicting grass growth and utilisation of grass are valuable tools for the management of grassland production, and an important element of agricultural farm systems (Trnka et al., 2006). A mathematical model simulated the potential impact of global warming on milk and forage production in Scotland by calculating growth on a daily basis taking into account herbage mass, temperature, radiation, carbon dioxide concentration, water and nutrients; concluded that global warming would not have an effect on the length of the grazing season (Topp and Doyle, 1996a, 1996b). GRASIM is a pasture simulation model replicating intensive rotational grazing systems to assess the impacts of financial and environmental scenarios for alternative dairy systems. The aim was to define efficient utilisation of pasture on a daily time step, while other outputs included biomass production, water and nitrogen levels (Mohtar et al., 2000, 1997).

Another model reproducing production, structure and digestibility of permanent pastures was designed to be simple, by using a practical approach as opposed to a species-based approach to simulate the growth of different species found in permanent pastures (Jouven et al., 2006). Moreover, due to the model's structure, the outputs could be used as inputs for an intake and production model of ruminant livestock (Jouven et al., 2008). A different model replicating rotational grazing conditions for cattle was presented by Brereton et al., (2005), and was also used in the simulation model Dairy-sim (Fitzgerald et al., 2005). This model approached grazing as a series of random encounters with clusters of connecting bites at feeding stations instead of random encounters with individual bites. The selection was forced by avoiding the lower nutritive diet, while both horizontal and vertical heterogeneity was taken into account as the sward was modelled to be three dimensional (Brereton et al., 2005; Fitzgerald et al., 2005).

GrazePro was able to predict pasture production and quality in perennial ryegrass swards and was developed to improve the sustainability of milk production systems in Europe through increasing dependence on grazed pasture (Barrett et al., 2005). A comparatively simple structure was adopted, as this model designed to be a farmer support tool rather than process understanding, supporting simulations of 'what if' scenarios to decrease the uncertainty present on dairy grass-based systems. Milk production systems for grazing dairy cows was also the focus of a model predicting herbage intake, which based its calculations on the French Fill Unit system predicting intake capacity and fill value of the feeds (Faverdin et al., 2011). The model's validation process revealed that it could predict intake over a range of herd management and feeding scenarios to a satisfactory level. It was proven to be sensitive to feeding management during the lactation period, and it was further developed to considering sward characteristics and grazing management before it was adapted for Irish conditions (O'Neill et al., 2013).

While Beukes et al., (2002) designed an ecological economic simulation model for grazing systems in the Nama Karoo region of South Africa, characterised by low and variable annual rainfall, which results in grass and shrub biomass production to be low and highly variable in space and time. The model comprises of vegetation, production and financial sub-models while simulating 'what if' scenarios involving different stocking rates and numbers of environmental buffers of forage reserves by restricting access of livestock within numerous small sites.

A decisions support tool (GrazPlan) was used to translate scientific research into direct suggestions for farmers in Australian grazing enterprises (Donnelly et al., 1997). GrazPlan consisted of four sub-models (i.e MetAccess, LambAlive, Grazfeed and GrassGro), which were used to gather and analyse weather data, make decisions on the time to mate the ewes or to provide them shelter, determine level of supplementation, and analyse grazing systems in terms of pasture growth and herbage intake (Freer et al., 1997; Moore et al., 1997). It was a model more suited for describing specific situations that covering a range of scenarios, as it required specifications in great detail. Nevertheless, it was widely adopted by farmers and consultants to improve the profitability and environmental sustainability of grazing enterprises (Donnelly et al., 2002).

Another model exploring the impacts of weather, stocking rate and grazing management on livestock and pasture growth for a 15-month bull beef production system was designed by (Doyle et al., 1989). The aim was to address issues like optimal stocking rates, the impact of feeding silage during shortages in pasture herbage and the best system of grazing management. Subsequently, a simple simulation model was designed to depict the dynamics of forage growth and standing crop and cattle production, and to estimate the ecological sustainability of management alternatives for extensive cow-calf production systems in north-eastern Mexico and south Texas (Diaz-Solis et al., 2003).

Coléno and Duru, (1999) designed a model replicating a dairy forage system that allows dairy spring grazing, by combining a grass growth model that accounts for weather and nitrogen supply with a decision model responsible for production planning and monitoring. The same model was later employed to evaluate nine feeding management strategies with spring rotational grazing over a sequence of sixteen climatic years (Coleno et al., 2002). The model introduced by Andrieu et al., (2007) simulated forage management strategies considering farm-level land diversity. The model used an example of dairy farms, to study the impact of different scenarios to yield, considering both management (fertilisation, grazing, and cutting) and environmental factors (altitude, aspect, soil water capacity) of land diversity for management decisions.

A dairy farm model (SEPATOU) was developed to simulate interactions between management factors (e.g. turnout date, length of the feeding period, etc.) and production performance (e.g. milk yield) for managing grassland in France (Cros et al., 2003, 2004). The model captured the activities of a dairy farm daily, which allowed the evaluation of management decisions. Another model that employed a daily time step was the Sustainable Grazing Systems Pasture Model, which simulates sheep production, with the possibility to be adopted for beef production, and was designed to be used by researchers to explore the behaviour of the system (Johnson et al., 2003). The biophysical model consists of water dynamics, herbage accumulation and utilisation, nutrient dynamics and animal intake and performance, which are interconnected sub-models, operating in generic pasture systems for a range of soil types under specific grazing management.

3.4.1.4 **Whole-farm models**

The synthesis of scientific knowledge from many different areas of research like animal performance, grass growth, utilisation and management is integrated under whole-farm system models to assist decision-making process (Tess and Kolstad, 2000). One of the earliest attempts includes a deterministic model for simulating growth rate and milk yield of beef cattle production under a wide range of environments, genotypes and management styles (Sanders and Cartwright, 1979). The model employed equations that were explicable, was shown to represent systems accurately and was then employed in several situations around the globe (e.g. Colombia, Botswana and Venezuela).

A deterministic bio-economic model was developed to identify the economically optimum replacement strategy in beef enterprises, by evaluating the impacts of changes in breeds and mating systems based on UK economic data (Roughsedge et al., 2003). The model predicts physical and financial performance over a planning horizon of 20 years and could be used to simulate the transition between different breeding strategies.

Another whole-farm simulation model was developed for the Salado region of Argentina, to study a pastoral cow-calf production system representing interactions between herd organisation, climatic variations and farm management over several decades (Romera et al., 2004). The concept of 'paddock bank' was introduced to allow flexible handling where blocks of paddocks where arranged in a way, so if a block had more pasture than the animals needed it could loan the paddocks to the bank for other groups of animals to use. The same model was later used to model spring and autumn calving systems in beef herds of the Salado region of Argentina (Romera et al., 2008). Spring calving was more profitable than autumn calving, especially at higher stocking rates. However, the model estimated that the combination of spring and autumn calving leads to more flexible cash flow throughout the year.

Three cow-calf production systems in Brazil were compared to determine the most profitable system, using a deterministic simulation model that runs for ten years and calculates net present value cash flow (Guimarães et al., 2006). One whole-farm simulation model that incorporates a beef herd sub-model with other farm components such as crop growth, harvest, storage, feeding, grazing and manure handling is the Integrated Farm System Model (IFSM) developed by Rotz et al., (2005). Both biological and physical aspects of farming systems are considered, offering a powerful tool to evaluate and compare performance, economics and environmental impacts of beef. A similar approach is used to study an integrated beef cow-calf system and sugarcane production in Tanegashima Island of Japan (Gradiz et al., 2007). The simulation exercise is based on the total requirement for energy and protein, and subsequent losses of nitrogen, throughout the reproduction cycle of a mature cow and the growing stages of her calf. When modelling economic values for genetic enhancement of multiple traits, a complete beef production system representation is necessary to capture market signals that flow down in the supply chain to those making the breeding decisions (Koots and Gibson, 1998).

Another model that described the situation of complete beef production is the Alberta Beef Production Simulation System (ABPSS), a model used to estimate the effects of management strategies and production traits on the bio-economic efficiency of beef production systems (Pang et al., 1999a, 1999b). The model consists of four sub-models, namely the herd inventory, nutrient requirements, forage production and economics. The herd inventory evaluates population dynamics in the herd, while the feed requirements for calves and cows depending on their physiological status and climate conditions are simulated by the nutrient requirements sub-model. The forage production module predicts forage growth rate, cattle grazing rate, available forage biomass, and total hectares required for grazing, while the economic sub-model measures net return per animal as an indicator of bio-economic efficiency.

The whole-farm simulation model SIEBEN adopts a bio-technical approach to investigate the seemingly conflicting objectives of system production and biodiversity conservation in grassland-based beef suckler systems (Jouven and Baumont, 2008). The decision rules applied in this model were identified with the help of surveys, research experts and extension services (Jouven et al., 2008). Another model was developed to evaluate the effect of management approaches on the nutrient balance, using dairy farms for illustration (Buysse et al., 2005). Three farm systems were simulated (zero-grazing, winter milk and summer milk), and the results supported the positive effects of maize feeding in addition to grazing.

Similarly, MELODIE is a whole-farm model concerned with the study of the dynamics of nutrients in dairy and pig farms with crops (Chardon et al., 2012, 2007). The model intended to be used in research, dynamically simulates the flows of carbon, nitrogen, phosphorus, potassium, copper, zinc and water within the whole-farm and over the long-term, aiming to evaluate the environmental impact of production strategies in integrated dairy, swine and crop farms. Likewise, FARMFLOW was applied to compare simulated organic and conventional management of a Swedish experimental dairy farm and was proven to be a useful tool for analysing the impact of management phosphorus (P) dynamic mass flow on farm (Modin-Edman et al., 2007).

A model applying mathematical equations to analyse the nutrient management in Dutch dairy farms demonstrated that farm systems can be re-designed in a way that adjustments in the internal nutrient cycle could support the same production with lower inputs and lower emissions (Groot et al., 2003). Another model focused on environmental impacts is REPRO (REPROduction of soil fertility) designed for investigating interlinked changes in the cycles of carbon (C) and nitrogen (N), and estimating the greenhouse gas emissions from organic and conventional farming systems (Küstermann et al., 2008). A dynamic model for modelling resources management for agricultural systems and farms in the Central Highlands of Nicaragua was developed by Pfister et al., (2005). This model was designed to increase the understanding of how systems in developing countries operate, taking into consideration factors often underestimated in models depicting developed countries, like the farmer's household.

Matthews et al., (2006) developed a model to analyse policy impacts of Common Agricultural Policy (CAP) reform for upland agriculture in Wales using different scenarios by implementing a livestock system model, simulating three enterprises, upland sheep rearing with lamb finishing, spring- and autumn-calving suckler-cattle with calf rearing. The Sustainable and Integrated Management Systems for Dairy Production (SIMSDAIRY) is a modelling framework which depicts a dairy farm and compares the scope for improving its sustainability by future system alterations aimed at improving genetic characteristics of plants and animals with current system structural modifications aimed at improving nutrient management efficiency (Del Prado and Scholefield, 2008).

MAGMA is a model simulating the management of various kinds of animal manure or slurry production and utilisation modes (waste spreading on cultivated crops and fallow land and compost making), to study several scenarios based on animal and crop production characteristics, capacity of manure or slurry spreading equipment, and distances (Guerrin, 2001). Hervé et al., (2002) developed a model able to represent the farming activities of labour allocation, cattle feeding systems and farm crop production, using an object-oriented modelling approach. The aim was to build a tool able to simulate the effects of changes in productive and social organisation in traditional Andean rural communities.

Another simple dynamic model was developed to simulate pasture-based grazing steer fattening enterprises in New South Wales, Australia. Livestock growth is based on pasture consumption, while pasture growth and ageing for the two pasture species with competition between the species for soil nutrients and the light was considered in the model as well (Kaine and Tozer, 2005). Subsequently, a simple dynamic farm model was developed and used to analyse the net worth of a family farm grazing enterprise producing wool on the New South Wales of Australia. The relationship between family costs and expenditure on fertiliser is explored under alternative assumptions regarding family expenses and investments in fertiliser, providing feedback on farm net worth and viability (Scott and Cacho, 2000). Another beef systems model capable of simulating livestock production for north Australian enterprises, based on energy and protein supply from natural C4 pastures was developed to assess production and financial implications of a range of technology interventions, including genetic gain in cattle, nutrient supplementation, and alteration of the feed base through introduced pastures and forage crop (Ash et al., 2015).

A whole-farm computer model which simulates farmer's action based on studies of decision-making processes aimed at identifying farmers' needs and predicting farmers' reactions to technical innovations, was designed by (Vayssières et al., 2007). The decisional component of a whole-farm model was built according to a multi-step, multi-tool methodology involving engagement, visits and meetings with farmers, while the biotechnical element was mainly built based on already existing models and some new implementations by researchers. Hierarchy growth factors and other concepts from production ecology that were initially developed or plant production, were applied to livestock production to analyse two livestock production systems, one in intensive dairy farming in a temperate climate and the other system simulated the limited feed availability typical for cattle production in the tropics (van de Ven et al., 2003).

Correspondingly, Ezanno, (2005) employed a deterministic matrix model to simulate the dynamics of a tropical cattle herd while identifying periods and animals to target with specific management efforts to increase productivity. In matrix models, discrete classes are used to represent the life cycle and/or the reproductive cycle of the animals and can prove a useful tool for simulating possible effects and management interventions.

3.4.2 Simulation stochastic models

3.4.2.1 Animal production models

Since animal production models include parameters associated with animal utilisation, which encompasses a random element, employing a more appropriate stochastic approach for modelling could simulate more realistic levels of variability (Stygar and Makulska, 2010). Applying Dynamic programming and Markov process in stochastic simulation models is very common, as it allows comparison of the impacts of different policies while taking into account the probabilistic nature of these systems (Plà, 2007).

A model to represent the productive and reproductive lifecycle of sows was developed by Plà et al., (2003). The model, initially intended for farmers, employs a Markov decision process to simulate the herd structure and was validated by comparing observed and simulated outputs from specific farm data (Plà et al., 2003). Another stochastic dynamic model was developed to describe reproductive processes in beef cattle (Azzam et al., 1990). The model was employed to simulate various management systems that varied in level of reproductive efficiency. Results recommended that increased length of the breeding season and breeding heifers ahead of cows lead to a higher proportion of females in the breeding herd becoming pregnant. Also, the average age of calves at weaning increased with increasing first-service conception rate and decreased the length of the breeding season.

A model for determining the effect of silage energy concentration and price on finishing decisions for Norwegian Red young dairy bulls was developed by Bonesmo and Randby, (2010). The model was based on previous work of (Bonesmo et al., 2010) and was used to explore the concentrate levels, slaughter ages and carcass weights that maximised daily return, which was calculated as the sale price minus feed costs and animal purchase price. This study concluded that the highest profit derived from finishing young dairy bulls on silage with an energy concentration of 0.90 feed unit beef kg^{-1} DM and a live weight gain of 1.2 to 1.3 kg day^{-1}, while it was noted that the model overestimated the live weight of bulls consuming very high energy diets and underestimated the live weight of the bulls consuming low energy diets (Bonesmo and Randby, 2010).

A different simulation model that incorporated stochastic elements was the Colorado beef cattle production model, which was used to determine whether in beef cattle production systems the level of simulated variability affects the simulation results (Shafer et al., 2007, 2005). The model can produce and examine the effects of additional variability in several animal traits, beyond the ones created by deterministic equations that describe known biological relationships and direct input. The study concluded that by failing to simulate realistic levels of variability, models based on nonlinear functions may yield misleading outcomes (Shafer et al., 2007).

3.4.2.2 **Disease modelling**

A dynamic and stochastic simulation model was developed to examine different strategies for containing paratuberculosis (Johne's disease) in dairy herds, both in terms of epidemiological and economic impacts. The high levels of uncertainty characterising the epidemiology of Johne's disease led the model's input to be based mainly on estimates from literature and expert knowledge, while this study employed herd and prevalence data from Netherlands and Pennsylvania, USA (Groenendaal et al., 2002).

A similar model simulating paratuberculosis in a dairy herd was developed by Kudahl et al., (2007), aiming to become the basis for a decision-support tool, which could predict specific hard and production-related effects from alternative control strategies. Transmission of paratuberculosis in cattle herds was also the subject of the study by Pouillot et al., (2004), where a model was built able to execute a cost/benefit analysis for intra-herd transmission to evaluate the economic consequences of the purchase of a single infected heifer in a French average herd.

Smith et al., (2009) developed a model using Monte Carlo simulation to evaluate the risk of introducing bovine viral diarrhoea virus (BVDV) to cow-calf farms, and the effect of different testing strategies. Another stochastic simulation model was developed to explore the dynamics of the spread of the BVDV within a dairy herd (Viet et al., 2004). This model accounted for herd management factors influencing BVDV spread that were common in several countries, while various spread dynamics were simulated, from early elimination to the virus persisting ten years after its original introduction.

An epidemiological model simulating an outbreak BVDV within a Scottish beef suckler herd was designed to provide an estimation of costs related to the virus occurrence (Gunn et al., 2004). While a model that simulating contagious bovine pleuropneumonia (CBPP) within-herd outbreaks, was used to economically assess local control strategies in a mixed crop-livestock system in Ethiopian highlands (Lesnoff et al., 2004). Further stochastic simulation disease models include studies by Stacey et al., (2007) applying a Monte Carlo model to evaluate the impact of interventions on the risk of cattle and sheep carrying Escherichia coli O157:H7 to the abattoir, and by Lurette et al., (2008) modelling salmonella spread within a pig herd using a stochastic discrete-time model representing both the population dynamics in a pig herd and salmonella infection spread.

3.4.2.3 **Grass management models**

GRAM is a statistical model developed to predict herbage production from meadows and permanent pasture under various different management regimes in Austria, accounting for the considerable year-to-year and seasonal variation in grassland production (Trnka et al., 2006). The model also considered factors like the number of days with snow cover, cut number and nitrogen application rate per cut as independent variables. GRAM showed reasonable accuracy when issuing a probabilistic forecast of the harvestable herbage DM production early in the season, allowing spatial herbage accumulation monitoring and forecasting even in areas or sites where complete data sets are not yet available.

3.4.2.4 **Whole-farm models**

A model containing both deterministic and stochastic elements was designed to assess possible means of interaction between reproductive performance and management practices in a cow-calf enterprise for a yearly production cycle, and analyse their influence on net income in beef production (Werth et al., 1991). Reproduction performance of the cow-herd was simulated by applying a stochastic dynamic model, while outputs from the stochastic model were subsequently used as inputs into the deterministic cow-herd economic simulation model that calculated the net income.

Parsons et al., (2001) studied the potential impact of climate change by the year 2050 in British grazing livestock systems. The effects of climate change were evaluated using a stochastic simulation model. The model consists of grass production, livestock feeding, and livestock thermal balance components, along with a stochastic weather generator. The integrated model that can also facilitate systems for sheep, beef calves and dairy cows, is using the stochastic weather generator to allow infinite sequences of weather data for any scenario.

A dynamic stochastic model simulating mountain cattle beef production systems in the Spanish Pyrenees was used to determine the effect of four feeding regimes over the winter on production from autumn calving suckler cows (Villalba et al., 2006). The study considered available information on animal production and reproduction variability and focused on evaluating the relationship between nutrition and reproductive performance of cows. In addition, Villalba et al., (2010) further developed the model by simulating to consider the results of five different management strategies (i.e. calving and finishing systems) on beef herds in the Spanish Pyrenees. The model was capable of representing variability originating from both management and animal components. In the first case, variability was generated by practices at the batch level implying animals of different physiological status, and variability within animals was introduced because of permanent environmental or genetic differences.

A stochastic model that captured the dynamic relationships present in beef production systems among cattle genotypes, physiological states, forage quality and management was parameterised to represent range environments of Montana, USA (Tess and Kolstad, 2000). Forage intake, energy and protein metabolism, growth, reproduction, lactation and differences in chemical body composition were simulated for individual animals. The model was applied to assess the influence of the production and marketing system to alterations in breeding and management strategies (Tess and Kolstad, 2000). Furthermore, the same dynamic bio-economic model was employed to study the consequences of calving season and marketing strategies on the profitability of farms in the Northern Great Plains, Montana, USA (Reisenauer Leesburg et al., 2007). The model determined that moving from spring to summer or autumn calving would not improve profitability, but in cases where delaying calving to summer implied improved survival rate, then it may improve profitability.

A tool that explores sow herd dynamics in terms of performance and the way it links to work organisation problems was developed by Martel et al., (2008). The study aimed to describe dynamic, stochastic object-oriented herd model that could simulate herd dynamics and performance, and predict the number of events workers will have to address. Østergaard et al., (2000) designed a dynamic, stochastic, and mechanistic Monte Carlo model simulating a dairy herd with emphasis on feeding, health and production interlinkages. The model manages to simulate the technical and economic effects of scenarios on dairy herds, by stating biological parameters at cow level and then a management strategy at the herd level.

Another stochastic simulation model was developed to be employed as a decision support system tool for animal production in irrigated pastures within semi-arid grazing lands (Diaz-Solis et al., 2006). Initially, different spreadsheets were developed in EXCEL to calculate animal production under various stocking rates and pasture characteristics. Successively, functions from the spreadsheet and the literature were incorporated into a dynamic stochastic simulation model programmed in a visual programming language named STELLA (Systems Thinking, Experimental Learning Laboratory with Animation).

While, a stochastic simulation model depicting pasture-based beef production systems in Appalachia, USA was used to assess the viability of these farming systems as alternatives to conventional production (Evans et al., 2007). Marketing paradigms and stochastic budgets representative of several hypothetical producers of each type were constructed and evaluated via Monte

Carlo techniques in terms of relative profitability and risk, with model outcomes supporting the case of pasture-raised production over conventional strategies.

Biophysical as well as econometric-process simulation modelling approaches on agricultural production systems were integrated into a trade-off analysis model, which was applied for the potato–pasture production system in the Ecuadorian Andes (Stoorvogel et al., 2004). This approach allows the analysis of the current status as well as alternative scenarios. A stochastic budgetary simulation model of a dairy farm, the Moorepark Dairy System Model, was developed by Shalloo et al., (2004) to investigate the effects of varying biological, technical, and physical processes farm profitability. The model combines animal inventory, milk supply, feed requirements, land and labour utilisation with the economic analysis. The model's output is presented in the form of an estimated distribution of farm profitability, which is a function of total receipts from milk, calves, and cull cows less all variable and fixed costs. The model was validated and found to accurately depict milk production systems for Ireland.

3.5 Optimisation modelling

Linear programming (LP) is a mathematical programming methodology usually employed to design optimisation deterministic models, in which the objective is to maximise or minimise linear function subject to the restrictions normally referred to as resource constraints (Stygar and Makulska, 2010). LP models seek to optimise some criterion or set of criteria, subject to a set of constraints. The planning aim of the model is the objective function. A linear programming model aims to find the choice set, which minimises or maximises the objective function subject to the available resources. For determining whether LP method is suitable for addressing a particular issue, basic assumptions like additivity and linearity in input and output coefficients, divisibility in resources and products, finiteness of alternative processes and resource restrictions, and single-valued expectations must be fulfilled (Jalvingh et al., 1997).

Agricultural systems modelling was employed in an attempt to optimise decisions at a farm-scale and evaluate the effects of policies on the economic benefits of rural development (Jones et al., 2017). The farm optimisation models that were developed and applied by Heady and students at Iowa State University established the use of linear programming methods for agricultural production. One of the methods regularly used to deal with linear programming problems is the simplex algorithm, which specifies each step to be taken during the solution routine, and is an experimental process for problem-solving. This algorithm is designed so that each trial produces an enhanced answer, making sure that if an optimal value exists, it will be discovered within a finite number of steps (Heady, 1957). Farm managers and animal producers value economic information on the relevant contribution of various resources to the determinative measure of performance. By applying the simplex method, information can be obtained in the form of shadow prices for particular resources become available. The shadow price for a given resource measures the marginal value of this resource, that is, the rate at which profit would be increased with the increase of the amount of this resource (Jalvingh et al., 1997).

On the other hand, Dynamic programming (DP) has become widely accepted as one of the main tools for optimisation of whole-farm problems, which may be characterised as dynamic, stochastic, non-linear or discrete (Stygar and Makulska, 2010). Dynamic programming was the creation of American mathematician, Richard Bellman, who described the way of solving problems where you need to find the best decisions one after another (Nielsen et al., 2004). The principle of dynamic programming allows for determining the optimal investment pattern in multi-period decision problems while having the advantage of defining optimal decisions without requiring an extensive account of all sequences of transition possibilities (Kennedy, 1972; van Asseldonk et al., 1999). Dynamic programming starts at the final stage of the planning horizon and works backwards in time (Howard, 1960). Markov chains are models of computations with probabilities for each transition, in a sense that the probability of the next stage depends on the current stage. These models involve a sequence of decisions over a given planning horizon (finite or infinite) split into stages, where the procedure is observed and a decision regarding the process has to be made at each one. At the beginning of each stage, the state of the system is observed and a decision has to be made. Depending on the state and the decision made, an immediate reward is obtained (Nielsen et al., 2004).

Howard, (1960) combined the dynamic programming with the mathematically well-established notion of a Markov chain, into a novel method characterised by sequential and stochastic approach; the Markov decision process (MDP). Dynamic programming methods are mainly applicable to processes like Markov decision problems, involving a sequence of decisions over a given planning horizon (finite or infinite) split into stages, where the procedure is observed and a decision regarding the process has to be made at each one. The value iteration algorithm is used to address the finite stage decision problems, where a value function that represents expected total outcomes from the present stage until the end of the planning horizon is maximised or minimised accordingly. Although value iteration can handle large models, it is not as exact and efficient as the policy iteration algorithm when used to solve infinite planning horizons problems (Howard, 1960). Policy iteration algorithm was based on the notion of the policy being iteratively improved until an optimal strategy is found, and can only handle rather small models because of a more complicated mathematical formulation based on the solution of simultaneous linear equation (Howard, 1960; Nielsen et al., 2004). The multi-level hierarchic Markov process (MLHMP) combines these two processes, by involving a series of Markov decision processes built together in the founder process (Kristensen and Jørgensen, 2000).

As most of the optimisation deterministic models employ linear programming methods, for this literature review, the models outlined were divided into four categories. The first type includes models used to investigate policy revisions, the second production and market changes, the third models that investigate environmental adjustments, and the fourth models that consider multiple criteria. Subsequently, numerous optimisation stochastic models are reviewed. Classification in this part reflects the type of modelling employed, with models using dynamic programming, Markov decision processes, multi-level hierarchic Markov process, and other procedures to address optimisation problems.

3.5.1 Optimisation deterministic models

3.5.1.1 Policy related models

Farmers often need advice on the implications of policy changes on their farm to help them with the decision-making process due to their high dependence on European subsidies to support their income (Veysset et al., 2005). The Opt'INRA model captured the effect of European Union Agenda 2000 of Common Agricultural Policy (CAP) reform on farms in France, while aiming to determine the optimal combination of resources to achieve farm maximum profit, subjected to numerous constraints (agronomic, agri-environmental, CAP, farm area, housing, animal production, etc.). However, it did not investigate the potential impact of new or improved production technologies would have on profitability, which may be relevant in the context of changing policies. Furthermore, the profit figure did not cover labour and the model calculated that the CAP would have a small negative impact on the profitability of these types of enterprise.

Another deterministic linear programming model was developed to maximise farm profitability by matching feed availability with animal requirements while considering a number of alternative land uses (Conway and Killen, 1987). The model showed that the optimum level varied according to the profitability of alternative land uses in a situation of limited milk quota. The model investigated the best solution for the whole farm and not just one enterprise, and it could be further employed to examine the impact of a variety of policy restrictions.

A model designed to simulate changes of Spanish mountain cattle farming system changes under diverse agricultural policies and off-farm labour scenarios was built after the decoupling of subsidies in 2003 CAP reform (García-Martínez et al., 2011). The objective was to explore potential adaptation strategies of mountain cattle farms in various scenarios as a result of changes in policies and markets. The re-structuring of the beef sector in Ireland resulted from the Agenda 2000 was investigated by using two integrated modelling approaches to generate projections for the sector that include both agricultural policy changes and the evolving macroeconomic environment (Binfield and Hennessy, 2001).

A different model able to analyse the regional implications of the decoupling of direct payments for farmers in Ireland was developed by Shrestha et al., (2007). The model showed that under the historical decoupling scheme, milk quota should probably shift from less efficient to larger and more efficient farms in all regions. Similarly, Ridier and Jacquet, (2002) investigated the impact of decoupling direct payments from production on producers' decisions, considering price uncertainty and risk aversion, using a multi-period mathematical programming model. Application of the model to beef cattle farms in the French regions of Limousin and Pays de la Loire suggested that decoupling policies produce a homogenous response from different types of farmers, while the share of cattle production on farms decreases and techniques become less intensive.

Vosough Ahmadi et al., (2015) developed an optimising farm-level model to explore the way that Scottish beef and sheep farms might be affected by the greening and flat rate payments under the latest CAP reforms. The model considered nine different types of beef and sheep farms, with outcomes indicating that the greening measures of the CAP will not have much impact on net margins of most of the beef and sheep farm businesses. Nevertheless, results also indicated that a move to regionalised farm payments increased the negative financial impact of greening on most of the farms but it was still substantially lower than the financial sacrifice of not adopting the greening measure.

Another study investigated the implications of decoupling of subsidies from production decisions means on farm incomes, land use and upland ecology for agricultural systems in the United Kingdom (Acs et al., 2010). By developing linear programming models for each farm type, it was possible to examine the impacts of policy changing (i.e. removal of the Single Farm Payment). The model showed that the main effects of decoupling are to reduce stocking rates and to change the mix of livestock activities.

A study from Barbier and Bergeron, (1999) introduces a bio-economic LP model which examines the impacts of state policies on farmers' incomes and natural resource conditions in central Honduras. By comparing outputs of alternative model scenarios using historical data, the model showed that the policy had a positive influence on small farmers, though, the change to intensive vegetable production did not reduce erosion, as the greater opportunity cost of labour increased the cost of investing in land conservation. A different study combines yield and pollution data generated from an agronomic crop growth model into a linear programming model to estimate the impacts of CAP price changes on farm types representing the regions of South East England and South-West France (Donaldson et al., 1995). Compared to previous years, none of the farms examined showed reduced incomes since the implementation of CAP reforms in 1992.

3.5.1.2 Production and Market related models

A model created by Anderson and Keatley, (2009) aimed to identify the optimal beef and sheep production systems for Less Favoured Areas (LFA) in Northern Ireland while considering alternative market and policy assumptions. The model accounted for all the probable production systems on these farms and performed cluster analysis to define the level of resources available on the farms. A linear programming model to decide the optimal strategy for a dairy farm to achieve the maximum profit was presented by McCall et al., (1999). Pasture management strategy, feed inputs, stocking rate, calving date, lactation length and milk production were determined for grazing systems in both New Zealand and the Northeast United States. The difference in the grain-milk price ratio between the two countries was the reason why the optimal level of cow production remained higher in Northeast America.

An alternative LP model was developed to examine the influence of possible changes in milk to milk-quota-leasing price ratios, nitrogen fertiliser and concentrate prices on the profitability of technically efficient dairy farms in the UK (Ramsden et al., 1999). The model benefits from the detailed specification of the physical relationships which allowed the model to give a full range of adjustment strategies to farmers in responding to changing input/output ratios. In addition, a bio-economic model for breed evaluation that reflected both the physical and economic factors in commercial cattle breed selection was developed by Melton et al., (1994), and applied to a cow-calf production system in the range areas of the West Texas Panhandle. Results indicated that smaller early maturing breed types (Sahiwal) were more economical than the larger slower maturing breed (Charolais).

Similarly, a simple model designed by Olson et al., (1980), employed linear programming analysis to determine the expenditures and the most optimal way of conducting beef cattle breeding experiment to compare the level of heterosis among beef breeds. The LP model generated information regarding expected costs, numbers of purchased animals required numbers of calves to be produced from each cow type and the land, as well as labour and feed resources needed for the experiment.

A model was developed to define the effect of alternative management strategies on profit and animal welfare in extensive sheep production systems in Great Britain (Stott et al., 2005). Initially, farmers were asked to compare alternative policies in five areas (labour, housing, veterinary treatment, feeding and gathering) and give a score for each. Subsequently, a linear programming model investigated the financial impact of each welfare profile on the business. The study found that there was a negative correlation between gross margin and perceived animal welfare. As considerable variation in welfare score was observed at most income levels, there was the potential to improve welfare by tailored strategies for individual farms.

Another study presented a model that allowed the assessment of interactions between profit and animal welfare on extensive sheep farms in Great Britain

(Stott et al., 2012). The model could estimate the profit of each farm in a consistent way, and then compare the impact of the decisions applied to the land and flock performance in each case on a welfare assessment. This approach could identify measure gaps in service quality as provided by management in support of animal welfare rather than animal welfare per se. Also, the model showed that a number of lambs weaned per ewe to be significantly positively correlated with welfare score; therefore, indicating that production indicators could be useful indicators of welfare.

An alternative model that evaluates economic performance and productivity was designed for different genetic lines in Angus cattle managed under contrasting nutritional regimes typical of southern Australia (Anderton et al., 2018). The model optimised stocking rates by matching the energy requirements for the whole herd with the energy available from pasture and supplementary feed on a representative farm. Results suggested that genetically leaner cows due to the selection for low fat or low residual feed intake generated more income than those of genetically fatter cows, by selling more liveweight due to heavier weights and higher stocking rate achieved.

A model investigated financial performance of different calf rearing systems while considering the effects of suckling and milk feeding on production, health and welfare of dairy cows, and on growth, milk and feed use, health and welfare of calves (Asheim et al., 2016). The LP model, which was used to maximise profit on dual-purpose dairy beef farms in lowland eastern Norway, suggested that suckling for up to at least 7 weeks had a positive influence on the farm profitability due to the positive influence on calf growth and health as well as lowered costs. A different LP model was developed by Bartl et al., (2009) to evaluate the economic viability of current and alternative dual-purpose cattle systems for smallholder farms in the central Peruvian highlands. Two groups of communities were divided according to their dependence on income from milk and animal sales, and various market scenarios were tested. The modelling results implied that the best development strategy depends on factors such as production costs, access to the markets, irrigation and availability of different feed resources.

An LP model that was driven by a combined yearly risk of high and low precipitation and beef prices, was developed to investigate the efficacy of intensification for different beef production ranches in Utah, USA (Coppock et al., 2009). Profitability generally increases with operation size, and supported the idea that intensification could be cost-effective and sustainable under several sets of conditions.

An additional model was developed as a decision support tool for the farmers of Central Mexico simulated the complex interactions observed between the farmers and their crops and cattle, including traditional maize management practices (Castelán-Ortega et al., 2003). It was used to discover the optimal combination of resources and technologies that maximised farmers' income by utilising a model simulating maize yield response to different management systems, another model simulating alternative cow feeding systems and a multi-period mathematical programming model integrated the outputs of the previous models with the survey database.

A modelling approach to maximise the sustainability of Dutch dairy farming systems for different stakeholders was proposed by van Calker et al., (2008). A dairy farm LP model that included a sustainability function was used to maximise individual and overall sustainability using stakeholder preferences while revealing trade-offs between different aspects of sustainability. Outcomes suggested that conventional dairy farms can achieve equal sustainability scores in comparison with organic dairy farms under Dutch policy conditions. A model based on two static linear programming models was developed to determine the effects of different limiting factors on the conversion process of Dutch arable farms from conventional to organic farming over time (Acs et al., 2007). Results based on the analysis of a basic scenario showed that conversion to organic farming is more profitable than staying conventional. However, an economically challenging two year period for farms preceded the profitable phase of organic farming.

3.5.1.3 Ration formulation related models

Ration formulation is a central business and operational aspect for livestock enterprises. The method of formulation depends on the system used to specify the nutrient requirements of the animals. Glen, (1980) employed a method involving linear programming to formulate rations that corresponded to the recommended nutrient standards. After obtaining a representation of the cost of the ration in the form of a function related to the energy level of the ration using

LP, the model determined the most cost-effective choice. Another example of applying linear programming to feeding ration formulation is the model and computer program of beef cattle management (TAURUS) developed by Oltjen and Ahmadi, (2013). The objective of TAURUS was to formulate the most cost-effective rations and to project financial figures in beef feedlot operations. The program could predict days on feed, live weight, carcass yield, carcass quality and the digestible energy of five different feed groups used in beef cattle diet formulation, while outputs included cost and performance, ration composition, price ranges, nutrient analysis of the ration, equations, and nutrient analysis of feeds in the ration.

Likewise, an Excel-based model to optimise rations for beef fattening diets by applying a mathematical deterministic programming approach was developed to support beef farmers in Slovenia (Zgajnar et al., 2008; Zgajnar and Kavcic, 2008). To increase precision on feed expenditures management, the model could formulate a least-cost ration without risking a decrease in the ration's nutritive value or affecting the balance between nutrients.

3.5.1.4 **Environment related models**

Shrestha et al., (2015) presented a farm-level LP model aiming to determine regional variation in Irish farms responses under climate change. A set of growth models to determine crop and grass yields under current and future climate scenarios were used, along with farm-level data taken from the Irish National Farm Survey to form an optimising model, which maximises farm profits under limited resources. The model showed that even though, substituting concentrate feed with grass was the main adaptation on all livestock farms, regional variability between farms responses to the climate change scenario exists regarding the extent of such substitution. An ecological–economic LP model designed for exploring trade-offs between biodiversity and agricultural incomes (Osgathorpe et al., 2011). Changes in the low intensity agricultural system typical to the Highlands and Islands of northern Scotland typified by small scale mixed livestock production and rotational cropping activities (crofting), negatively affects the populations of rare bumblebees associated with this system. Results conclude that there are cases where it is likely that both agricultural profits and bumblebee densities can be enhanced, which could assist policymakers when designing effective cost-effective agri-environmental regulations.

Dogliotti et al., (2005) presented a methodology for investigating the consequences of reducing soil erosion and improving physical and biological soil fertility on vegetable farmers' income in Uruguay. The mixed integer LP model provides insights into the influence of farmers' resource availability on opportunities for sustainable development while revealing trade-offs between economic and environmental objectives. It was developed to manage with complex temporal interactions in crop rotations and spatial heterogeneity on farms, to support possible re-designing of farming systems in this region. Another LP model aiming to identify the best cropping and machinery options that are both profitable and beneficial to the environment was presented by Annetts and Audsley, (2002). The model reflects the difficulties for designing farming systems within a world of increasing environmental concerns and allows for optimisation of environmental or economic outcomes, or both. Results indicate that for UK-based scenarios, substantial environmental improvements can be achieved with minor reductions in farm profit, relative to the annual variation due to yields and prices.

A deterministic static LP model that examined the effects of institutional and technical change on dairy farms, aiming to maximise labour income was presented by Berentsen and Giesen, (1995). Different farm sizes and stocking rates were considered, while the prediction of economic performance was based on production levels and nutrient losses. The model optimised a typical dairy farm facing penalties on N losses and an increase in milk and plant production. Subsequently, the model was further developed by Berentsen et al., (2000), by applying an extra seasonal and spatial element to grass production and utilisation. Additional growing seasons and separate land areas were employed to measure farm organisation, economic results and nutrient balances in a situation with and without tariffs on nutrient surpluses. A later study further advanced the model to investigate the influence of increasing animal efficiency on the economies of dairy farming for different levels of intensity, while considering environmental policies and quota restrictions (Berentsen, 2003). The original model was adopted to examine the economics of ecological sustainability; using indicators like eutrophication potential, nitrate concentration in groundwater, water use, acidification potential, global warming potential, terrestrial and aquatic eco-toxicity (van Calker et al., 2004). Results indicated that an increase in ecological performance could lead to considerably lower net margin and a reduction in fertiliser usage.

Another model was presented by Gibbons et al., (2006) that could assess uncertainty in greenhouse gas emissions from UK agriculture at the farm level was created after the model SUNDIAL (Smith et al., 1996) was combined with a modified version of the model developed by (Ramsden et al., 1999). The model represented a typical dairy and beef farm and employed Monte Carlo to study the effect of uncertainty on total GHG emissions and the most cost-effective adaptations for reducing these emissions to 60% of the baseline level.

A bio-economic LP model was developed to evaluate the economic and ecological impacts of different cattle management practices on riparian areas in north-eastern Oregon, USA (Stillings et al., 2006). The impacts of off-stream water and salt on livestock distribution and the subsequent impact on riparian use, water quality, and livestock production was evaluated. The Dynamic North Florida Dairy farm model (DyNoFlo Dairy) is a decision support tool, which integrates nutrient budgeting, crop, and optimisation models created to assess economic and ecologic sustainability under various climatic conditions (Cabrera et al., 2005). The model responds to dairy-specific environmental and managerial characteristics by incorporating a range of techniques including Markov chain probabilistic simulation of cow-flows and crop simulation for historical climatic years, and automated optimisation of managerial options. A model explored the most profitable ways to formulate feed rations, to utilise cropland, production and manure handling facilities, labour and capital resources to generate optimal whole farm plans for different sizes of swine finishing enterprises in Ontario, Canada (Stonehouse et al., 2002). The model revealed trade-offs between economic and environmental goals, and different optimal feed and manure handling prectices depending on the focus of environmental protection attention.

The Integrated Suckler Cow Optimisation model (INTSCOPT) was designed to evaluate different GHG mitigation options as well as the biophysical and economic potential of agroforestry for representative Swiss suckler cow farms (Briner et al., 2012). INTSCOPT was based on LP and showed that GHG offset by agroforestry systems had the potential to significantly reduce emissions. A multi-period optimisation model focused on central Brazilian savannah (Cerrado) was used to define abatement costs arising from various national mitigation measures (de Oliveira Silva et al., 2015). The model optimised the use of the farm resources while meeting demand projections and maximising profit, and found that pasture restoration is the most promising mitigation measure in terms of abatement potential volume and that it offers a cost-saving for the livestock sector.

3.5.1.5 Multiple-criteria related models

Sustainable development of beef production and environment protection is reflected on Beef and Grassland Biodiversity Production Optimisation Model (BEGRAB_PRO.1), a model developed by Havlik et al., (2006) to investigate organic suckler cow farms in the Czech Republic. BEGRAB_PRO.1 allows agri-environmental policy analysis by accounting not only for beef but also for biodiversity production, which is illustrated by the implementation of various technical limitations and tasks to produce particular environmental goods.

Costa and Rehman, (2005) developed a bi-criteria multi-period linear programming model meant to maximise the asset value of cattle and the economic returns from Brazilian beef production systems, in the situation of a rapid spread of pasture degradation. The model explored farmers' attitude towards overgrazing, pasture costs and capital availability. Outcomes suggested that farmers multiple objectives could encourage or constrain overgrazing, depending on whether the farmer's objectives were to maximise profit or asset value of the cattle.

An optimal whole-farm plan was generated using a linear programming model and then used to assess the economic implications of introducing alternative rice cropping systems on subsistence farming in Ghana (Yiridoe et al., 2006). The model assisted in understanding potential resource allocation and financial implications associated with the introduction of a new rice production technology. While, Benoit and Veysset, (2003) investigated the consequences of the transition of a cattle and a sheep suckler system to organic farming, driven by the global demand for organic meat. Louhichi et al., (2004) presented a dynamic model that allows an integrated analysis of complex interactions in dairy farming systems on the Réunion Island, in which biophysical, technical, socio-economic and policy components intervene. The aim was to use a linear programming model to perform analysis on investment decisions and management strategy in the livestock system and to predict its future evolution under different agricultural policies and technical opportunities.

Standard linear programming farm modelling techniques extended with emission and evaluation figures retrieved from ecological models formed a holistic ecological-economic model that was applied for the case of northern

Tuscany, under current EU regulations and different policy scenarios (Pacini et al., 2004). Outcomes indicated that organic farming systems were environmentally more beneficial than conventional farming systems and that the current CAP market and income support schemes gave cause for an intensification of farm production and an increase of environmental damage.

A multiple-criteria model that minimises environmental risks of nutrient loss, and maximise economic returns in a complex management decision process regarding manure allocation on dairy farms to meet crop nutrient requirements on a farm-scale was developed by Giasson et al., (2002). The structure of the model is nonlinear, which allows obtaining solutions that meet different management objectives for manure allocation but also makes the model complex and problematic to adapt for general use. Nevertheless, the optimised recommendation resulted in a 31% reduction in the average P-Index weighted by field area and in a 50% reduction in the standard deviation of the P-Index among fields.

3.5.2 Optimisation stochastic models

3.5.2.1 Dynamic programming

A stochastic dynamic programming model was employed by Stott, (1994) to determine the optimum replacement strategy for the UK dairy industry. Future selection index included the economic advantage of longevity of dairy cows, which was examined by expressing the expected net present value of the replacement heifer under various scenarios of voluntary and involuntary culling. The dynamic programming technique uses an objective function aiming to optimise the expected net present value of returns over a series of annual stages. The analysis revealed that longevity could add an extra £20 per lactation per year on to the investment potential of the replacement dairy heifer, while this figure was sensitive to replacement costs, but could be used as part of an economic breeding objective for dairy cattle in the UK.

Van Asseldonk et al., (1999) used dynamic programming to explore potential investment in information technology (IT) applications on Dutch dairy farms. The model was based on representing three probable investment decisions paths considering price reduction and technical progress over time; not to invest, keep or re-invest. The IT applications considered were automated concentrate feeding systems, measurement of daily activity of cows, in-line automated parlour systems recording milk production, milk temperature and electrical conductivity of milk. Then, optimal investment patterns were calculated for the variables describing price and performance of the applications, farm characteristics and farm-scale showed the conditions when in-line milk measurement, temperature measurement and electrical conductivity measurement. Outcomes indicated that the optimal investment pattern for typical Dutch dairy farms included automated concentrate feeders.

A different model that could solve established decision rules with recursive dynamic programming, was employed to determine optimal cattle management solutions under alternative policies, price and forage cost scenarios for beef farms in Finland (Pihamaa and Pietola, 2002). Dynamic programming was used to simultaneously optimise feeding and timing of slaughtering. The three policy scenarios examined were based on prices and subsidies observed in 1998, expected prices and subsidies for 2002, and projected prices and subsidies for 2002 with an extra premium subsidy for heavier animals. An important input to the model was subsidies, which influence significantly the optimal carcass weight and farmers' income in Finland. The model found that estimated prices and subsidies for 2002 would probably increase revenue and the proportion of concentrates in the diet while decreasing carcass weight (i.e. supply of domestic beef).

A dynamic bio-economic farm model was developed to investigate mechanisms of managing the consequences of shocks and subsequent production adjustments on the evolution of farm earnings and production over time for suckler cow farmers (Mosnier et al., 2009). The model allowed for simultaneously adjusting herd size, herd composition, diet composition, diet energy content, as well as crop rotation, haymaking and feedstock. Farm evolution was assessed on both short and long-term horizons when unexpected shocks occurred. Modelled adjustments for weather shocks were purchasing feed to maintain animal production objectives and harvesting area of pasture for haymaking.

A stochastic dynamic model for livestock systems and forage production was developed to investigate dynamic flock performance on Kazakhstan's extensive rangelands (Kobayashi et al., 2007). The model covers several states and control variables allowing for realistic characterisation of the biophysical relationships and economic trade-offs typical of these systems. Outcomes showed that capital costs affect flock size and productivity, driven by the current low stocking density.

3.5.2.2 **Markovian decision process**

A model established to study the economics of fertility in the dairy herd employed Markov chains to model the reproductive performance of the cows in a herd, separately to the feeding and lactation equations (Stott et al., 1999). Long-term implications of the mating strategy were incorporated in the gross margin to compare different fertility performance indicators by establishing the monthly distribution of cows by stage of calving interval that would arise over a year using Markov chain. Comparison of results generated by the model with the literature showed that the economics of fertility in the dairy herd were reasonably represented in the model.

Similarly, Santarossa et al., (2004) presented a bio-economic model of a dairy farm using Markov-chains to determine the input/output relationships for conception rates, heat detection and calving interval. The model was driven by input probabilities and oestrous detection and conception rates that acted through the calving interval and was capable of estimating the economics of fertility traits expressed as conception rate and calving interval. Decisions on dairy heifer replacement were modelled by reintroducing the issue as a multi-component Markovian decision process and solving it with the help of an LP model (Yates and Rehman, 1998). Consequently, selecting replacements from heifers was the best way to increase genetic gain.

Dynamic programming proved to be a flexible tool for dealing with problems of animal production, especially when handling only rather small models, with a few hundred states (Kennedy, 1972). This drawback is connected with the "curse of dimensionality", described as the state when several variables are considered simultaneously and each variable is considered at a realistic number of levels, then capacity space grows to prohibitive dimensions and the model becomes disproportionately large (Kristensen, 1994). In addition, decisions on agricultural livestock models are made usually on different mutually dependent levels and time horizons, contributing more to the dimensionality problem (Stygar and Makulska, 2010). A novel method for optimising complicated multi-state processes, involving decisions with varying periods was developed by Kristensen, (1988). Hierarchical Markov process (HMP) was defined as a sequence of Markov decision processes built together in one main Markov process (hierarchic structure of decision processes).

Makulska and Kristensen, (1999) developed a model that was using HMP to optimise the fattening strategy of an individual bull and a group of bulls, focusing on identifying the optimal time to terminate the finishing process. Scenarios considered numerous breeds (beef, dairy and crossbred bulls), two scales of production (single- animal level – small farms, and group level – large farms) and different finishing intensities (intensive, semi-intensive, extensive).

An alternative stochastic dynamic programming model was designed to facilitate economic optimisation of Dutch dairy heifer management decisions, by examining rearing strategies for individual heifers using the HMP methodology

(Mourits et al., 1999). The decisions considered were growth rate, insemination, and replacement. The model's accuracy was limited due to the scarcity of precise information on the interrelationships of rearing strategies with the productivity of the dairy replacement. However, sensitivity analysis provided valuable information on the critical components affecting heifer rearing.

An adaptation of the hierarchic Markov process technique, the multi-level hierarchical Markov process (MLHMP) methodology, was introduced by Kristensen and Jørgensen, (2000), and manages to expand stages of the main process to a so-called child process, which again may expand stages further to new child processes leading to the creation of multiple levels. A Java software system has been developed by Kristensen, (2003), to solve and represent multi-level hierarchical Markov processes. An example of applying MLHMP is the model developed to optimise the feeding level and slaughtering policy of organic steer production (Nielsen and Kristensen, 2002). The model consists of four levels responsible for decisions including grazing strategy (ryegrass or clover), feed level in winter (high and low), time for the beginning of fattening (19-27 months) and time of slaughter (19-30 months).

Nielsen et al., (2004) employed the same model to optimise the grazing strategy, feed level in winter and time of fattening and slaughter in organic steer production. Outcomes recommended feeding at a low level during first, second and third winter period irrespective of month of birth and live weight. Feeding permanent pasture in the third grazing season and feeding ryegrass/clover pastures in the third grazing season were found to be the most economical production systems. The model was applied in another instance for deciding optimal strategies for organic beef production from steers regarding grazing strategy, feeding level in winter, finishing and slaughter in organic beef production using a multi-level hierarchic Markov process, and analysing the stability of these results by sensitivity analysis (Nielsen and Kristensen, 2007). From an economic point of view, after considering price changes in feed, beef and premiums, finishing steers was not the optimal decision.

3.5.2.3 **Risk and uncertainty**

Agricultural models addressing risk and uncertainty are designed to assist farmers to increase their ability to predict elements like the weather, prices and biological responses to different farming practices (Pannell et al., 2000). A model used to determine the trade-offs between risk and returns for various beef-forage production systems and enterprises of Oklahoma livestock producers (Rawlins and Bernardo, 1991). The techniques of quadratic programming, minimisation of the absolute deviations (MOTAD) and target-MOTAD were employed for performing the risk analysis. The risk was calculated by the mean absolute deviation from expected net returns due to variability in forage yields, livestock prices, and selected input costs. It was concluded that MOTAD was valuable at detecting optimal livestock plans for a specific degree of risk the farmer was willing to accept. Target-MOTAD studied the effect of applying a ‘safety-first’ risk criterion on the model by which a target income was set. However, the model proved to be inflexible for forage and animal activities.

A whole-farm MOTAD model was applied to farm management decision making in Scottish cow-calf herds and was linked to an epidemiological model of bovine viral diarrhoea (BVD) (Stott et al., 2003). By combining epidemiological and economic concepts and modelling techniques, a risk assessment of the relative contribution that disease prevention could make to whole-farm income and the variability in farm income was possible. Disease-related losses were investigated in the context of a farm business rather than as a disease outbreak in isolation. Maintaining a cow-calf herd free of BVD contributes to farm income and risk management indirectly through its effect on the management of the whole farm. Measurement of the economic impact of BVD requires a whole-farm perspective that includes a consideration of risk, because farmers generally are considered to be risk-adverse; meaning that the least-cost disease-control option might not always be the favoured option.

The bio-economic model Orfee (Optimization of Ruminant Farm for Economic and Environmental assessment) representative of French farms producing beef, milk, grass and annual crops was developed to assist researchers by investigating trade-offs among various prospects, and directing future livestock production toward sustainability targets (Mosnier et al., 2017). The Orfee model operates in Gams (General Algebraic Modeling System), employing a mean variance (Markovitz-Freund) equation as the objective function, which introduces farmers' preferences for profit distribution, and assumes that a risk-averse farmer will consider both the highest expected profit and its variability. Variability is expressed in the form of prices and agricultural policy over ten years

(2005–2015). Livestock, crop production and equipment were optimised under economic risks to maximise the mean variance function of net profit.

Furthermore, a discrete stochastic programming model (DSP) was developed by Jacquet and Pluvinage, (1997) to investigate the effects of climatic variability on production choices for cereal-livestock farms in Algeria. The model simulated both the cropping pattern and the end purpose of the crops. The resistance to specialisation and intensification of production systems was a result of barley cropping being more resistant to drought than wheat and sheep flocks using the fodder resources of stubble fields and plant growth fallows. Employing DSP tends to lead to the creation of large-scale data-consuming models that require powerful resolution computers.

3.6 Grange models

Emphasis will be given to four models originally developed in Teagasc, Ireland that provided the basis of further developing models to tackle beef production issues in Scotland. For this literature review, the presentation will follow a chronological; first the Grange Beef Model will be introduced, followed by the Grange Feed Costing model, and finally, the Grange Dairy Beef Systems model will be discussed in detail.

3.6.1 Grange Beef Model

The Grange Beef Model (GBM) is a deterministic linear programming model developed to determine financially optimal beef production systems in Ireland for a range of resources as well as economic parameters (Crosson et al., 2006b). The model development was mainly driven by the changes on payments scheme introduced by the reform of Common Agriculture Policy (CAP), and the impact these had on beef farmers, who were particularly dependant on these payments to maintain margins. Its operation involves a complex interaction of feed costs, animal maintenance costs, beef price, animal intake requirements, farm capacity and policy environment. The model was constructed around a typical beef cow herd based on spring calving of Limousin × (Limousin × Friesian) cows (Drennan, 1999). Beef cows, replacement heifers, calves, stockers, and finishing animal groups were included in the model, while cows were defined as either young (first lactation) or mature (after the first lactation). Animals' nutritional needs were described in terms of energy requirements and intake capacity, which was energy driven, but potentially limited by physical fill. Pasture, grass silage, corn silage, and concentrates were among the available feeds and, due to the prevalence of pasture-based systems in Ireland, the model specifies a detailed set of grazing options that are typical of those available to Irish cattle producers. Various options were included to facilitate winter feeding and feeding in periods of temporary grass shortage during the grazing season. The main nutritional variables were taken from INRAtion (Jarrige et al., 1986) and forage production was based on historical Irish yield data, with yield specification to occur monthly. Each activity was assigned a cost or revenue, for the program to be able to identify the optimal net farm gross margin. Costs for farm equipment, buildings, energy, etc. were allocated based on farm type and size. Land rental and labour were established from the model-predicted land and labour resources required to operate each production system.

The model's objective function aimed to maximise farm gross margin, while the main constrains were animal nutritional requirements. Applications of the model were illustrated through the analysis of numerous scenarios concerning variation in beef and concentrate prices; technical development through the integration of an alternative forage and the impacts of participation in an agri-environmental scheme (Crosson et al., 2006a, 2006b). In the scenarios investigated, interest and principal payments on loans for expansion and development were categorised as overhead costs. Depreciation costs for existing and additional capital assets were allocated as expenses in the trading, profit and loss account in the calculation of farm net profit. The Grange Beef Model is an Excel-based model that consisted of 1009 activities and 425 constraints and was solved with the assistance of an Excel-based optimisation software.

To facilitate scenarios involving multiple years, the model employs, after finishing the first year run, the end of year cash balances, stock inventory changes, yearling cattle numbers and store cattle numbers as input parameters for succeeding years and gets solved again. In addition, since cow and calf numbers were a function of the scenarios investigated, these values were fed directly into the linear programming matrix and were unchangeable within each model solution. Hence, the model could identify the optimal feeding system, nitrogen application policy and finishing system for the various systems investigated (Crosson et al., 2006b).

The GBM was further employed by Crosson et al., (2007) to model the nitrogen and phosphorus inputs and outputs of financially optimal Irish beef production systems. The model aimed to tackle challenges faced by beef producers in reducing their adverse environmental impact and maintaining farm economic margins, as fertilizers are essential for livestock farms in Ireland but they can be damaging to the environment when inappropriately or excessively applied to crop and pasture land. The GBM was used to optimise cost-effective strategies for beef cattle production in high- and low-price market scenarios, while another simulation model, the Integrated Farm System Model (IFSM) originally developed by Rotz et al., (2005), was used to evaluate the long-term performance and environmental impact of these beef production systems (Crosson et al., 2007).

McGee et al., (2014) employed the GBM to study the effect of concentrate feeding level in winter and turnout date to pasture in spring on the biological and economic performance of weanling cattle in suckler beef production systems. The model was used to simulate the impact of feeding strategies on whole-farm economic performance, expressed as net farm margin. Also, the model was further developed to include a stochastic element to calculate the economic risk, defined as the degree of variation due to changes in the cost and price ratio. Afterwards, a stochastic analysis was performed using Monte Carlo assessment, which specifies a probability distribution for each sensitivity parameter. The values for parameters used in the model were chosen from their respective probability distribution for a large number of draws to give estimates of the output distributions. For young late-maturing cattle, the successive compensatory growth at pasture reduces the growth and economic advantage gained from concentrate supplementation or early turn-out to pasture.

3.6.2 Grange Feed Costing Model

The Grange Feed Costing Model (GFCM) was a static, spreadsheet-based, agro-economic simulation model that was developed to facilitate comparison of the impact of management, market and biological factors on the cost of providing ruminant livestock with feed grown on the farm (home-produced feed) in Ireland (Finneran et al., 2010). It was applied to measure the impact of alternative biological, management and market variables on the cost of producing and utilising the most common feed crops grown in Ireland.

A deterministic approach was employed to model feed crop costs and agronomic defaults (e.g. sowing dates, field operations, and harvest and utilisation options) were relevant to Irish conditions. The deterministic crop yields were calculated based on specified biological and management factors rather than simulating growth rates. Fifty-three distinct feed crop production and utilisation options are modelled in the GFCM categorised as grass/legumes, cereals, brassicas and beet. The aim was to design a research tool to be used by advisors and agricultural systems researchers, to quantify the costs and values of changing feed cropping options and management practices in the production and utilisation of a comprehensive range of feed crops for ruminants on Irish farms. Although grazed perennial ryegrass was the cheapest feed, a wide range of feeds were shown to be competitive with grass silage as winter feed options in terms of cost.

The GFCM was further developed to include random year-to-year variation in crop yields and input prices as quantifiable measures of risk affecting feed cost, allowing a stochastic analysis to study their impact on feed cost for eight feeds grown in Ireland over a 10-year period (Finneran et al., 2012a). Historic values were adopted on the premise that historical ranges of outcomes of uncertain events can provide a satisfactory guide to likely variability of future outcomes. Studying risk was possible using "@RISK" software for MS Excel, which employs the Monte Carlo sampling technique of taking a specified number of iterative samples from the input variable distributions and simulating outputs for each sample. Outcomes showed that the lowest cost feed was intensively grazed perennial ryegrass. Also, the yield risk identified to be the most significant factor affecting feed cost variability, while maize silage was the riskiest feed crop, with potential to be both the cheapest and the most expensive conserved feed.

Subsequently, the GFCM was modified to simulate the economic implications of grassland management strategies for a grass-based suckler beef calf-to-weanling system at the whole-farm level (Finneran et al., 2012b). The model allowed for calculating the cost of annual grass consumed as grazed grass and silage when the farm grazing and conservation areas are integrated. Grass growth data were collected from different sites in Ireland. While several scenarios were simulated to explore stocking rate and silage strategy consequences on total annual feed cost for the grass forage production system. The model showed a tendency towards reduced annual feed cost under a two harvest, relative to one harvest and silage strategy, while site-specific differences (e.g. seasonal growth distribution and nitrogen fertilizer response rate) had the greatest influence on the annual cost of the grass-based feeding system.

3.6.3 **BEEF systems Greenhouse gas Emissions Model**

A whole-farm stochastic simulation BEEF systems Greenhouse gas Emissions Model (BEEFGEM) was developed by Foley et al., (2011) to measure the impact of alternative management practices on greenhouse gas (GHG) emissions from pastoral beef production systems. The model simulated the direct GHG emissions of methane, nitrous oxide and carbon dioxide from on-farm livestock production activities and the indirect GHG emissions including emissions from inputs used on the farm and the ones associated with nitrate leaching and ammonia volatilisation. Various emission sources were not included in the model; for example, emissions generated from meat processing and transport, emissions associated with buildings, as well as GHG sinks associated with land use. The model was developed in Microsoft Excel and operates as a single-year, static model. At first, it deterministically identified the most significant GHG emission, and then, these variables were assigned probability distributions based on triangular distributions where the minimum, maximum and most likely values are included. Subsequently, a stochastic analysis was used to simulate the effect of uncertainty around key input variables on production system GHG emissions.

The purpose of this model was to investigate the effect of alternative production systems at the farm-level on GHG emissions. Emissions from five contrasting beef production systems were modelled; one based on average farm conditions in Ireland and four based on research farm conditions. In addition, both direct and total GHG emissions per hectare increased with increasing stocking rate for all scenarios investigated. The model showed that livestock systems finishing males as bulls had lower GHG emissions than production systems finishing males as steers. The lowest GHG emissions per kg beef carcass were achieved for bull beef production systems at moderate stocking rates. Also, the highest GHG emissions were generated for the scenario representing average farm conditions, which was also proven to be the least profitable scenario (Foley et al., 2011).

3.6.4 Grange Dairy Beef Systems Model

The Grange Dairy Beef Systems Model (GDBSM) is a mathematical model that was designed to simulate grassland based dairy calf to beef systems (Ashfield et al., 2013). The model was developed as a whole farm, static and deterministic simulation model that enables the technical and economic evaluation of beef production systems in Ireland. It operates on a monthly time step, was developed in Microsoft Excel, and consists of four sub-models i.e. the farm system, animal nutrition, feed supply and financial performance. The model is empirical and adopted data from production research experiments to specify coefficients and production functions (e.g. grazed grass dry matter digestibility and energy content, liveweight gain and the monthly proportions of grazed grass and grass silage in the diet). Model applications are presented through the analysis of production scenarios concerning three cattle breed types and two finishing ages. The production systems simulated were based on three breed groups which represent the progeny of Holstein Friesian dairy cows which were bred to Belgian Blue, Aberdeen Angus, and Holstein Friesian sires. These particular breeds were chosen to represent late maturing and early maturing sires, respectively because they characterise the extremes of beef breeds in terms of conformation, fat class, slaughter weight and carcass weight. The model results highlight the small net margins of the dairy calf to beef systems even with technically efficient management. The economic performance of all systems examined was sensitive to variation in beef price but relatively insensitive to variation in concentrate and fertiliser prices.

The GDBSM proved to be widely applicable, as it was later adopted in several instances to measure the effect technical and biological parameters on Irish systems (Ashfield et al., 2014a, 2014b, 2014c). The model was modified to model more accurately compensatory growth for grass-based dairy calf-to-beef production systems (Ashfield et al., 2014b). Compensatory growth is a period of rapid growth after a period of reduced growth due to nutritional restriction and can be used to take advantage of lower cost feedstuffs (e.g. grazed grass) during the grazing season. For the model to be able to simulate the effects of compensatory growth, the energy demand of beef cattle was partitioned into energy required for maintenance and energy required for growth. Three different production systems were evaluated where the male progeny of dairy cows were finished as steers at 24, 28 and 30 months of age. Results suggested that the economic performance of all systems was very sensitive to variation in the beef carcass and calf prices but less sensitive to concentrate and fertilizer price variation. Additionally, sensitivity analysis showed that the level of maintenance energy reduction and the duration of this reduction had a modest impact on results.

A later study presented by Ashfield et al., (2014c), utilised the GDBSM to simulate the relationship between grazed grass supply and demand to determine the cost-effectiveness of male Holstein-Friesian dairy calf-to-beef production systems on Irish farms. The male animals were finished as bulls at 16, 19 and 22 months of age and steers at 24 months of age, with a further evaluation about various combinations of these cattle finishing options. The model indicated that the most profitable system was finishing steers at 24 months of age. All bull systems were found to be more sensitive than the steer system to variation in beef, calf and concentrate prices. In addition, combining systems in terms of utilisation of grass grown or bulls and steer systems would not benefit a farms' profit. Furthermore, another study by Ashfield et al., (2014a) employed the GDBSM to simulate beef production from male and female calves born to Holstein-Friesian dairy cows bred to late maturing, early maturing and Holstein-Friesian sires and finished at different ages. Scenarios examined were: a. Holstein-Friesian males finished as steers at 24 and 28 months of age, or as bulls at 16 and 19 months of age, b. late maturing males finished as steers at 24 and 28 months of age and as bulls at 16 months of age, and late maturing heifers finished at 21 months of age, and c. early maturing males finished as steers at 20, 22 and 28 months of age, and early maturing heifers finished at 19 months of age. The most profitable system was finishing steers at 28 months of age and the least profitable system was finishing male animals as bulls at 16 months of age. In addition, authors found that maximising the proportion of grazed grass in the diet and the percentage of live weight gain from grass while also maintaining a high carcass output per hectare are the main drivers of profitability, regardless of the choice of system.

Furthermore, Murphy et al., (2017a) employed the GDBSM to measure animal performance and economic implications of alternative production systems for dairy bulls slaughtered at 15 months of age. The objectives were to investigate the influence of varying levels of concentrate supplementation during the grazing season, alternative finishing strategies for dairy bulls, and economic trade-offs for management strategies. Although the greater animal performance was observed from the higher plane of nutrition, overall the profit calculated was lower.

An additional study that evaluated the economic performance and GHG emissions of pasture-based dairy calf-to-beef production systems was presented by Murphy et al., (2017b). For this study, the GDBSM was used to simulate whole-farm system effects of production systems, while GHG emissions associated with the production were simulated using the BEEFGEM. There were five available production systems modelled involving male cattle finished as either bulls of steers on different feeding regimes and finishing strategies. The objective was to investigate the effects of production system on Holstein-Frisian bulls and steers and also to evaluate the profitability and greenhouse gas (GHG) emissions of these production systems. Model results showed that slaughtering bulls at 19months of age and finishing at pasture was the most profitable production system with moderate GHG emissions.

3.7 Conclusion

Mathematical models are significant tools for studying agricultural systems. Models from the two main types (i.e. simulation and optimisation modelling) have been reviewed along with the advantages and disadvantages of both modelling techniques. For this study, both simulation and optimisation modelling approaches will be employed. The project aims to examine issues of the economic and environmental performance of Scottish beef finishing systems identified in Chapter 2. Hence, a more detailed investigation will include mainly two different models that offer two types of investigating techniques; one simulation model using stochastic elements and one optimisation model using linear programming.

Initially, a simulation model will be employed because of its ability to investigate the performance of systems under various production scenarios. Also, simulation models can be used for in-depth investigation of livestock systems, for testing management rules or exploring farm management problems, and for discovering opportunities for a farm (Oriade and Dillon, 1997). Interest in beef finishing systems has increased in recent years in Scotland, both in terms of their economic underperformance and negative environmental consequences. Simulation models were useful tools to enable the integration of scientific concepts and to assist scientists, consultants and producers comprehend the production systems that they study and manage (Tess and Kolstad, 2000). Therefore, the development of a simulation model for beef finishing systems will facilitate further understanding of the complex interactions and the drivers of profitability for these systems. Simulation modelling could enable a detailed and flexible specification of the production relationships within the farming system. Hence, a more accurate depiction becomes possible for a large number of genders and finishing ages that are present in beef finishing systems. Moreover, simulation modelling allows researchers to explore the solution space in a more comprehensive way, while taking account of several criteria that influence each solution. Therefore, systems can be compared on profit, environmental impact, labour requirements and financial risk involved.

Subsequently, after the solution space has been explored by the simulation model, another optimisation will be employed to investigate the optimal cost-effective and environmentally friendly beef finishing systems in Scotland. Farmers have little control over beef prices, so attempts to improve the economic results of beef production focus mostly on better management of the available resources. Management involves decision-making to accomplish the set goals and objectives (Stygar and Makulska, 2010). Being managers, farmers need to allocate limited resources to competing activities in the best possible way, with the choice of the optimal decisions can be supported by the use of optimisation modelling. Linear programming models can be used to address the problem of allocating farm resources and determine an optimal plan (Jalvingh et al., 1997). The main advantages of optimisation modelling include building a concise framework for a combination of information from different sources and efficient search algorithms for the determination of optimal decisions. This type of modelling intends to solve a well-defined problem in the best way (Plà, 2007).

By employing both modelling techniques this project aims to present a comprehensive study of beef finishing systems in Scotland. Existing prevalent systems will be investigated and alternative options will be explored to attain a better understanding of the factors that make a beef system cost-effective, ways to maintain profitability as well as reasons for not producing a profit. These factors will be reviewed side by side with environmental impact mitigation strategies so that potential trade-offs could be recognised and optimal strategies identified.

Chapter 4: A bio-economic model for cost analysis of alternative management strategies in beef finishing systems

After article: Kamilaris, C., Dewhurst, R.J., Ahmadi, B.V., Crosson, P., Alexander, P. (2019). A bio-economic model for cost analysis of alternative management strategies in beef finishing systems. Agricultural Systems (in-press). See List of publications.

4.1 Introduction

Global consumer demand for food is expected to rise due to population growth and increased per capita incomes, with developing countries expected to experience a marked increase in consumption of animal products (Alexander et al., 2015; Godfray et al., 2010; Tilman and Clark, 2014). During recent decades, there have been large changes in the structure of the developing world's diet, with a move away from a starch dominated diet to one with more energy from animal products (Popkin, 2006). A shift to a more western diet, with higher levels of protein intake, will lead to an expected 21% increase in beef consumed in developing countries over the next decade, with 45% of additional beef demand attributed to Asian markets (Agriculture and Horticulture Development Board, 2017; OECD/FAO, 2017). This "westernization" of Asian diet results in increase demand for high-value temperate zone products, transforming food supply systems and providing export opportunities (OECD/FAO, 2017; Pingali, 2007).

Every region's agriculture activities are related to land type; the pasture-based agricultural landscape of Scotland indicates that the ruminant livestock sector, and principally cattle production, is the main agricultural activity (ERSA, 2016;

Vosough Ahmadi et al., 2015). Scotland's economy is extremely reliant on ruminant livestock farming, while in terms of dependency on cattle production across the European Union (EU) states, the region is second only to Ireland (Ashworth, 2009). Nevertheless, producers tend to report low or negative margins and rely greatly on Common Agricultural Policy (CAP) support payments to sustain their farming activities (Scottish Government, 2014). This increasing reliance on subsidies raises concerns over the sector's financial performance and stability (AHDB, 2016b). To capitalize on future opportunities, the challenge for Scotland's beef industry will be to make optimum use of resources and unlock the best combination of management practices to improve production efficiency and profitability. Scottish forage-based beef production systems might be sustainable in environmental terms, but economic sustainability is yet to be achieved for most farms, partly due to a volatile business environment and uncertain price conditions (Scottish Government, 2014). There is a need to investigate adaptations that counter the effects of uncertainty by helping farmers building strategies to capitalize on the region's unique assets (AHDB, 2016b).

Simulation models enable researchers to investigate and reveal the possible impacts of changes in agricultural production technologies. This often leads to designing tools that can complement, and even substitute for, conventional, 'on-the-ground' experimental methods (Antle et al., 2017a; Bywater and Cacho, 1994). Beef production systems can be investigated with mathematical models to explore various sets of farm constraints, policy parameters and management alternatives (Nielsen et al., 2004; Rotz et al., 2005; Tess and Kolstad, 2000; van Calker et al., 2004; Veysset et al., 2005). A number of authors have established simulation models to study beef cattle growth and carcass composition (Hoch and Agabriel, 2004; Kilpatrick and Steen, 1999), beef production systems (Crosson et al., 2006), ration formulation (Oltjen and Ahmadi, 2013), slaughtering policies (B.K. Nielsen and A.R. Kristensen, 2002), feed intake and animal performance (Rotz et al., 2005), feeding strategies (Bonesmo and Randby, 2010), decisions during the fattening process (Makulska et al., 1870), systems' technical efficiency (Ruiz et al., 2000) and various innovation options (Ash et al., 2015).

Although these studies have covered various beef production issues, there is a need for livestock simulation modelling approaches based on region-specific robust datasets that will be effectively pre-parameterized for conditions common to the system examined (Antle et al., 2017a). Here, a static simulation model utilized Scottish beef farm systems as a case study for a methodology that could be used to explore cost-effectiveness of beef finishing in other regions. The aim of this study was to assemble information to support a decision-making process contributing to the development of cutting-edge farm-management systems that address low profitability (Jones et al., 2017). The chapter describes the structure of the Grange Scottish Beef Model (GSBM). The model is then applied, to investigate scenarios that study the effects of variation in market conditions, policy environment and management practices on enterprise profitability.

4.2 Model description

The GSBM shares a common structure with farm systems models developed by Teagasc (The Agriculture and Food Development Authority in the Republic of Ireland) (Ashfield et al., 2014b, 2013; Bohan et al., 2016; Crosson et al., 2015;

Crosson et al., 2006; Finneran et al., 2012). Thus, the approach was to develop a biophysical depiction of the farm system within a single year, adopting a static and deterministic framework with provision for an economic analysis of annual performance. The animal nutritional data and equations used in another model developed by Teagasc were considered appropriate due to the similarity of production systems, climate and breeds between Scotland and Ireland (Ashfield et al., 2013; Heaton et al., 2008). Furthermore, European market specifications are shared between the two regions (Quality Meat Scotland, 2017a). The GSBM diverged from previous Teagasc models to provide a dedicated depiction of the Scottish beef finishing sector, including a range of production systems reflecting the variety of options available to beef farmers.

4.3 Origin of experimental data

Data were obtained from experiments in Scotland to define the main coefficients and production functions (Bell et al., 2016; Hyslop et al., 2016). Production systems modelled were based on the "Lifetime growth pattern and beef eating quality" ("Growth Path") project, previously reported by AHDB Beef & Lamb (Hyslop et al., 2016). This three-year study was selected because Limousins were the most used beef sire in Scotland and the UK between 1997 and 2017 (Quality Meat Scotland, 2017a). A total of 72 animals entered the study at 12 months of age (yearlings) and were taken through divergent finishing strategies; offered either a mixture of concentrates with forage-based finishing diets or grazing on diverse quality grasslands. Steers and heifers, representative of the Limousin crossbred beef cattle genotype, experienced three different treatments that led to three distinct “growth-paths” (Hyslop et al., 2016). Further details of the Growth path study are included in the Supplementary Material.

The model simulates two genders of one important genetic type (Limousin crossbreds) under three management regimes. Modelling of individual systems was based on growth patterns recorded in the study, which represent production systems typical of commercial practice for the UK and Scottish farms (Hyslop et al., 2016). Six production options were modelled, which represent the short, medium and long finishing treatments along with two genders (steers and heifers), reproducing the continuous experimental design of the “Growth Path” trial.

Instead of employing generic growth curves, animal growth curves were adopted from the “Growth Path” experiment dataset (Hyslop et al., 2016). Figure 4.1 shows the difference between these curves and those produced using INRA equations for late-maturing steers and heifers (Sauvant et al., 2018). Whilst the standard INRA curves corresponded closely for medium-duration finishing systems, they under-predicted for short-duration and over-predicted form long-duration finishing systems. In beef finishing systems, when animals are sufficiently fed after a period of reduced energy via restricted nutrition, the physiological process of compensatory growth is observed, which signifies a period of enhanced growth compared with those not submitted to feed restriction (Hornick et al., 2000; Sainz et al., 1995). Previous studies have highlighted the role of compensatory growth when estimating beef cattle performance (Hoch and Agabriel, 2004; Keele et al., 1992; Oltjen et al., 1986). In addition, compensatory growth could influence a farm' financial performance (Ashfield et al., 2014b), as it can be employed as a strategy to reduce feeding costs (Lopes et al., 2018), and it was found to have an effect on meat's sensory characteristics and quality (Keady et al., 2017). The variability in experimentally-derived growth curves was a result of actual feed availability, and this was particularly obvious for the long-duration finishing systems which incorporated two grazing periods.

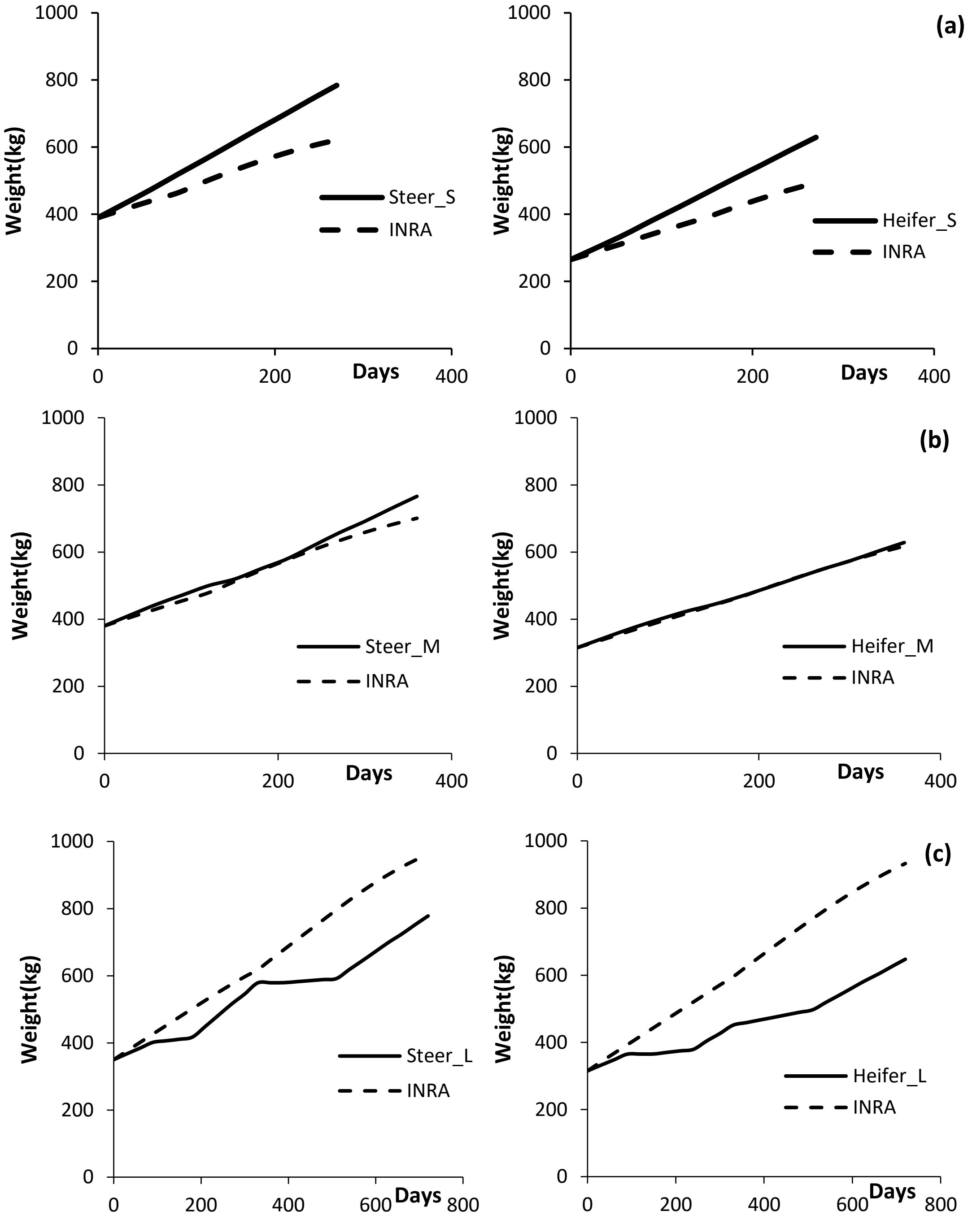

Figure 4. 1 *Comparison of growth curves used in the GSBM with generic curves taken from the INRA model (Sauvant et al., 2018) for three different production options (finishing durations: short, medium, long) along with two genders (steers and heifers).* ***(a)*** *Steers and heifers on short duration system (i.e. Steer_S and Heifer_S),* ***(b)*** *Steers and heifers on medium duration system (i.e. Steer_M and Heifer_M),* ***(c)*** *Steers and heifers on long duration system (i.e. Steer_L and Heifer_L).*

4.4 Model components

To investigate production-related scenarios, an existing model, the Grange Dairy Beef Systems Model (GDBSM), was used as a base, re-parameterized and adjusted to fit Scottish conditions (Ashfield et al., 2013). The GDBSM was developed to evaluate grassland based dairy calf to beef production systems in Ireland (Ashfield et al., 2014c, 2014a, 2013). Similar to the structure of GDBSM, this model also consists of four sub-models i.e. the farm system, animal nutrition, feed supply, and financial performance. Each component of the model will be briefly discussed, along with alterations and adjustments made to develop a regionalized model for Scotland. A representation of the approach adopted during the development of the GSBM is demonstrated in Figure 4.2.

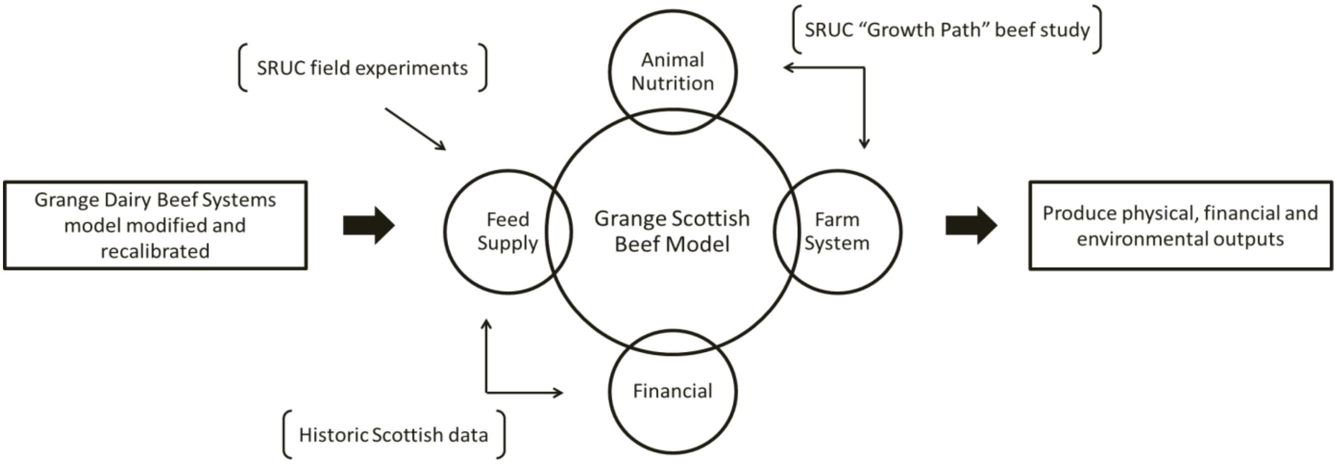

Figure 4. 2 *Process of developing the Grange Scottish Beef Model. The development involved assembling data-sets from diverse sources, and employing them to inform the input values re-shaping the systems forming the GSBM sub-models to parameterise the model for Scottish conditions.*

4.4.1 **Farm system sub-model**

The farm system sub model simulates the beef finishing system and calculates the animal numbers monthly, individual live-weights, housing requirements, and slurry production during the indoor period. The finishing systems of the farm system sub-model were re-designed to replicate animal treatments during the "Growth path" study. Simulation initiates when animals enter the farm on 1st May, which is typical for spring-born yearlings in Scotland (Hyslop et al., 2016). The exception to this is cattle on short-duration systems, which entered the farm on 1st March. Animals were assumed to be purchased at the prevailing yearling store price. Additional cattle purchases can occur at any time during the finishing stage. The default mortality rate was set to 2%, equally distributed over the year (SAC Consulting, 2017).

Live-weights were simulated based on initial variability measured during the "Growth Path" experiment and were calculated at the start of each month and based on the previous month's starting live-weight and live-weight gain. Key default parameters like starting live-weight and monthly live-weight gains used data from the "Growth Path" experiment (Hyslop et al., 2016). The amount of slurry produced was based on the number of animals, the number of days spent indoors, as well as the volume of slurry produced per animal per day (SAC Consulting, 2017). All animals were accommodated in straw bedded systems and were supplied primarily with grass silage diets. Another assumption was that cattle were sold directly to abattoirs, and carcass data were obtained from the same experiment (Allen, 2014; Hyslop et al., 2016).

4.4.2 Animal nutrition sub-model

The animal nutrition sub-model controlled the energy demand and feed requirements of the modelled herd. It has been designed to calculate animal requirements and formulate diets using grazed grass, grass silage and concentrates to meet these demands (Ashfield et al., 2013). Nutritional specifications were described as animal energy requirements and were subject to a maximum intake capacity, which was described in Cattle Fill Units (CFU's). Energy requirements were specified in UFL's (Feed Unit for lactation) and UFV's (Feed Unit for maintenance and meat production) for growing and finishing animals respectively (Jarrige et al., 1986). The equations of Ashfield et al. (2013), based on liveweight and liveweight gain were adopted to calculate the net energy requirements and animal intake capacity for GSBM (Ashfield et al., 2013). In this version of the model, protein requirements were not considered, as it was assumed that fulfilment of energy requirements simultaneously satisfies protein requirements (Crosson et al., 2006b). The outputs of the model have been verified to ensure that the protein requirements of animals are satisfied (Crosson et al., 2006b). For a possible scenario where protein requirements have not been fulfilled, the user must specify to feed appropriate concentrates until requirements are met (Ashfield et al., 2013). Actual growth rates adopted from the "Growth path" study controlled the animal intake and were used as inputs to calculate net energy requirements. Moreover, feed grown in the farm was modelled as a constraint for forage intake, while brought-in concentrates offered to compensate for the difference.

When simulating proportions of grass and forage fed, no silage was fed during the grazing period, and likewise, no grazed grass was fed during the housing period. In instances where the forage quantity calculated for satisfying energy demands surpassed its intake capacity, the amount of forage originally considered was fed at the maximum level, with supplementary concentrates used to meet the total energy demand (Ashfield, 2014). But, the inclusion of concentrate led to the reduction of forage intake and the extent of this replacement depends on the forage fill value and amount of concentrate fed. Thus, the "apparent fill" method was employed to calculate the change in forage dry matter per unit of additional concentrate fed (i.e. substitution rate) (Jarrige et al., 1986). The process selected was based on forage's apparent fill value (AFV), taking account of the ration energy density (RED) of the diet and the energy content of the forage (UFL or UFV). The model determined AFV based on tables previously published for a range of RED's and UFV's typical to temperate grasslands (Jarrige et al., 1986).

4.4.3 Feed supply sub-model

The feed supply sub-model regulates the forage system that calculated the grazed grass and grass silage production of the farm. Most of the land area of grassland based beef finishing systems in Scotland consists of permanent perennial ryegrass swards (Quality Meat Scotland, 2013). During peak growth periods, some of the perennial ryegrass swards are isolated for grass silage production. Supplementary concentrate feeds were purchased and used alongside the forage dietary components when required.

The grass grazing area was the total farm area minus the total area required for grass silage on a monthly basis. Grass growth (t DM/ha) was modelled based on a field experiment that took place at Crichton Royal Farm, Dumfries (55°02′N, 3°35′W) in South-West Scotland, UK, on a long-term permanent grassland site (Bell et al., 2016). The data were used to generate an equation that predicts grass growth based on the nitrogen response (organic and inorganic) application rates (kg/ha). The expected yield and monthly distribution of grass growth throughout the year was calculated based on historic Scottish data from Scotland's Rural College (SRUC) Dairy Research and Innovation Centre (Dumfries).

The utilization of grazed grass was fixed initially at 50% to reflect the level of performance of a set stocking grazing system for typical Scottish beef farms (Quality Meat Scotland, 2013). Two harvest regimens were modelled (one – harvest and two-harvests), using data published from the British Grassland Society to account for yield and quality parameters when cutting on different dates (Hopkins, 2000). It is typical on beef farms in Scotland for the first harvest to take place late in May or early June and the second approximately six weeks later, or else, depending on the weather and production systems selected, a single harvest might be taken in June (Farmers Guardian, 2017). Further details for modelled harvest dates, yields, and silage quality are provided in Supplementary Material. Demand for grass silage, driven by the animal nutrition sub-model, regulates the proportion of the area required for grass silage. When grass silage harvesting is complete, all farm area is available for grazing. Concentrate rations for the finishing animals were simulated as a typical Scottish barley-based concentrate with an energy content of 1.15 UFL or UFV/kg DM (Quality Meat Scotland, 2017a).

A key input was nitrogen (N) application to the grazed area since it determines the overall stocking rate. Stocking rates were defined as organic nitrogen output per hectare for cattle and, under the Nitrates Directive, the maximum amount of organic nitrogen output is limited to 170 kg N/ha for the UK (The Scottish Government, 2008). Specifications on nitrogen, phosphorus and potassium inputs originate from (Ashfield et al., 2013), as these figures were already embedded in the model, and they better characterize the stocking rate effect. The same principles apply to slurry production, its nutrient content and available nutrients. The slurry was allocated to the grass silage areas with 70% applied in spring and 30% over the summer, while its nutrient content was considered when calculating chemical fertilizer requirements. Whilst retaining the more complex Irish model, these estimates were consistent with the range of values suggested for Scotland in the Technical Note for fertilizer recommendations for grasslands (Sinclair et al., 2013).

4.4.4 Financial sub-model

The key purpose of GSBM is to simulate the biological operation and economic performance of Scottish beef finishing enterprises. Recent Scottish pricing data were used as a baseline. Beef prices were calculated by gathering and analysing monthly data, publicly available from the Scottish Farmer, from 2012 to 2017 (The Scottish Farmer, 2018). The beef price used in the model is a function of the conformation and fat class of the animal.

The seasonal and yearly fluctuation of beef prices were accounted for by employing ModelRisk, a risk analysis add-in for Excel (Vose Software, 2018). Options include monthly average, with minimum and maximum monthly prices taken from the last five years as an input for both carcass and yearling store prices. Additionally, a stochastic approach was used, where ModelRisk fits normal and lognormal distributions to the carcass and store prices based on weekly data over the five year period of 2012 to 2017. Thus, the model generates random carcass prices and yearling store values for each run. This technique enhances the model's capacity, as it enables testing of the resilience of beef finishing systems under diverse market conditions. In an attempt to understand enterprises' financial performance under different pricing schedules, pricing grids from two major beef processors were included. ABP and Dunbia, have pricing grids that reflect the supermarket specifications and consumer preferences, thus providing a lower price for over-age cattle and carcass weights above specific thresholds. The model included age penalties for cattle over 30 months, as well as weight penalties for carcasses outside the latest specifications (Dunbia, 2015; Robert Forster, 2015).

Pricing data were collected from various sources including Farm Management Handbook (2016), websites, publications from Scottish Government and personal communication with SAC Consultants (AHDB Beef & Lamb, 2018; Ashworth, 2009; ERSA, 2016; Hyslop et al., 2016; SAC Consulting, 2017; Scottish Government, 2014; The Scottish Government, 2015a, 2015b, 2008). Less critical prices were adopted from Ashfield (2014), converted from Euro to Pound

Sterling (OFX Group Ltd, 2018) and adjusted for inflation according to a process described by the Bank of England (Bank of England, 2018).

Variable costs typically include concentrate, fertiliser, silage making (contractor, additives, and polythene), veterinary and medicine, reseeding, straw, slurry spreading, milk replacer, interest on working capital, market and abattoir costs, transport costs and land rental (Ashfield et al., 2013). Data from the Scottish Government were collected to estimate land rental for different areas of Scotland, to account for the large variation encountered (The Scottish Government, 2015b). Fixed costs included expenses like electricity, car, phone, land improvements maintenance and interest on an assumed long-term loan. Other fixed costs included, machinery operating, building maintenance, and the corresponding depreciation, plus interest on machinery and land improvements. The initial method for calculating the cost of the buildings and machinery was described by (Ashfield et al., 2013). It was also assumed that the machinery owned by the farmer included a tractor and static machinery for routine field operations (e.g. fertiliser spreading and grass topping), while operations like grass silage harvesting, reseeding and slurry spreading were carried out by a contractor. The interest rate for long-term borrowing was set at 8%, including investments in land improvements, accommodation for animals during the indoor period and machinery. Paid labour was included in the fixed costs. Average labour hours per month for different categories of beef finishing system, as well as rates for skilled and casual agricultural labour for Scotland were used (Nix and Redman, 2016; SAC Consulting, 2017). The model does not account for the opportunity cost of owned land, or unpaid family labour. The main output from the financial sub-model is the monthly and annual cash flow and annual profit and loss account.

4.5 Model validation

Farm systems models are difficult to validate formally due to lack of independent datasets and therefore are often evaluated using a panel of experts (Crosson et al., 2006). As a result of the absence of a robust dataset for Scottish beef finishing systems, the process selected for evaluating the model was ''face validity'' by ''knowledgeable individuals'' as described by various authors (Qureshi et al., 1999; Rykiel, 1996; Sargent, 2010). During the design process for the GDBSM, regular consultations with researchers at Teagasc, Grange Research Centre were taking place, to ensure that the proper biological relationships were specified and to validate coefficients used in the model (Crosson et al., 2006).

A workshop to evaluate the GSBM took place with the Beef, Sheep & Dairy KT Strategy Group of SAC Consulting and SRUC. Thirteen knowledgeable individuals (e.g. beef specialist consultants, grass specialists, professors, farm managers, researchers) were present for the workshop, which purpose was to gain feedback from beef experts regarding the model's performance and accuracy. Workshop activities involved presenting the model's structure, testing several scenarios (e.g. resources, input prices, and performance indicators), and completing a questionnaire with twelve questions using a 5-point Likert response scale to measure how well they agree with model's outputs (Likert, 1932). The questionnaire also included open questions on the model's outputs. Workshop results are summarised in Figure 4.3.

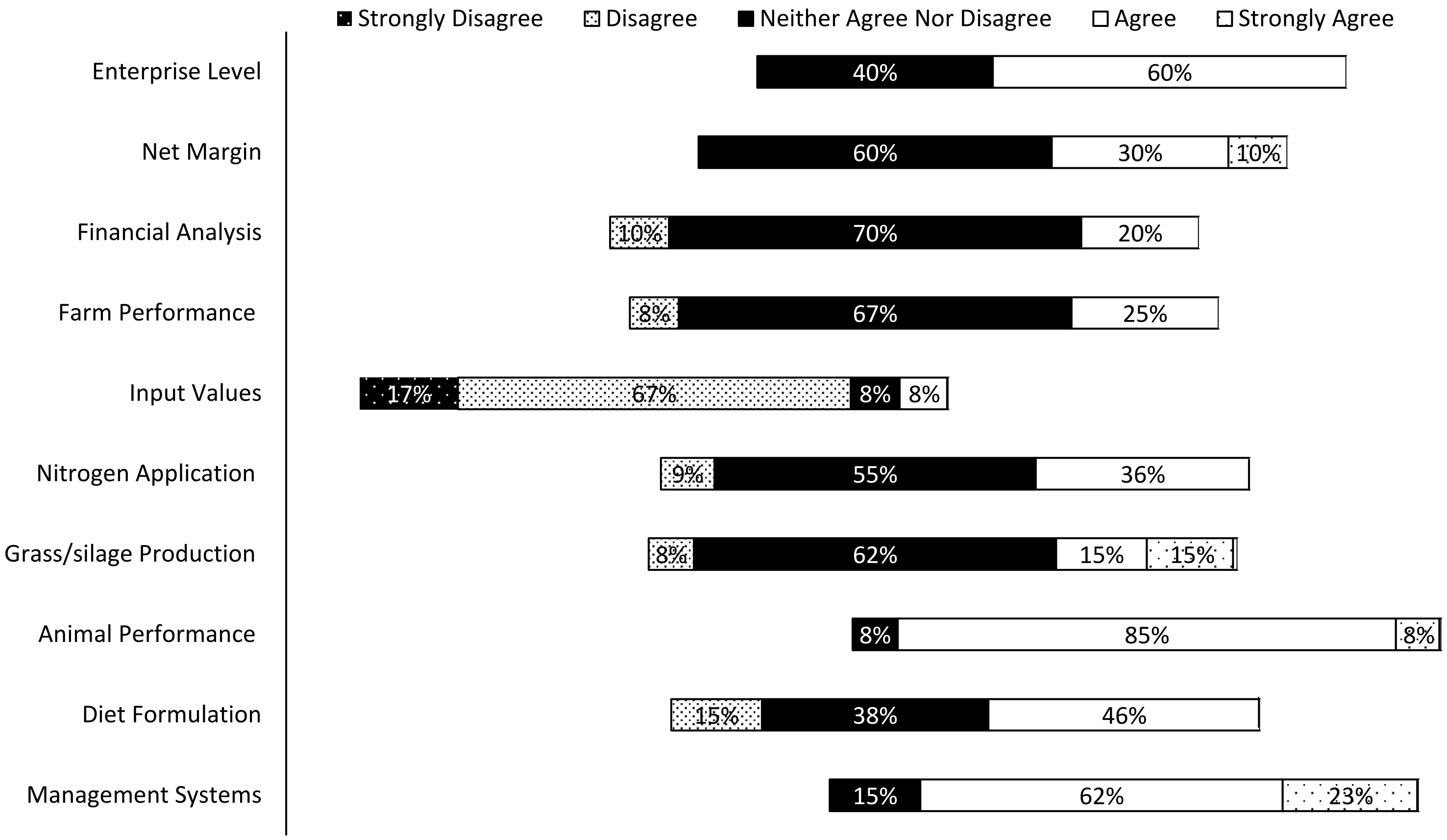

Figure 4. 3 *Workshop questionnaire results, which took place during the Beef, Sheep & Dairy KT Strategy Group of SAC Consulting and SRUC (2018) and was an attempt to validate the GSBS model by capturing the opinion of knowledgeable individuals. This is the summary of expert's workshop questionnaire results that indicates the extent to which participants agree or disagree with the model's outputs on a 5-point Likert response scale.*

Although the model appeared to accurately depict animal performance of continental breeds in Scotland; some aspects needed recalibration. The model was not accurate for the current financial situation of Scottish beef enterprises. In response to survey results, individual sessions were held with SAC consultants, where new values were estimated for input prices, and it was decided to include beef prices only for years 2015-17; excluding previous years with extreme volatility affecting the mean (The Scottish Farmer, 2018). Also, the equation used for grass production estimation was decreased by 20%, along with an option for second cut silage, which was decreased by the same amount for yield (t DM/ha) and dry matter digestibility (g/kg). After recalibrating the model, beef experts were contacted again and after a series of consultations aiding both to model verification and model validation process, they were content that GSBM was simulating beef finishing systems in Scotland within an acceptable range of technical and financial outputs.

Sensitivity analysis is the process of recalculating outcomes under alternative assumptions to determine the impact of an input variable and is considered critical to model validation (Pianosi et al., 2016). To identify which inputs cause significant uncertainty and test the robustness of the model, a sensitivity analysis was performed for a beef finishing system slaughtering heifers at 24 months of age. The main inputs examined were carcass prices, concentrate costs and yearling values (Figure 4.10).

4.6 Model application

GSBM was used to investigate the technical and economic performance of the most common beef production systems in Scotland. Scenarios involving finishing either male or female animals on a range of finishing ages for each of three distinct treatments, whereby cattle were slaughtered at monthly intervals of 14-17, 18-24 and 25-35 months of age (‘short’, ‘medium’ and ‘long’ durations respectively). Implications for the systems’ financial performance were of interest because the management approaches varied greatly in inputs and outputs. The land area was constrained to 120 ha, typical for a beef finishing farm in Scotland. Likewise, the inorganic nitrogen input on the grazing area was fixed at 175 kg N/ha across the different systems. Additional nitrogen quantity, which was attributed to extra concentrates, N mineralisation (i.e. from the soil) and potentially from N fixation by legumes, was assumed to enter the farm system yearly. All livestock were purchased as yearlings and the number of animals was matched to land area and forage production. For the shorter duration finishing systems, only one silage cut harvest date was modelled, on 29th May. In contrast, for the medium and longer pasture-based systems, two silage cuts were assumed with 6 weeks of regrowth.

4.6.1 Scenario analysis

To examine the resilience of Scottish beef production systems, scenarios based on altering factors that affect financial outcomes were constructed and investigated. These illustrate two different approaches: scenarios about finishing duration, choice of animal's gender, feed efficiency and within-herd variation take a bottom-up approach driven by what the farmer might be able to change, while the ones concerning a simulated governmental financial aid have a top-down approach, directed from the administrative authorities and what they might do to make up incomes.

Scenario 1. The first scenario explored the effect of different finishing durations on farm profitability. Several authors have identified system intensity variation in finishing durations to be vital determinants of profitability for beef systems (French et al., 2001; Keane and Allen, 1998; Keane et al., 2006). The GSBM was employed to determine the cost-effectiveness of different management practices and slaughter ages (at monthly intervals) for beef finishing systems. The most common beef finishing systems in Scotland were reflected in the different treatments (i.e. ‘short’, ‘medium’ and ‘long’ duration).

Scenario 2. The second scenario considered the effect of using different genders on profitability. It has been shown previously that steers consume more feed, gain weight faster, and are more efficient than heifers. Hence, steers tend to be more profitable than heifers (Koknaroglu et al., 2005). However, variation in sale prices, feeder prices, and feed conversion rates are also significant in explaining possible differences in steer and heifer profitability over time (Langemeier et al., 1992). Simulation results enabled a comparison between genders, to identify differences in performance for each finishing age.

Scenario 3. The third scenario investigated the effect of genetically selecting cattle for improved feed efficiency. Considerable resources and expenses of a beef enterprise are allocated to the feed budget (McGee, 2014). Consequently, feed efficiency in growing and finishing cattle, which translates as the ability of animals to reach a target body weight with the least amount of feed intake, is a key factor in the beef cattle industry (Cantalapiedra-Hijar et al., 2018). Several studies have attempted to gain an understand into the biological basis governing deviating phenotypes for feed efficiency in bovine by examining animals’ blood metabolites and hormones (Bourgon et al., 2017; Cônsolo et al., 2018; Gonano et al., 2014; Richardson et al., 2004), or by studying cattle’s hepatic function (Casal et al., 2018; Montanholi et al., 2017). Other studies focused on (Lu et al., 2013), analysing interactions with the rumen microbiome (Paz et al., 2018), associations with meat quality (Herd and Bishop, 2000), or concentrated in the host genomics (Lu et al., 2013; Snelling et al., 2011). Further studies on genetic selection using divergent breeds of cattle from around the world have shown that within any group there could be a variance of around 20% in feed efficiency between the most efficient and the least efficient animals (Fitzsimons et al., 2014; Grigoletto et al., 2017; Kenny et al., 2014; Lawrence et al., 2012; McGee, 2016; Takeda et al., 2018). GSBM simulated the genetic selection effect for feed efficiency by decreasing the daily energy requirements of animals by 20% while achieving the same level of live-weight gain. This scenario attempted to simulate the effect of selection across the national herd rather than an individual breeder selecting for feed efficiency, while all animals were bought into the farm.

Scenario 4. The fourth scenario explored the effects of within-herd variation in performance related to genetic differences (Jenkins et al., 1991). This scenario simulates the significant amount of animal-to-animal variation that occurs around the average feed efficiency observed in beef cattle reared in similar conditions (Cantalapiedra-Hijar et al., 2018). Intra-population genetic variation can have a long-term impact on genetic change for various productivity objectives. This approach is often used to complement the quicker and more targeted genetic selection between breeds, which was simulated in Scenario 3 (Jakubec et al., 2003). To formulate this scenario to effectively portray intra-herd selection outcomes, the best-performing animals within the group were identified and the model then assumed that all animals of the herd share these characteristics.

Scenarios 5 & 6. For the fifth and the sixth scenario, technical variability of prevalent beef finishing systems in Scotland was compared alongside the fixed effect of policy changes regarding a direct support payments scheme, simulating the current level of EU support payments. Age at slaughter profiles for cattle were retrieved from the Red Meat Industry Profile, which showed that during 2017, the most common systems for both steers and heifers in Scotland were finishing cattle at 24 months (Quality Meat Scotland, 2018a). Hence, 24-month finishing systems were used as the baseline for this modelling analysis. The current farmer support payments from the European Union were included; these are land-based and non-enterprise specific subsidies, aimed at supporting environmental, economic and rural development (SAC Consulting, 2017). The effect of policy change regarding financial support on a range of financial performance of beef farms in Scotland was examined using a stochastic analysis for two different scenarios using Monte Carlo simulation. One scenario excluded, and the other included, the current level of subsidies available for beef enterprises. Monte Carlo simulation, a method of risk assessment, was applied to measure the uncertainty generated by input values and carcass prices (Figure 4.4).

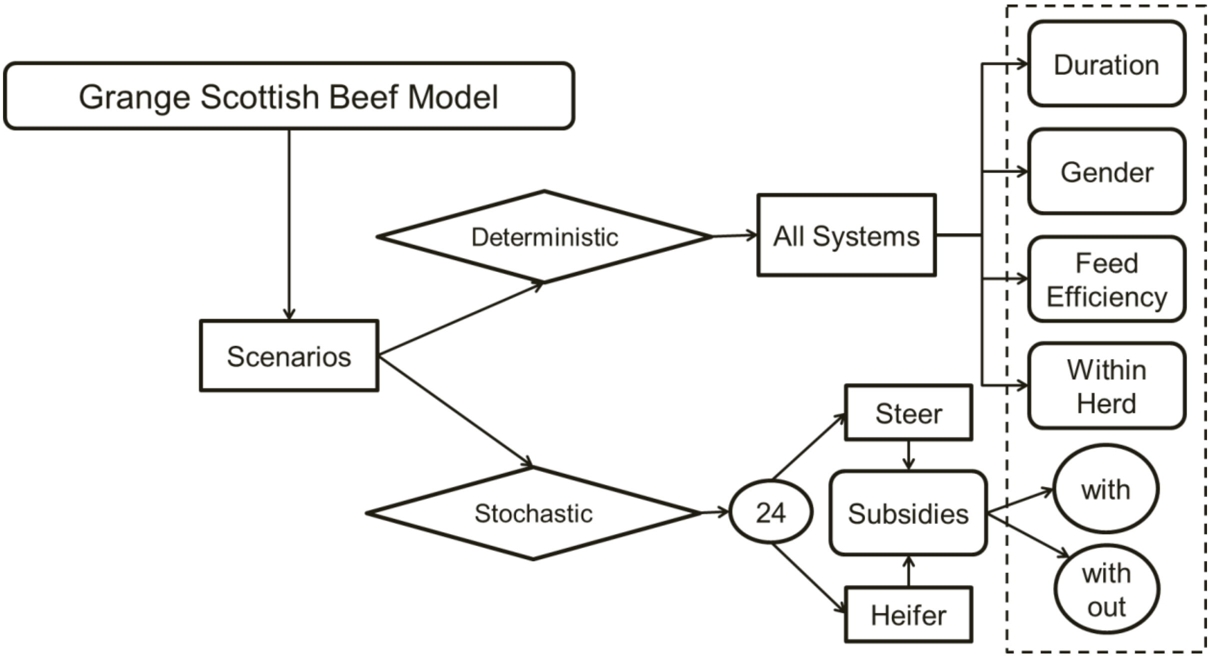

Figure 4. 4 *GSBM scenarios for determining the profitability on Scottish beef finishing systems. The scenarios simulated by the model were divided in deterministic and stochastic.* ***Deterministic simulations:*** *Examines systems of either steers or heifers, along with three different finishing durations ('short', 'medium', 'long') for each. Systems' profitability is examined with scenarios comparing between the financial performance of two genders (Scenario 1) and finishing durations (Scenario 2). In addition, the profitability of base results produced by the model were studied against scenarios employing animals genetically improved for feed efficiency (Scenario 3), as well as animals improved via intra-herd selection (Scenario 4).* ***Stochastic simulations:*** *Examines systems taking into consideration the probabilistic nature of agricultural inputs (Scenario 5 and Scenario 6). Systems' profitability is examined with scenarios concerning both genders (steers and heifers), but are focused on finishing duration of 24 months. Scenarios examined an enterprises' financial performance with and without support payments from the European Union (subsidies).*

4.7 Results

4.7.1 Scenario 1

Levels of applied organic nitrogen exceeded the level of 250 kg N/ha allowed by UK regulations (The Scottish Government, 2008) for some systems (e.g. 14 and 15 month systems) and these were rejected as non-compliant. Only thirteen of the forty systems examined were found to be profitable without subsidies. With steers, the least profitable systems were the longer finishing ones, with the largest loss of £563/animal reported for the 35-month finishing system. The most profitable system was the medium finishing at 18 months, with a profit of £169/animal. For the short-duration systems, the diet was set to only include silage and concentrates, thus, the model assumed that these types of systems could sustain a great number of animals, depicting larger intensive feedlot-type beef finishing enterprises. For the heifer finishing systems, positive net margins were reported for short-duration systems, with 16 and 17 month systems both generating profits of £134 per animal. Low financial returns were evident for long-duration systems, with the 34 and 35 month systems reporting heavy losses (net margins of -£459 and -£523 per animal respectively). Further details for each gender and finishing duration are provided in Supplementary Material.

4.7.2 Scenario 2

Steers showed higher financial returns than heifer systems in 17 out of the 20 different cases compared (Figure 4.5). Exceptions were noted when slaughtering at 30, 34 and 35 months of age, where heifer systems were more profitable. The largest difference between the two genders, £82 per animal, was recorded for 16-month finishing systems.

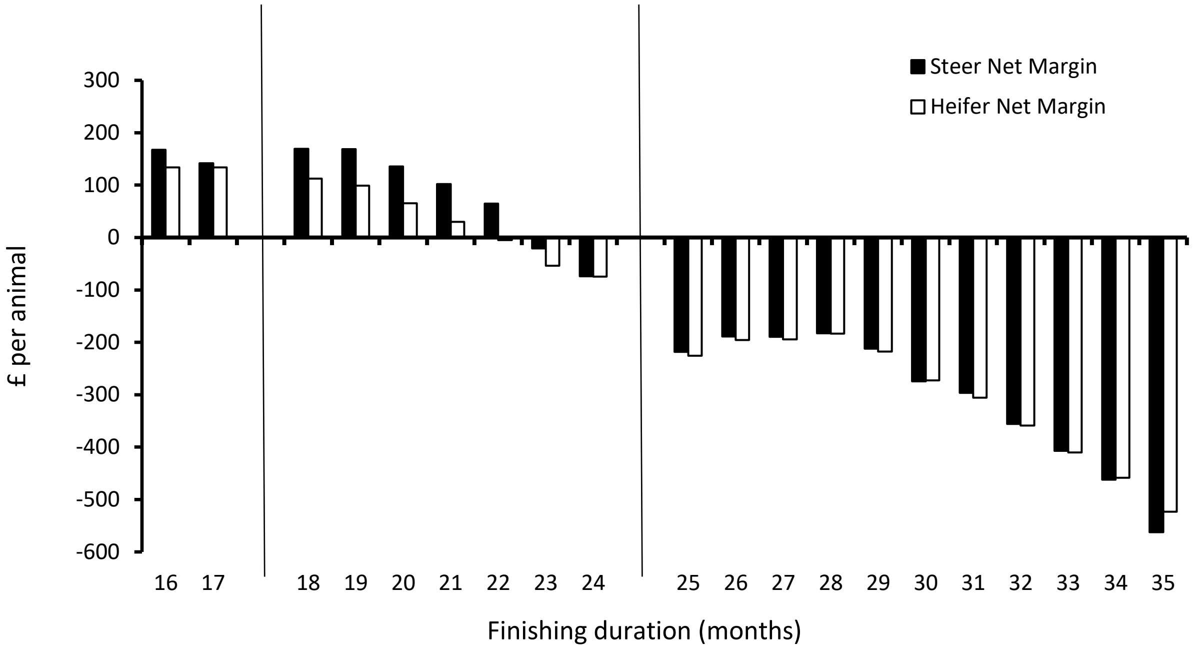

***Figure 4. 5** Comparing financial performance in terms of net margins (£/animal) for steer and heifer systems (Scenario 1 + Scenario 2). Scenarios include a range of finishing ages for each of three distinct treatments, by which animals were finished at monthly intervals of 14-17, 18-24 and 25-35 months of age ('short', 'medium' and 'long').*

4.7.3 **Scenario 3**

The impacts of selecting for feed efficiency on farm profitability were analysed for both steer and heifer systems. Unsurprisingly, net margins increased for all systems examined and five systems, (steers slaughtered at 23 and 24 months, and heifers slaughtered at 22, 23 and 24 months) transformed from loss-making to profitable. The full analysis of the effects of increasing feed efficiency for steers and heifers on systems with different finishing duration is presented in Figure 4.6. The impact of feed efficiency is greater in steers than heifers and becomes more pronounced with longer finishing durations.

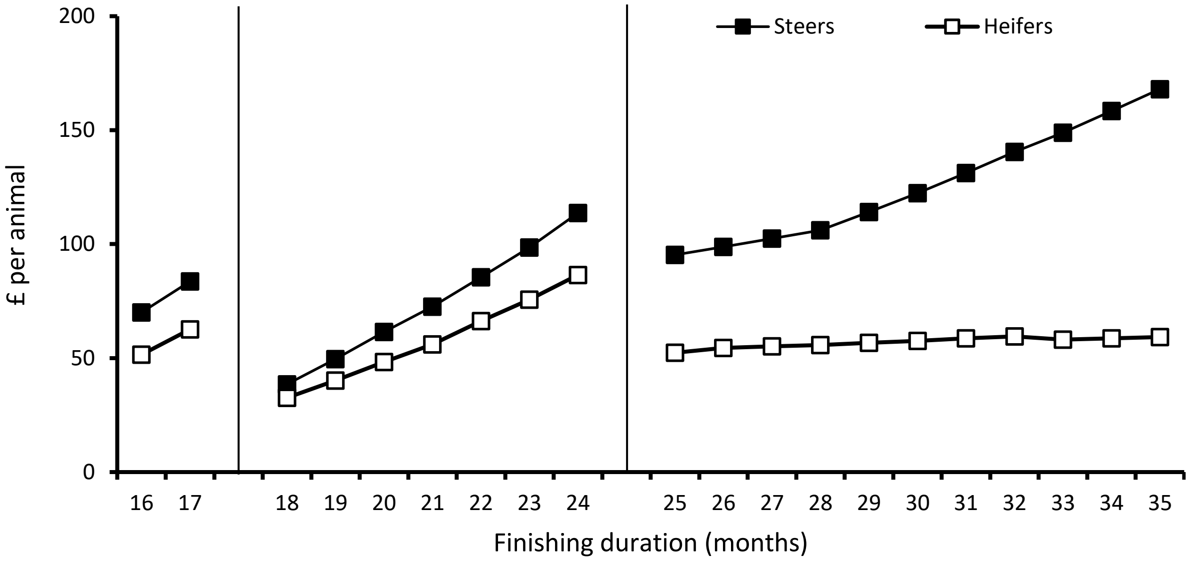

Figure 4. 6 *Improvement of profitability as a result of genetic selection on feed efficiency on steers and heifers (Scenario 3). Animals were finished managed to finish at monthly intervals of 14-17, 18-24 and 25-35 months of age ('short', 'medium' and 'long'), with x-axis represents increasing finishing durations.*

4.7.4 Scenario 4

In Figure 4.7 financial results for the highest growth rate animals in each group are compared with the average performing animals. There is potential to increase margins with better-performing animals of the same breed and sex, especially on short- and medium- duration fattening systems. The influence of within-herd performance variation delivered the highest increase in net margin in 17-month system for steers and 24-month system for heifers. The positive effect a high level of growth has on profitability decreases the longer the animals are kept in a system for both steers and heifers (though at different rates). It was interesting to compare on selection between the two sexes, as it had a large effect on profitability, especially for the longer duration systems with heifers. Figure 4.8 shows the comparison between the two genders and highlights the move to slightly more profitable heifer systems on longer finishing durations.

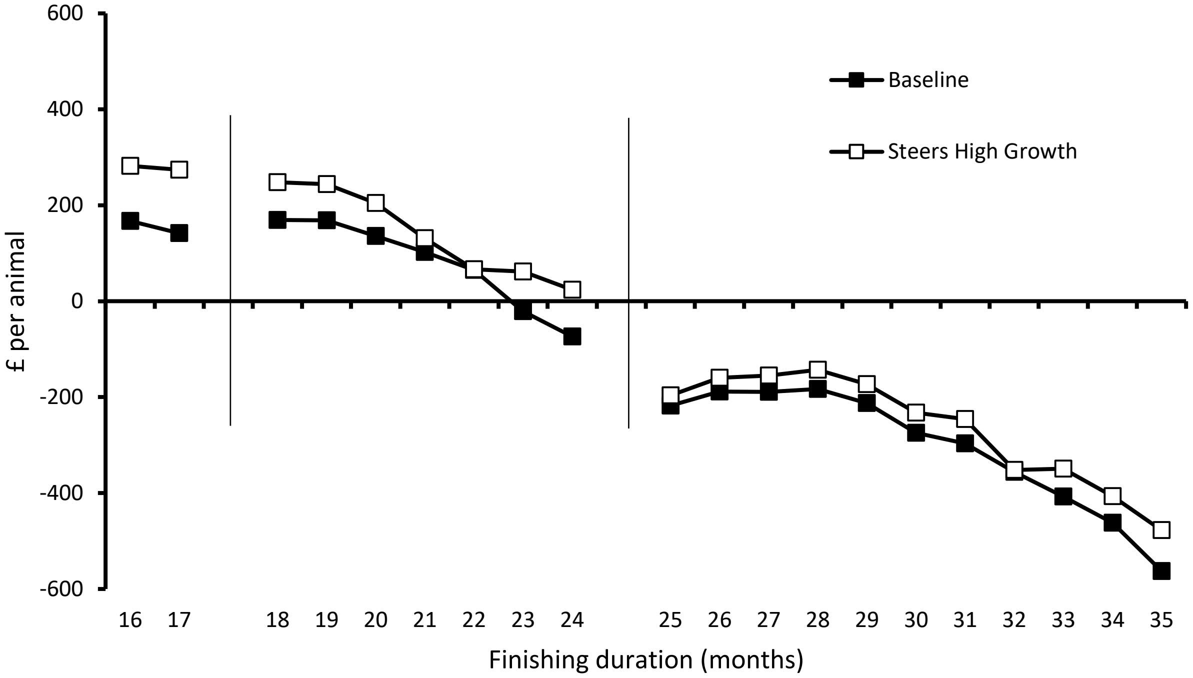

Figure 4. 7 *Comparison of financial performance in terms of net margins (£/animal) for average and high growth steer systems (effects of within-herd variation on profitability) (Scenario 4). Scenarios include a range of finishing ages for each of three distinct treatments, by which animals were finished at monthly intervals of 14-17, 18-24 and 25-35 months of age ('short', 'medium' and 'long').*

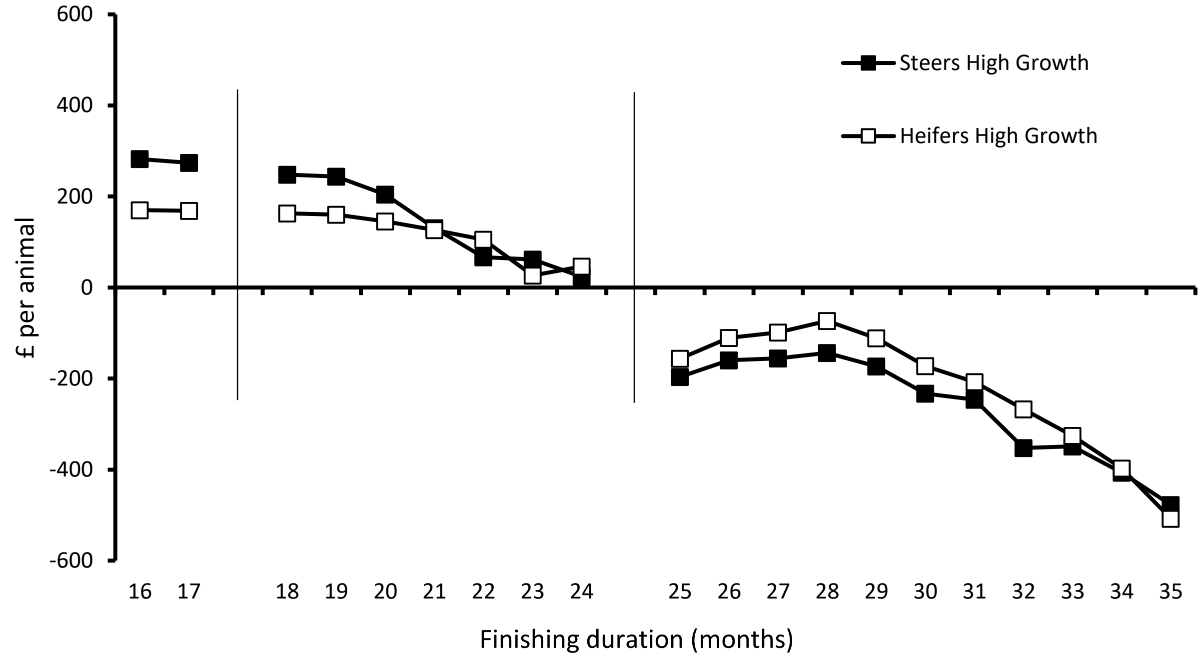

Figure 4. 8 *Comparison of financial performance in terms of net margins (£/animals) between steer and heifer systems with animals improved via intra-herd selection. Scenarios include a range of finishing ages for each of three distinct treatments, by which animals were finished at monthly intervals of 14-17, 18-24 and 25-35 months of age ('short', 'medium' and 'long').*

4.7.5 **Scenarios 5 & 6**

Distributions of net margin levels for 1000 simulations of 24-month steer systems, with or without the financial support provided by the state are presented in Figure 4.9. An enterprise without receiving economic aid was calculated to generate a loss of £69/animal, with a standard deviation of £52/animal. The likelihood of a farm making profit was only 9%. When financial support was included the mean shifted to producing a profit of £13/animal, with a standard deviation of £51/animal. After the incorporation of state economic relief, the probability of a farm recording loss was reduced to 39%. Following the same methodology, distributions of net margin for the 24-month heifer systems with and without financial aid were calculated. Results were similar with the steer systems, with the mean net margin for the examined scenario likely to be a loss. The probability of an enterprise recording positive net margins was as low as 2%. In contrast, when governmental fiscal aid was included only 33% of the simulation runs generated loses. Although these results look promising for both steers and heifers, there is still a significant chance that the system would record losses, even after the current level of financial support provided to beef enterprises was included.

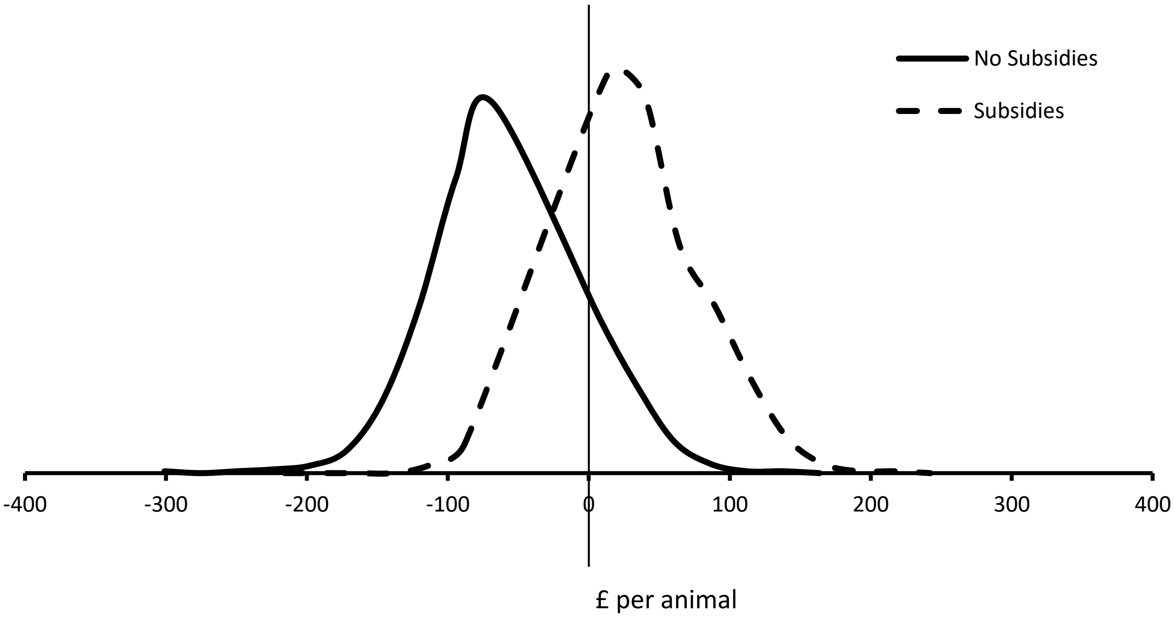

Figure 4. 9 *Results indicating the effect of support payments from the European Union of 24 months steer system. Enterprise performance in Scenario 5 and Scenario 6 was examined by employing stochastic analysis (Monte Carlo simulation). Similar results were obtained for the 24 month heifer system.*

Figure 4.10 reports the results of sensitivity analysis carried out for finishing heifers at 24 months on net margin change in response to a 25% variation in yearling price, concentrate cost and carcass value. Net margin calculated using the model values reported above resulted in a loss of £75/heifer. Further analysis revealed that the greatest effect on system profitability is attributed to carcass price variation. The effect of shifting carcass prices on net margin variance was £655/animal, while the effect of yearling costs and concentrates costs was £321 and £63 per animal, respectively. This analysis suggests that for the 24-month heifer system to generate a profit, yearling prices would need to decrease by 15%, carcass prices would need to increase by 10%, or there would need to be more than 25% decrease in concentrate costs.

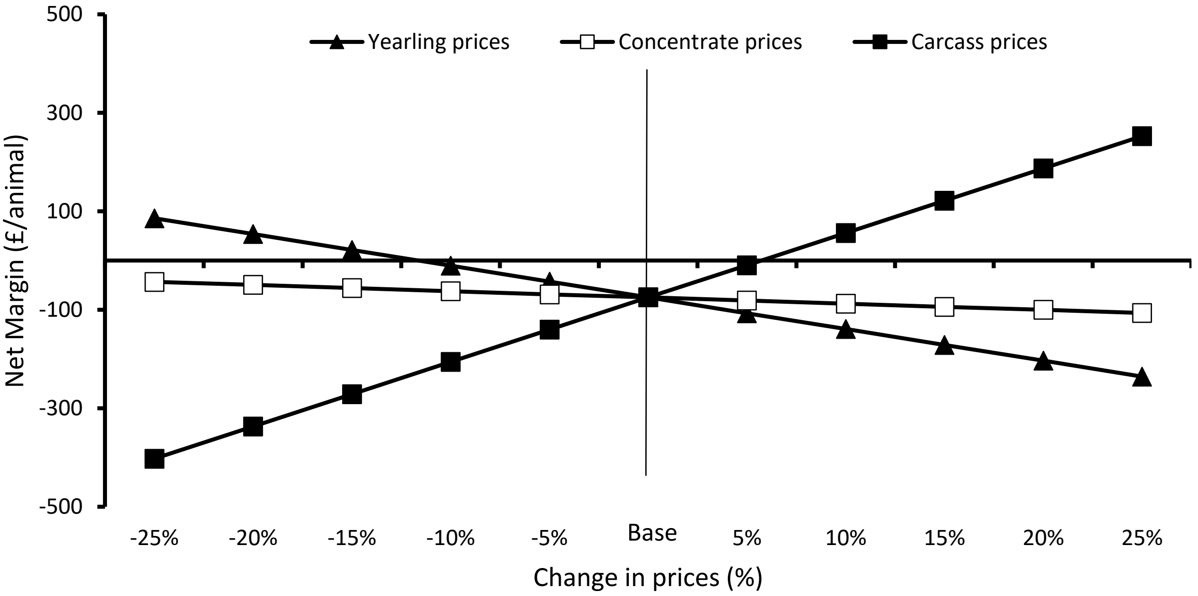

Figure 4. 10 *Sensitivity analysis studying the uncertainty regarding key input prices and the robustness of the GSBM. Results show the effects of variation in prices (yearlings; concentrates; carcass) on net margin from a 24 months heifer finishing system.*

4.8 Discussion

4.8.1 General discussion

A model for simulating beef finishing systems has been developed and Scotland was used as a case study. GSBM considers the complex relationships between enterprise efficiency, farm capacity, and animal performance. Several finishing systems relevant to Scottish conditions were simulated, and their financial performance was investigated under different economic scenarios.

Beef finishing operations decide on livestock to purchase considering the corresponding beef prices. Steer systems were found to be more profitable than heifer systems for continental breeds in Scotland. Continental steers tend to grow faster and producing heavier carcasses than heifers, resulting in a greater carcass output per area farmed (Steen and Kilpatrick, 1995). At the same time, heifers deposit fatty tissue quickly and it has a direct impact on their carcass profile and value (Keane and Drennan, 1987). The most cost-effective systems were the 18 and the 16-month slaughtering age for steers and heifers respectively. However, there are limitations to this simulation exercise, as the figures employed represent only one production cycle, due to restrictions on available datasets for Scotland. Another reason for caution is that in the current exercise grazing was excluded from shorter finishing duration systems, while a relatively large number of animals were assumed. All systems were based on the same available farming area, and simulate the most common slaughtering age options. Each system can be analysed in depth using the model highlighting its unique advantages and drawbacks, but these were considered to be outside the scope of this chapter, where the performance and accuracy of a new model are being discussed. For example, despite the apparent advantages of animal performance and profitability when mainly on concentrate based diets, there are niche markets for high-value products produced from grass-fed animals that could potentially offer higher returns. Consequently, opportunities for a region like Scotland may be found in the profitable medium-term finishing systems, where a proportion of grass is included in the diet as well (AHDB, 2016b).

When selecting for feed efficiency or including the current level of financial aid provided by the government, all systems benefited from the positive effect, while in some cases the influence proved to be critical, as it allowed systems to generate profit. Considerable genetic variation exists in beef cattle for feed efficiency, unaccounted for by differences in weight and growth rate (Fitzsimons et al., 2014; McGee, 2016). The use of a plausible decrease in animals' daily energy requirements derived from expert knowledge and guided by available literature may be considered inferior to a complex bio-economic model. However, instead of aiming for a detailed understanding of biophysical processes underpinning feed efficiency in cattle (Pitchford, 2004), this chapter investigates the potential range of variation in net margins associated with genetically select animals for feed efficiency changes for representative farms in a study region. Opportunities to improve the profitability of beef production systems occur when focusing on producing selection tools that incorporate biological and economic parameters to support breeding programs. Cattle that were bred for feed efficiency were found to have multiple benefits, such as decreased DMI, less manure production, and less emission of methane, thus; minimizing their environmental impact

(Cantalapiedra-Hijar et al., 2018; Fitzsimons et al., 2014; Hegarty et al., 2007; Nkrumah et al., 2006). Within-herd variation in animal growth rates had a substantial impact on the profitability of individuals. When comparing economic performance with the effect, margins increased noticeably for both steers and heifers, especially for the longer duration heifer systems. Although different breeds can be selected to optimize performance levels for growth traits more quickly than through selection within breeds, it might be a useful tool when used concurrently. It is argued that within-herd variation should have the largest long-term impact on genetic change for particular aims (Jakubec et al., 2003).

While, a system's performance may appear to be promising when applying average values, investigating its resilience and adaptability using stochastic analysis is crucial for gaining confidence in the predicted results (Villalba et al., 2006). During the analysis of the 24-month steer and heifer finishing systems, there were 39% and 33% chances of recording losses, despite adding basic grants. The rural schemes examined in this chapter were the Basic Payment Scheme available to Scotland along with the Greening payments; both part of the European Union Common Agricultural Policy (Pillar 1 - Direct payments). This study simulated the possible effects of changes in domestic policy agricultural policy, in the form of reinstating or maintaining a form of direct payments, would have on the profitability of beef finishing enterprises. The total abolition of CAP-related financial aid for Scottish beef farms presents only one of the factors that are considered to shape the future landscape of the UK's agri-sector. Measuring the possible consequences on agriculture is itself a complex and multifaceted task that requires extensive research in scenario developing (Davis et al., 2017; Feng et al., 2017; Harvey et al., 2019; Hubbard et al., 2018). It is worth noting that although there is some uncertainty associated with the UK leaving the European Union the UK government has pledged to keep overall payments to the same level until 2022 (SAC Consulting, 2017). These systems are highly reliant on direct payment schemes and given the economic status of agri-sector in Scotland, policy mechanisms should be in place to protect livestock systems from severe economic shocks.

4.8.2 Innovations of approach and other models

The GSBM facilitates a detailed economic analysis that leads to evaluating the performance of Scottish beef enterprises. This could contribute to developing a deeper understanding of complex relationships that govern beef production systems. This chapter builds on previous studies on feed efficiency by exploring the effects of breeding for feed efficiency along with the effects of within-herd variation on financial performance (Hill, 2012; Kenny et al., 2018). Furthermore, the knowledge gained could be employed to guide the design of novel systems, to be in a position to sustain self-sufficient and cost-effective enterprises. Afterward, the model could analyse the profitability of newly designed systems and compare them with the existing ones. By constructing and analysing a range of scenarios, GSBM supports a framework for investigating multiple effects of alternative policies, market and production conditions on profitability. This model simulates economic conditions for the livestock sector, while including a variety of options on genders, finishing ages and feeding strategies, to provide relevant flexibility when determining profitable systems or identifying areas that could cause a system to underperform. Also, the model supports sensitivity and Monte Carlo simulation analysis, while retaining the option of modifying input/output values as well as performance parameters.

4.8.3 Limitations of approach and future research

In principle, the GSBM is a general simulation model that can be employed for the evaluation of beef production systems in Scotland. Nevertheless, it is highlighted in the literature that simulation models are not able to represent a real system completely and hence, they will have to be constantly improved (Gradiz et al., 2007). In addition, when developing a general model there will be a trade-off between a more practical approach for less accuracy and precision (Hirooka et al., 1998). The model was able to take into account the variability created by fluctuation in prices. However, various areas that could significantly influence the model behaviour are yet to be fully studied and included, for example, animal performance, energy demands, grazed grass and grass silage yields.

Another constraint for the model was that the dataset employed, though it described typical Scottish systems, it included only one beef production cycle; therefore, limitations involve the exclusion of plausible year-to-year variation. Additionally, to further investigate implications of breed selection on farms' profitability, other breeds with different performance characteristics (e.g. Aberdeen Angus or Luing) should be included in the model.

Future research ought to focus on potential environmental factors and their effect on system profitability, an area of great interest in the last decades because of the collective effort to mitigate the greenhouse gas (GHG) emissions attributed to beef production sector (Bellarby et al., 2013; Foley et al., 2011; Lesschen et al., 2011). Beef production is considered to have a substantial environmental footprint, contributing around 41% of the entire livestock sector emissions (Gerber et al., 2015, 2013; Poore and Nemecek, 2018). Several studies point out to the fact that feedlot-based short-duration beef finishing systems have lower land requirements and GHG emissions per kilogram of meat compared to longer duration grass-based systems (Bragaglio et al., 2018; Capper, 2012; Nguyen et al., 2010; Peters et al., 2010). Nevertheless, grazing ruminant production systems provide ecosystem services (Dick et al., 2016), have a positive effect on long-term soil fertility (Horrocks et al., 2014) and a high potential for carbon sequestration (Conant et al., 2017), along with numerous health benefits that have been attributed to moderate consumption of grass-fed beef in comparison to concentrate-fed beef (Warren et al., 2008). The growing meat demand of an expanding human population, coupled with the challenges of global climate change, highlight the importance of exploring alternative beef production systems that have the potential to reduce environmental impacts from meat production and to guarantee long-term food security (Alexander et al., 2015; Eisler et al., 2014; Swain et al., 2018). The model described in this study has the potential to be employed in further livestock systems research for investigating environmental and economic scenarios, to enhance understanding of current systems and explore alternative strategies to address both low profitability and potential GHG mitigation.

4.8.4 Broader Implications

In this chapter, the region of Scotland was employed as a case study to demonstrate the capabilities of the GSBM. While in some cases, results from the GSBM were found to be relevant to beef production systems in other areas of the temperate climate zone, this approach focused on highlighting the region's unique conditions. However, the methodology employed to calculate the financial outcomes of beef finishing farms in GSBM was designed to be universally applicable. Inputs such as livestock live weights, growth rates and, ration composition will differ between regions, but the core methodology of the approach was not specific to a particular geographic region. Consequently, the same approach that was used to localize the model for Scotland could be employed to simulate beef finishing systems in other contexts and regions. In addition, GSBM could further assist the on-going efforts to breed cattle for feed efficiency, as it has the potential to examine scenarios simulating the effects of such efforts on farm profitability.

4.9 Conclusion

The GSBM simulated the physical and financial performance of Scottish beef finishing systems. It was demonstrated that it can be used to analyse current and future scenarios of interest. The model offers the user the opportunity to gain insights and tests various managerial options about the beef fattening stage. Profitable opportunities for finishing late-maturing cattle in Scotland were identified by investigating alternative finishing durations for different systems. It was more cost-effective to finish cattle on shorter or medium-duration systems.

Another crucial decision with economic impact would be the choice of livestock gender. Steers were more profitable than heifers on most occasions, especially for the short- and medium-length systems. In addition, the range of profit that specialised breeding could deliver to farmers was presented for different systems via simulating the effects of improving the cattle's feed efficiency and within-herd performance variation. These insights could contribute to making an informed decision regarding aspects of beef production that are under the farmer's control.

It is anticipated that the model will be employed to construct agricultural policy, as well as market and production-related scenarios. The model identified the level of dependence on the EU's financial aid, along with the effects of carcass and store price volatility on profitability for the most popular fattening systems in Scotland. It becomes pressing in the face of the latest political developments to further investigate the sector's dependence on receiving governmental fiscal support and adopt systems that would prove more reliant and well-adjusted to each region's strengths. Therefore, model outcomes could be then used to reduce costs or increase productivity to make systems more profitable. The methodology described can be employed to tailor the model for other regions.

Chapter 5: Modelling alternative management scenarios of economic and environmental sustainability of beef finishing systems

After article: Kamilaris, C., Dewhurst, R.J., Sykes, A.J., Alexander, P. (2019). Modelling alternative management scenarios of economic and environmental sustainability of beef finishing systems. Journal of Cleaner Production (in-press). See List of Publications.

5.1 Introduction

Greenhouse gas (GHG) emissions have gained attention due to their effect on the global climate. The role of GHG emissions in climate change and the urgency to mitigate its adverse effects to avoid further temperature rise has been highlighted during the United Nations Framework Convention on Climate Change, the Kyoto Protocol and the Paris Agreement (IPCC, 2013). Agricultural activities related to food supply chains are considered to have substantial environmental impact accounting for 26% of all anthropogenic GHG emissions, while non-food agriculture and other drivers of deforestation contribute a further 5% (Frank et al., 2017; Poore and Nemecek, 2018; Tubiello et al., 2015). The livestock sector has been associated with the main gases linked to climate change, i.e. carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Steinfeld et al., 2006), and its emissions represent an estimated footprint of 7.1 gigatonnes (Gt) CO_2-eq per annum, or 14% of all human-induced emissions (Gerber et al., 2013; Rojas-Downing et al., 2017). Within the livestock sector, the cattle industry, with over 1.3 billion cattle globally, accounts for 65% of sector emissions (4.6 Gt CO_2-eq) (Gerber et al., 2015, 2013). Beef production attracts more attention than dairy production since it contributes around 41% of the total sector emissions (2.9 Gt CO2-eq) (Gerber et al., 2015, 2013; Poore and Nemecek, 2018). Additionally, beef cattle are considered responsible for 54% of the global enteric CH_4 emissions and are currently the largest contributor of manure NH_3 emissions, accounting for 41% of all animal sectors (Wang et al., 2018).

Nonetheless, beef is a valuable commodity, as it provides high-quality protein to consumers and consistent income to producers (FAO, 2011). Global food security trends showed an increase in the absolute number of undernourished people in the world to 821 million in 2017, following a growing trend over the last years, returning the share of people suffering from hunger to levels recorded a decade ago (FAO, 2018). Meat is an important source of high-value protein and micronutrients; thus, inclusion of even small quantities on a diet could improve the nutritional status of undernourished populations, by addressing micro- and macronutrient deficiencies, particularly of children, pregnant and lactating women (Biesalski, 2005; FAO, 2011; Scollan et al., 2006). Additionally, global demand for beef as a protein source is increasing, driven mainly by the expected population growth, the rapid pace of economic development and the "westernisation" of diets in Asian and surrounding countries (Alexander et al., 2015; Godfray et al., 2010; Smith et al., 2018).

Several studies proposed decreasing the amount of meat in current global diets, as a measure to reduce the environmental impacts of food production (Aleksandrowicz et al., 2016; Springmann et al., 2018). However, considering the scale of beef's environmental footprint and projected growth in meat demand, other pathways should also be investigated in the effort to reduce adverse global effects. Feedlot-based finishing systems have lower land requirements and GHG emissions per kilogram of meat (Bragaglio et al., 2018; Capper, 2012; Nguyen et al., 2010; Peters et al., 2010). Nevertheless, such intensive production practices are amongst the least efficient use of human-edible legumes and cereals in the agri-food industry, while raising concerns over routine use of antibiotics, pollution from manure, and animal welfare (Opio et al., 2013; Swain et al., 2018). Grazing ruminant production systems utilise land unsuitable for arable crop production, whilst converting forages to human protein sources without driving the food-feed competition for resources (de Vries et al., 2015; Wilkinson, 2011). The growing food requirements of an expanding human population, coupled with the challenges of global climate change, press towards exploring alternative beef production systems that have the potential to reduce environmental impacts from meat production and guarantee long-term food security (Eisler et al., 2014; Swain et al., 2018).

Post-2020 climate change related policies adopted after the Paris Agreement (Hof et al., 2017; Rogelj et al., 2016) employed a methodology based on the Intergovernmental Panel on Climate Change (IPCC) guidelines for quantifying and reporting national greenhouse gas emissions (IPCC, 2013, 2006). Since beef systems are complex systems, with inter-relating components like soils, crops, feeds, animals and manures, optimal GHG mitigating strategies will depend on local conditions requiring explicit individual management approaches to identify specific entry points and evaluate mitigation opportunities (Del Prado et al., 2013). Models and predictive tools have been developed to estimate GHG emissions from livestock systems (Del Prado et al., 2013), based on process simulation modelling (Schils et al., 2007), emission factor calculation (Amani and Schiefer, 2011) and life cycle assessments (LCA) (Cowie et al., 2012; de Boer et al., 2011; de Vries and de Boer, 2010). Several attempts, either empirical or mechanistic (Jose et al., 2016; Kebreab et al., 2008), to predict beef cattle GHG emissions, were based on research with cattle in temperate climates (Ellis et al., 2009; Escobar-Bahamondes et al., 2017; IPCC, 2006; Kebreab et al., 2006; Yan et al., 2009). A key barrier to mitigate emissions from beef production systems is regional and local variation in conditions and production practices, leading to a complicated and problematic process of capturing an optimum value (Opio et al., 2013).

The concept of sustainability for livestock farms is a wide-ranging notion that encompasses economic, social and environmental dimensions, taking into account a great number of factors (e.g. GHG emissions, eutrophication, groundwater pollution, working conditions, profitability, animal welfare, etc.) (Galioto et al., 2017; Van Calker et al., 2005). Currently, more emphasis has been placed on environmental sustainability of farming systems, aiming to minimise GHG emissions and their impact on nature, but the main primary focus and principles of sustainability is sensitive to changes over time and location, as social values evolve and differentiate (Boogaard et al., 2008; Oudshoorn et al., 2011). Nevertheless, economic viability will always be necessary for a sector to be sustainable, and so it is important to consider profitability alongside any livestock environmental assessments (Oudshoorn et al., 2011).

Here we investigate the environmental impact of a range of beef finishing systems, as well as the trade-offs generated between mitigating emissions and increasing farm profitability, using Scotland as a case study. We combine a bio-economic simulation model (Grange Scottish Beef Model) and a farm-level GHG footprinting tool (AgRE Calc) focused on temperate grassland-based beef systems. Environmental and economic scenarios were explored to enhance understanding of current systems and explore strategies to address both low profitability and potential GHG mitigation. The novelty of this study lies in the way it utilised and combined two distinct models to develop a common methodology for investigating GHG emissions and profitability in beef farms, offering insights by analysing various scenarios for the beef finishing stage.

5.2 Materials and Methods

5.2.1 Model description

5.2.1.1 Grange Scottish Beef Model

The Grange Scottish Beef Model (GSBM) is a static bio-economic simulation model that was specifically developed for studying the finishing phase of the beef production cycle. GSBM consists of four sub-models, i.e. the farm system, animal nutrition, feed supply, and financial performance. The farm system sub-model simulates the beef finishing system and calculates on a monthly time-step the animal numbers, housing requirements, and slurry production during the indoor period, whilst the animal nutrition sub-model controls the energy demand and feed requirements of the modelled herd. The feed supply sub-model regulates the forage system which calculates the grazed grass and grass silage production of the farm, and the financial sub-model calculates the economic performance of the beef fattening enterprise. The model was then used to investigate the technical and economic performance of the most common beef production systems in Scotland.

Production systems modelled were based on the “Lifetime growth pattern and beef eating quality” (“Growth Path”) project that represented systems typical of commercial practice for the UK and Scottish farms, previously reported by AHDB Beef & Lamb (Hyslop et al., 2016). During the study, all animals representative of the Limousin crossbred beef cattle genotype experienced three different treatments that led to three distinct “growth-paths” (Hyslop et al., 2016). The six production options modelled represent short, medium and long finishing treatments along with two genders (steers and heifers), reproducing the continuous experimental design of the Growth Path trial. Scenarios involving finishing either male or female animals at a range of finishing ages for each of three distinct treatments, whereby cattle were slaughtered at intervals of 16-17, 18-24 and 25-35 months of age (‘short’, ‘medium’ and ‘long’ durations respectively). Land area was set to 120 ha, typical for a beef finishing farm in Scotland. Likewise, the inorganic nitrogen input on the grazing area was fixed at 175 kg N/ha across the different systems. All livestock were purchased as yearlings at 12 months of age and the number of animals was matched to land area and forage production. For the shorter duration finishing systems, only one silage cut harvest date was modelled, on 29th May. The one-cut silage system assumes poor utilisation of the forage production area, which is typical for beef systems with animals housed throughout the finishing period. In contrast, for the medium and longer pasture-based systems, two silage cuts were assumed with 6 weeks of regrowth. An extended summary of the GSBM containing additional information regarding the creation, evaluation and validation processes is included in the Supplementary Material.

5.2.1.2 **AgRE Calc**

The Agricultural Resource Efficiency Calculator (AgRE Calc) was developed as part of the Scottish Government's Farming for a Better Climate initiative by the consulting division of Scotland's Rural College (SRUC) and has been previously described by Sykes et al. (2017). The carbon footprint tool was developed in alignment with IPCC (2006) Tier I and II methodology and is PAS2050 certified (IPCC, 2006; Sykes et al., 2017). AgRE Calc employed IPCC (2006) Tier II methodology to estimate emissions stemming from livestock and manure management, whilst IPCC (2006) Tier I methodology is used to calculate N_2O emissions from fertiliser applications and crop residues (IPCC, 2006). The model considers embedded emissions from the production of fertilisers, which were calculated using emission factors (EFs) from (Kool et al., 2012), while embedded emissions for imported feed and bedding were calculated according to Vellinga et al., (2013). Emissions from electricity and fossil fuels were estimated using emission factors from DEFRA/DECC (2011) Conversion Factors for Company Reporting (Sykes et al., 2017). Results include an analysis detailing separate emission types and sources.

5.2.2 The synthesis of the Grange Scottish Beef Model and AgRE Calc

The bio-economic model (GSBM) and farm-level carbon footprinting tool (AgRE Calc) were combined to simulate typical beef production systems in Scotland. Scenarios that replicate current production systems were developed in GSBM and the results produced were then introduced to AgRE Calc to provide estimates of emissions intensity for animals within the finishing systems (Figure 5.1). One of the key challenges during the process of linking and coordinating the two models was to establish a common time step that could be used for recording results. By taking advantage of the flexible design of GSBM, it was possible to break down each system on a monthly basis and then generate the carbon footprint through AgRE Calc on the same basis. This level of detail, assessing dietary and performance parameters at the herd level for a monthly time-step, allowed the carbon footprint results for different finishing durations to form a statistically comparable dataset. Furthermore, Microsoft Visual Basic for Applications (VBA) was used to optimise the linkage between the two models, as well as to automate the footprinting process. Data collected from the amalgamation of the two models, provided the basis for comparison of different durations and types of finishing, identifying sustainable methods of beef production in Scotland.

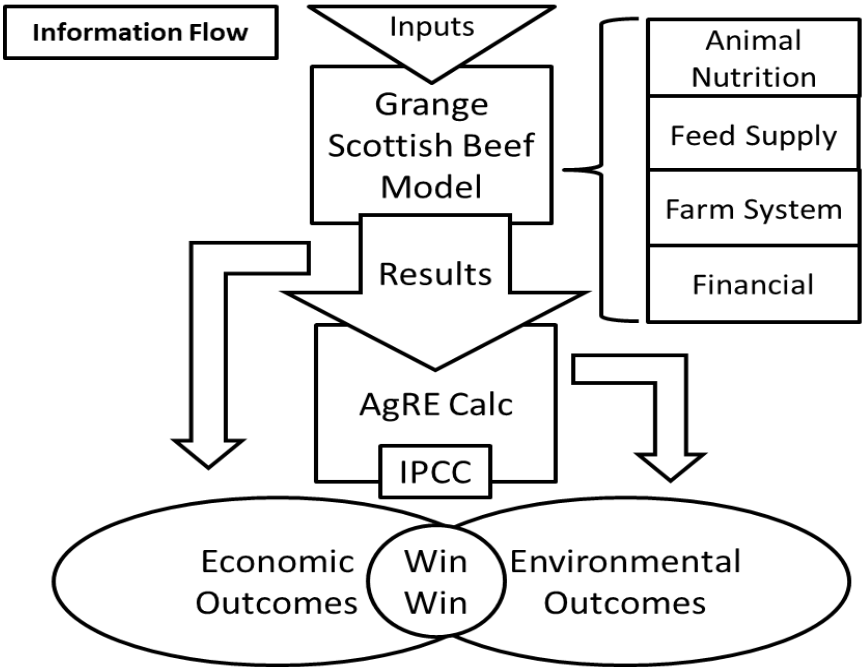

Figure 5. 1 *Information flow between the two models and output representation.*

Subsequently, results from the GSBM simulation model were adopted as input values to AgRE Calc to calculate the GHG emissions of different beef finishing systems. To examine the impacts of factors such as fattening duration, type and gender selection on emissions intensity, broader categories that included emissions with interconnected sources were established. Five groups were identified; land and crops (N_2O, CO_2 and embedded), enteric emissions (CH_4), manure (CH_4 and N_2O), feed and bedding (embedded) and fuel and electricity use (CO_2 and embedded). Land and crops represented primarily N_2O emissions, grouping emissions from crop residues, fertiliser application (organic and inorganic) or (manure from farm and synthetic), lime and urea, as well as embedded emissions from fertilizer and lime. Enteric methane included the methane emissions from livestock's enteric fermentation process. The manure category consisted of methane emitted during the anaerobic decomposition of organic matter while in storage and nitrous oxide emitted during storage and soil application. Finally, the feed and bedding category included the embedded emissions from feed and bedding, while fuel and electricity considered CO_2 and embedded emissions from diesel, electricity and other fuel, as well as the embedded emissions from transporting and disposing of carcasses.

5.2.3 System boundary

This study focuses on the fattening stage of beef production, comparing different systems and management practices. A “gate-to-gate” approach was adopted, where the main costs concerning the post-weaning period of cattle production until slaughtering the animals were included in the model (Berton et al., 2016; Mahath et al., 2019; Ogino et al., 2004). The finishing phase was defined as beginning with the purchase of yearling cattle (either 10 or 12 months old) and ending with the marketing of finished animals (16 to 35 months of age). The beef finishing cycle also included activities like pasture management, feed (silage) production, feed transport, animal management, and cattle waste treatment (Figure 5.2).

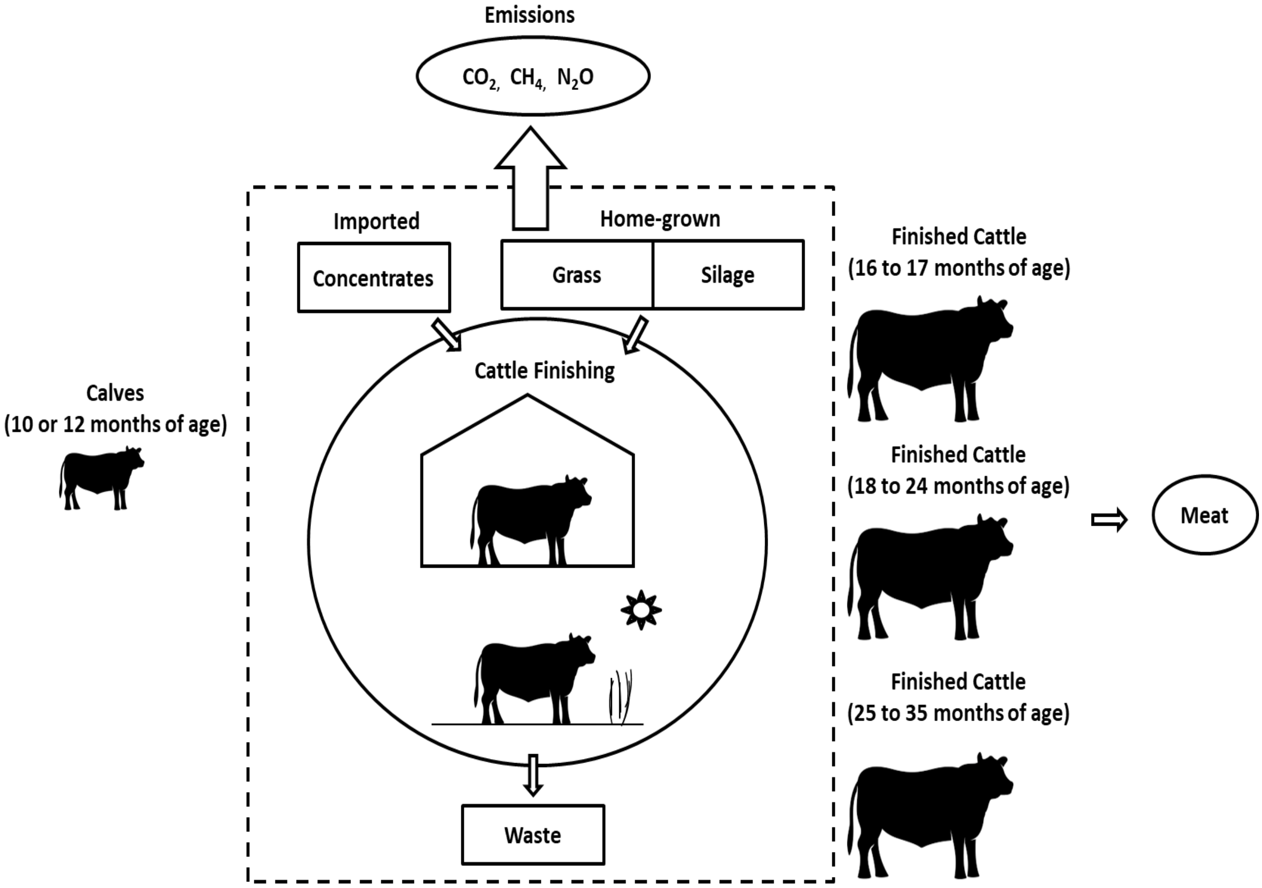

Figure 5. 2 *Graphical illustration of the Scottish beef finishing system's alternative pathways examined in the current study.*

The systems examined here did not include the cow-calf phase, even though it is recognised to have the main impact on the total carbon footprint associated with beef production, regardless of the finishing strategy (Pelletier et al., 2010). One cow will produce one calf per year; thus for every animal entering the finishing stage a mature cow, along with replacement heifers and bulls, is retained. This aspect doubles the resource requirements and emissions per live-weight kg of beef produced in the system (Phetteplace et al., 2001). The study assumed that all animals were treated in the same way prior to entering the system and were randomly assigned across alternative management regimes (Hyslop et al., 2016), so excluding this stage from the calculation of lifecycle emissions intensity does not affect the relative ranking of systems. In addition, by excluding this part from the model, the variations in the economic and environmental performance of finishing systems become independent from early-life performance of calves, which is affected by the mothers' body condition, and cannot be fully attributed to management strategies (McAuliffe et al., 2018). The aim was to further explore factors during the beef finishing stage, such as finish duration, diet, and gender, which have been identified as significant determinants of emissions intensity (Ogino et al., 2004). As such, several factors were studied through scenarios designed to provide a comprehensive assessment of beef finishing systems in Scotland, with an emphasis on identifying key features that contribute to emissions mitigation.

5.3 Scope of the Study

5.3.1 Factors

5.3.1.1 Finishing duration

Several factors have been identified as having a key impact on the emissions intensity of production, including the duration of the finishing period. Most studies comparing production strategies and various finishing durations reported that shorter periods represented better efficiency from the perspective of GHG emissions (Casey and Holden, 2006; Pelletier et al., 2010). However, studies following alternative approaches showed longer finishing systems with low inputs, to be more environmentally efficient in comparison to more intensive approaches (Subak, 1999). Scenarios modelled involved finishing animals at a range of finishing ages for each of three distinct treatments, whereby cattle were slaughtered at monthly intervals of 16-17, 18-24 and 25-35 months of age (‘short’, ‘medium’ and ‘long’ durations respectively) (Hyslop et al., 2016). To examine the effect of varying finishing periods on emission intensity, the relative contribution of different sources to the absolute GHG emissions of systems are presented for heifer finishing systems. Results provided insights into the effects of duration of finishing on a monthly time step for the financial and environmental performance.

5.3.1.2 **Finishing type and diet**

Global beef production systems demonstrate additional complexity, since many systems, particularly in the northern hemisphere’s temperate zones, display a highly seasonal nature (Opio et al., 2013). In temperate climates, it is common for animals to be housed during the colder or wetter part of the year (Beauchemin et al., 2010; Casey and Holden, 2006). This seasonal movement between housed and grass-based situations represents a distinct change in diet and activity levels and is different from the feedlot-based diet treatments. These changes in diet regimes affect animal performance and impact the carbon footprint of finishing systems (Pelletier et al., 2010). The effects of housing type (housed/pasture) and diet (concentrates/grass) on total GHG emissions were explored and reported on a monthly basis. When the animals were housed, they were fed mainly concentrate-based diets, while when out on pasture they grazed perennial ryegrass swards

Diet is a key driver of the carbon footprint and the amount of GHGs emitted from beef cattle, particularity at the finishing stage (Beauchemin et al., 2010). During the finishing stage, feeding treatments that include substituting roughage with concentrates result in reduced enteric methane (CH_4) production by lowering the pH of the rumen and switching fibre for starch (Knapp et al., 2014). However, producing concentrates for feed is also emissions-intensive, resulting in potential trade-offs between enteric CH_4 and land-based N_2O emissions (Hünerberg et al., 2014). Nutritional strategies to decrease cattle emissions usually depends on interactions between the production of enteric CH_4, rates of liveweight gain (LWG), and emissions generated in the production, as well as processing and transport of concentrates, leading to uncertainty regarding the most efficient approach to finishing beef cattle (Beauchemin et al., 2008). It is also evident that feeding approaches could achieve a reduction of methane emissions, especially when combined with genetic and management approaches (15-30%) (Knapp et al., 2014). Simulation results enabled the investigation and comparison of scenarios involving both feedlot- ("short") and pasture-based ("medium" and "long") diets use through different finishing systems (Hyslop et al., 2016).

5.3.1.3 **Gender selection**

Differences in animal performance between steers and heifers have been previously presented, with steers consuming more feed, growing faster, and more efficiently than heifers, resulting in contrasting carcass outputs per area farmed (Koknaroglu et al., 2005; Steen and Kilpatrick, 1995). However, recent studies found notable differences between genders in emission intensities, with steers producing lower emissions than heifers (McAuliffe et al., 2018). The model includes both steer and heifer systems for the simulation, to capture the magnitude of gender effects in Scottish beef finishing systems. Simulation results enabled a comparison between genders, to identify differences in performance for each finishing age.

5.3.1.4 Farm profitability in relation to greenhouse gas emissions

In order to examine the essential relationship between an enterprise's cost-effectiveness and carbon footprint performance, financial results previously generated from the GSBM for the corresponding beef finishing systems were employed (Kamilaris et al., 2019). An analysis of the profitability of each system was performed alongside each system's total emissions, and the two main GHG emission categories, namely the land and crops, as well as the enteric emissions groups. Lower financial returns were evident for the longer finishing systems, with the largest losses reported for the 35-month finishing system. The most profitable systems were the medium finishing at 18 months for steers and the short finishing at 16 month systems for heifers. For the short-duration systems, the diet was set to include only silage and concentrates; thus, the model assumed that these types of systems could sustain a great number of animals, representing larger intensive feedlot-type beef finishing enterprises. Overall, the systems that generated profit were the short- and most of the medium-duration finishing systems for both steers and heifers (Figure 5.3).

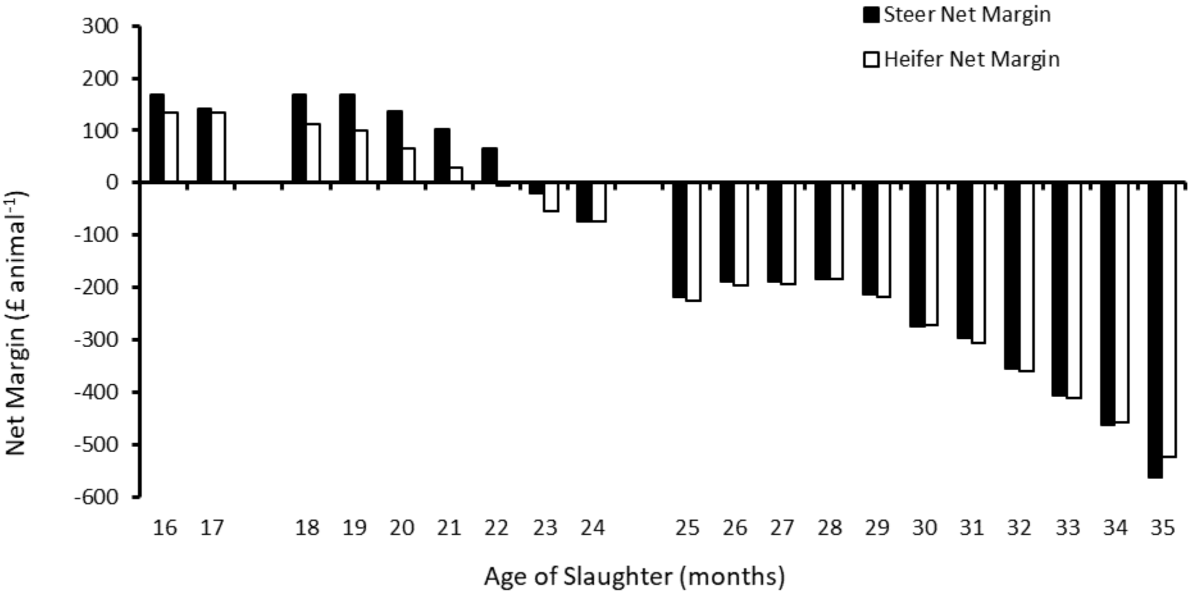

Figure 5. 3 *Comparing profitability (£/animal) for steer and heifer enterprises (adopted from Kamilaris et al., (2019).*

5.4 Results

5.4.1 Effects of finishing duration

Figure 5.4 shows the relative contribution of different sources to the absolute GHG emissions of heifer finishing systems. In all systems examined, the dominant emission source was enteric fermentation. Common trends occur for different systems, particularly in terms of the relevant contribution of land and crops as well as enteric methane emissions to the total of systems' GHG emissions. For the land and crops category, a trend for an increasingly large contribution over time was noted, while the opposite tendency resulted in emissions from livestock enteric fermentation on finishing systems. The feeding and bedding category contributed more to short-duration systems (16-17 months), as these represented more intensive methods of production, compared to the medium (18-24 months) and long-duration finishing systems (25-35 months), where the relative contribution was reduced. Manure emissions remained relatively stable for all systems over time, while the fuel and electricity category increased with duration.

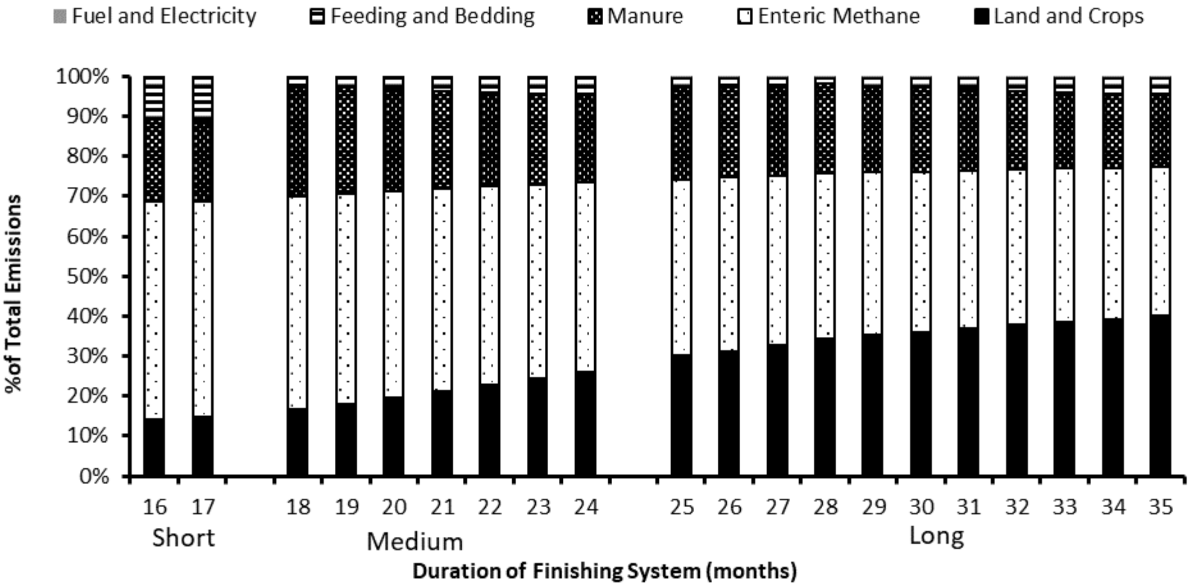

Figure 5. 4 *Relative contributions of different emission categories to the total GHG emissions from heifer finishing systems.*

5.4.2 Effects of finishing type and diet

Analysis revealed a strong relationship between LWG (kg day^{-1}) and emissions intensity (CO_2-eq kg LWG^{-1}) for each treatment (Figure 5.5). It was evident that when LWG was low, which is typical for cattle during grazing periods, high levels of GHG emissions were observed. On the contrary, for high levels of growth, livestock systems with housed cattle had fewer total emissions. Furthermore, for LWG, around one kg per day, the gap in emissions intensity between housed and grazing systems effectively closed. It is key to focus on systems that facilitate animals achieving a relatively high LWG while on pasture as the environmental impact was significantly lower than similar cases with low LWG. Results generated can be related to experimental data obtained by other UK studies, by employing the linear regressions produced (McAuliffe et al., 2018).

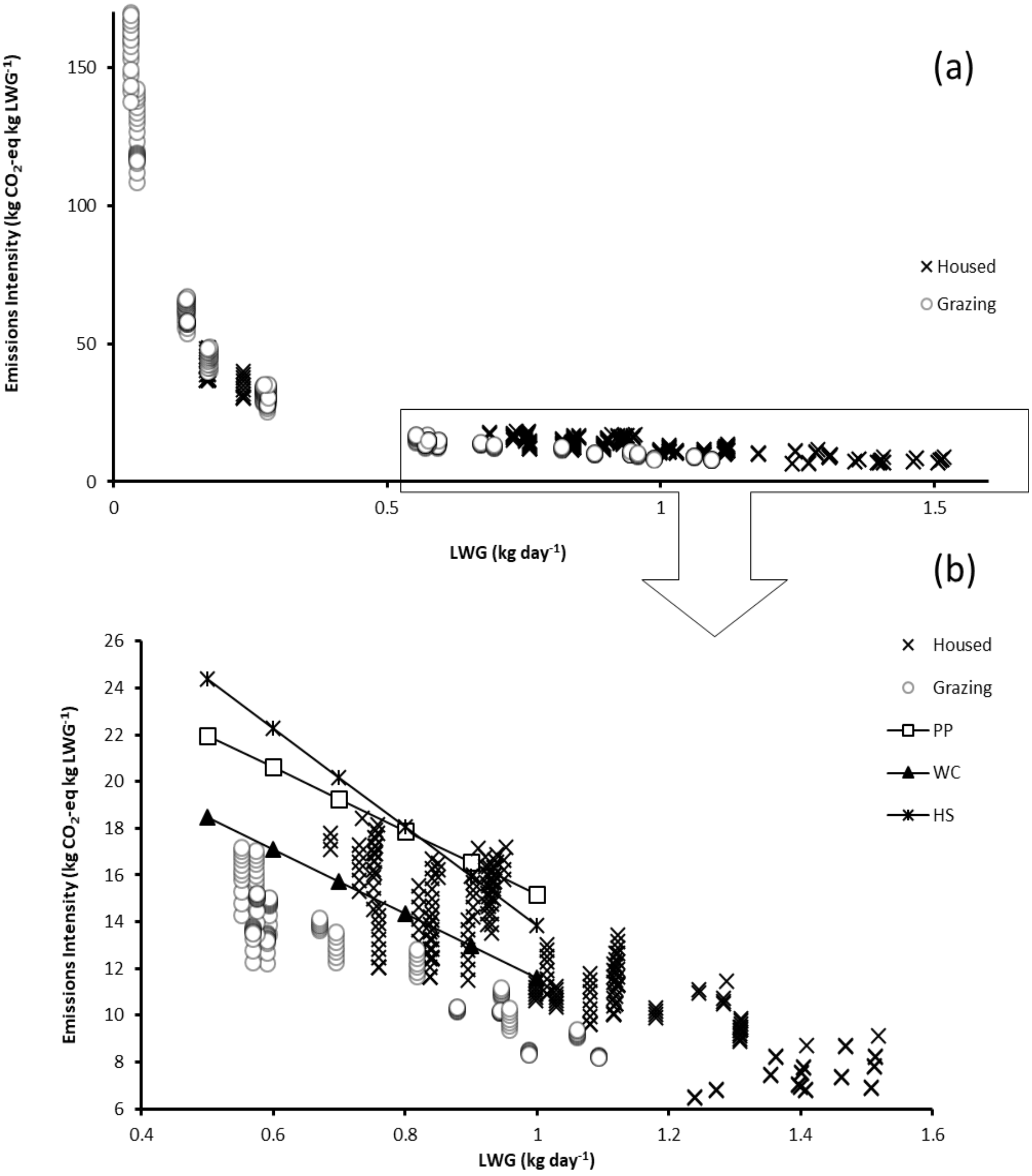

Figure 5. 5 **(a):** *Relationship between Total emissions Intensity and animal LWG under two different types (housing/pasture) and diets (concentrates/grass) of finishing. Each data point presented in the panel corresponds to a single month within a single system. Housed cattle were on concentrate-based diets; else, they were grazing on permanent perennial ryegrass swards,* **(b):** *Comparison of emissions intensity for a range of live weight gains from 0.5 to 1.5 kg per day, between results generated from the combination of GSBM and AgRE Calc with linear regressions models taken from McAuliffe et al., (2018). The three linear regressions represent data acquired from cattle finished under different pasture management systems with swards of permanent pasture (PP), white clover (Trifolium repens)/high sugar perennial ryegrass (Lolium perenne) mix (WC), and high sugar perennial ryegrass monoculture (HS).*

5.4.3 **Effects of gender**

Results for total GHG emissions produced on systems simulated to finish exclusively either steers or heifers are reported in Figure 5.6 (Supplementary Material). For the two short-duration systems at 16 and 17 months, the steer systems resulted in slightly higher emissions intensities than heifer. For the remaining systems of medium- and long-duration, a shift was observed with heifer systems surpassing the steer systems in terms of total GHG emissions. Finishing female animals on less intensive systems, from 18 to 35 months appeared to be less environmentally efficient than the corresponding fattening systems that were simulated to finish steers.

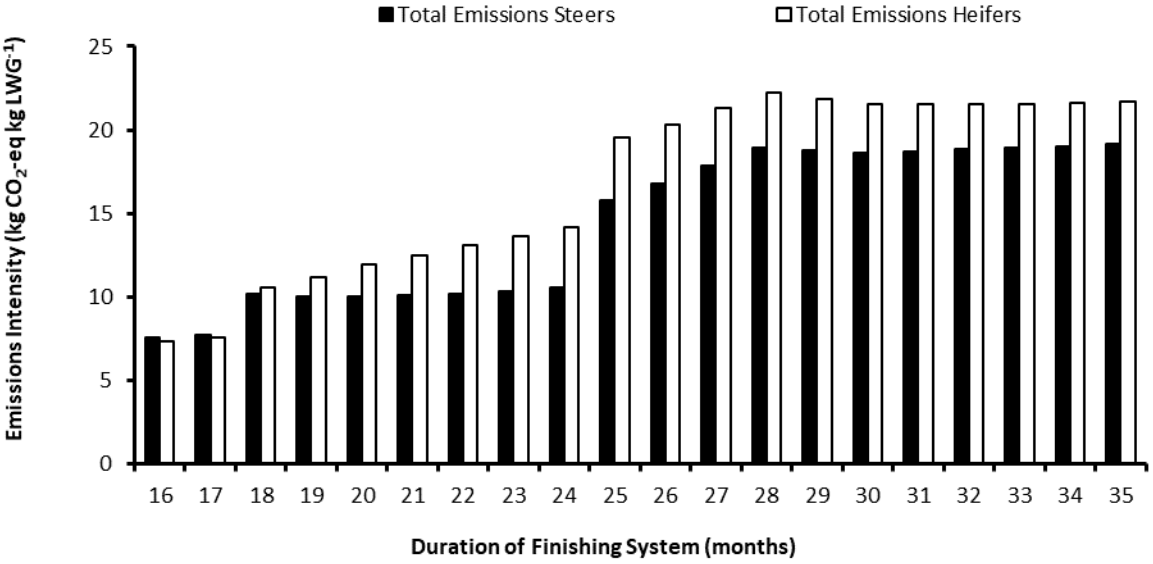

Figure 5. 6 *Comparison between the emissions intensity of steer and heifer finishing systems.*

5.4.4 Effects of farm profitability in relation to greenhouse gas emissions

Figure 5.7a shows the relationship between the land and crops emissions and profitability. Particularly, for the medium- and long-duration systems, the emissions from land and crops were higher as the cost-effectiveness decreased. As a result, the longer duration less profitable systems recorded higher land and crops emissions. Figure 5.7b shows the association between emissions intensity from cattle enteric methane emissions and the farm’s net margins for every system. Two distinct groups appeared on this figure, for both steers and heifers, one included the long-duration systems and the other the medium and the short-duration systems. The medium and short-duration systems performed better on profitability, but showed increased enteric methane emissions compared to long-duration systems. Finally, in Figure 5.7c, the relationship between the carbon footprint evaluation, measured with the total GHG emissions, and the cost-effectiveness analysis of the systems considering the financial aspect of the rural producer, expressed as the net margin of an enterprise is shown. Here, after grouping results for different systems (short, medium, long), a negative relationship was revealed for each category of finishing systems (e.g. “short”, “medium”, “long”), where lower emissions were associated with higher profitability.

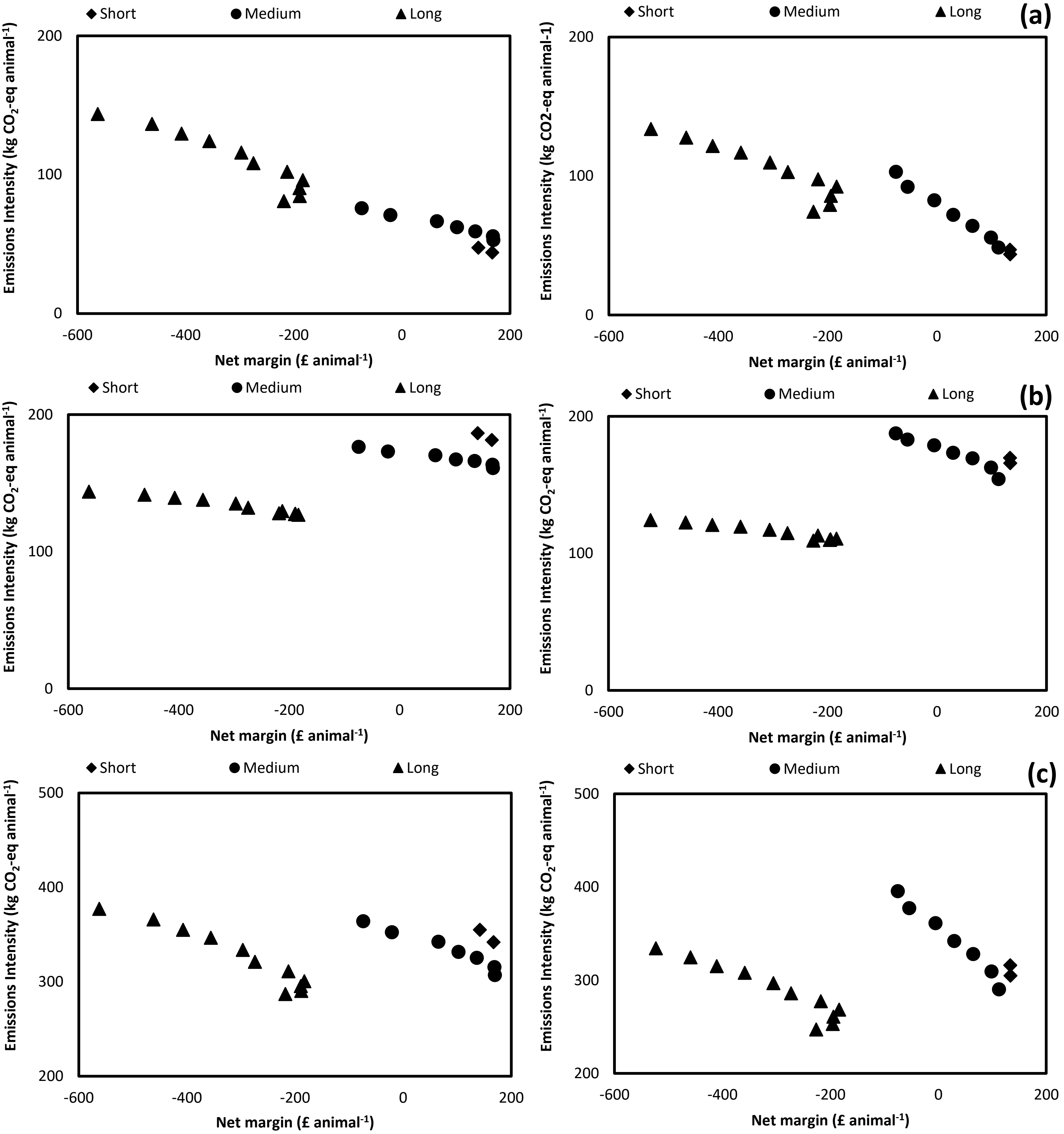

Figure 5. 7 *Relationship between farm's profitability and:* **(a):** *Land and Crops emissions for steer (left) and heifer (right) finishing systems,* **(b):** *Enteric CH4 emissions for steer (left) and heifer (right) finishing systems,* **(c):** *Total emissions for steer (left) and heifer (right) finishing systems.*

5.5 Discussion

5.5.1 General discussion

The long extensive systems ("long") have a greater environmental impact when compared to both intensive housing systems ("short") and medium duration grazing-based approaches ("medium"). These findings were in accordance with other studies on livestock systems emissions, which reported shorter finishing periods could reduce emissions (Cardoso et al., 2016; Casey and Holden, 2006). This outcome was driven mainly by the greater land and crops emissions produced in the longer duration systems, for both steers and heifers. A conclusion linked with findings from recent studies, which confirmed that intensive finishing systems tend to display a lower land use intensity than extensive, pasture-based systems, even after the crop production area for feed was included (Bragaglio et al., 2018; Capper et al., 2012). Forage and concentrate feeding during the finishing stage accelerates growth and allows more beef to be produced per unit grazing area (Swain et al., 2018). Additional reasons include the lower requirements for inorganic N fertiliser in short and medium systems (McAuliffe et al., 2018). In addition, livestock methanogenic emissions from the rumen were the single greatest source of GHG emissions for most of the systems, in consonance with other studies on beef production systems (de Vries et al., 2015). It is worth noting that, in the last three long-duration heifer systems (33, 34 and 35 months), emissions from land and crops surpassed those of enteric CH_4.

At growth rates around 1 kg per day, animals performed similarly in terms of emissions intensity, regardless of the finishing type and diet. These findings indicate that high-input grass-based systems with quality pastures supporting high-growth rates have a low environmental load that is analogous to that for intensive concentrate-based systems with the similar growth rates. Results from this study were compared with similar findings from McAuliffe et al., (2018). Slight differences between emissions intensities were noted, with lower values reported in this study. These differences could be attributed to animal physiology expressed through different genotypes of cattle measured in each study (i.e. Limousin and Aberdeen Angus two-breed reciprocal crosses (Kamilaris et al., 2019) in contrast to Charolais x Hereford-Friesian cattle (McAuliffe et al., 2018)), along with the effects of variability in grass quality.

Differences were noted between the two genders in terms of emissions intensity for all systems examined. Systems that finished steers had significantly lower emissions intensity than those with heifers, in agreement with other studies (McAuliffe et al., 2018). It was hypothesised that part of this difference was due to the fact that continental steers tend to grow faster, producing heavier carcasses and meeting the carcass specifications more easily (Steen and Kilpatrick, 1995); while heifers tend to deposit fatty tissue more quickly, which has a direct impact on their carcass profile (Keane and Drennan, 1987). These results could be linked to the concept that dairy beef production models, focused on rearing and finishing more males than females, may prove to be more sustainable livestock systems (de Vries et al., 2015). However, further research is needed prior to designing novel systems, taking into account issues like the implications of bull rearing as well as the typical lower growth rates of the dairy breeds compared to beef cattle breeds for each treatment and specific environment (McAuliffe et al., 2018).

While investigating the relationship between a farms' profitability and environmental performance, results reveal two distinct groups for both steer and heifer systems; one includes the long finishing period systems and the other the short- and medium-duration systems. Longer period grazing systems appear to have low emissions per animal but score low in profitability with negative net margins in all cases. In contrast, most of the medium and all of the short-duration systems appear profitable but show higher emissions intensity. In the search for a solution that could satisfy high profitability and sustainable environmental performance, attention is directed towards those high input grazing medium duration systems that suffice in both categories. Despite, the higher profitability demonstrated from the intensive systems, two medium systems appear to score similarly on profitability and reducing GHG emissions. To be more specific for both steers and heifers', the 18 and 19 month systems appear to belong to a range of realistic scenarios for both profitable and more environmental-friendly beef production. To further support the case for medium duration grass-based beef finishing systems, studies on alternative beef forage-based systems have reported promising results in terms of their potential as mitigation strategies to balance GHG emissions produced, especially for systems with animals grazing on improved pasture (Kamali et al., 2016) and systems employing adaptive multi-paddock (AMP) grazing (Stanley et al., 2018). This observation is especially for Scotland, where opportunities may be found for finishing systems, where a proportion of grass is included in the diet, resulting in high-value products from grass-fed animals that could potentially offer higher returns (AHDB, 2016b).

Furthermore, wider implications could support the case for medium duration pasture-based beef production systems. Well-preserved grasslands provide ecosystem services and could have a positive effect on long-term soil fertility (Dick et al., 2016; Horrocks et al., 2014). Promoting pasture-based beef production systems may have wider socio-economic implications in terms of increased rural employment as well as valuable ecosystem services. Grass-based systems are closely associated with a range of social and economic benefits like rural tourism, recreation, which alleviates burdens linked with progressively urban lifestyles, and many distinctive features of the rural landscape with historic and aesthetic significance (e.g. patchwork of fields bounded by hedgerows and stone walls, etc.) (Chatterton et al., 2015). The potential for carbon sequestration in grazing lands is significant, but at the same time the estimates are highly uncertain. Synthesis of evidence suggested that even though responses varied greatly, improving grassland management practices could lead to soil carbon sequestration, by an average of 0.47 Mg $C \cdot ha^{-1} \cdot yr^{-1}$ (Conant et al., 2017). Other sources suggest that long term pastures would likely have a limited carbon sequestration potential, as this specific land-type had already accumulated a great amount of carbon over the years (Viglizzo et al., 2019). Nevertheless, despite the substantial reported increases to soil organic matter, concerns have been expressed regarding the magnitude of the potential climate change mitigation credited to enhanced soil management (Schlesinger and Amundson, 2018).

Livestock grazing production systems convert forages into edible food while utilising lands unsuitable for arable productions; thus avoiding direct competition with humans for valuable resources (de Vries et al., 2015; Van Kernebeek et al., 2016; van Zanten et al., 2016). In addition, various health benefits have been attributed to moderate consumption of grass-fed beef in comparison to concentrate-fed beef (Warren et al., 2008). Meat from pasture-based cattle has proven to be a great source of omega-3 polyunsaturated fatty acids, promoting a healthy diet by contributing towards a balanced intake ratio of omega-6/omega-3 ratio, which promotes prevention and management of obesity (Simopoulos, 2006). Recent studies suggest that beef's intrinsic high nutritional value could prove to be the basis for re-assessing the role of livestock production systems in global food security (Coelho et al., 2016; Pighin et al., 2016; Wyness, 2016).

5.5.2 Limitations of approach and future research

This study was concentrated on the environmental impacts linked to the finishing stage of beef production. Although, it has been shown that the cow-calf phase was the largest contributor to GHG emissions (Pelletier et al., 2010); it was important to study emissions during the fattening stage particularly in Scotland, as longer finishing strategies are common and often associated with inefficiencies and additional emissions (Ogino et al., 2004; Quality Meat Scotland, 2018a).

A significant reason for caution when modelling agricultural emissions would be implications induced by a system's inherent variations and uncertainties (Gibbons et al., 2006). For instance, weather, spatial or temporal related uncertainties could reduce the robustness of emission factors, and variation surrounding farm system parameters could influence the GHG emissions calculated from a model (Basset-Mens et al., 2009; Crosson et al., 2011). Although this study is limited in the sense that modelling uncertainty was not explicitly considered, future work could explore ways to incorporate this aspect on the analysis of the GHG emissions. For example, other studies have developed distributions for uncertain model parameters by utilised Monte Carlo simulation (Basset-Mens et al., 2009; Gibbons et al., 2006), or performed sensitivity analysis on a set of important factors, resulting in the calculation of a range of outputs (Casey and Holden, 2006; Foley et al., 2011).

Future work could focus on optimizing results and improving identification of both profitable and environmental-friendly scenarios. Further analysis and optimisation of the modelling outcomes could result in a greater understanding of the underlying connections between profitability and GHG emissions of beef production systems. It is common for the short duration systems to divert the focus and the farm resources in managing and feeding the housed animals as efficiently as possible, often at the expense of the pasture system, which is neglected and its utilisation rate remains low over the year. This might have caused an overestimation of the reported emissions for these systems - an issue that could be further examined by employing optimisation modelling and studying scenarios involving land use optimisation. Furthermore, potential modelling could involve an exploration of possible mitigation techniques including different feeds, manure management, animal husbandry, and the interactions between them as well as implications on profitability for beef fattening farms in Scotland (Hristov et al., 2013).

A more comprehensive evaluation of other environmental and economic issues related to beef production in beef finishing systems was not possible in this study, because essential data on biodiversity, carbon sequestration, acidification, water footprint and macroeconomic factors of production were not available. Future research should concentrate on collecting data to support an extensive analysis of the environmental and economic sustainability performance of Scottish beef finishing systems. Moreover, further research is needed to determine the socio-economic implications of shifting between alternative beef farming systems. Future research should assess the "gate-to-gate" social risks and benefits of Scottish beef finishing systems considering indicators of socio-economic sustainability like demographics, economic activity and community aspects (Pelletier et al., 2018; Revéret et al., 2015). Working with a social life cycle assessment framework to identify the relevant stakeholder groups (e.g. workers, local community, society, value chain partners) and social themes (e.g. access to resources, fair salary, health and safety, social benefits, equal opportunities, local employment, community engagement) could provide insights, supplementing research done on financial and environmental aspects to inform future policies (Pelletier, 2018; Pelletier et al., 2018).

5.6 Conclusion

The model synthesis described here to assess scenarios regarding the environmental impact of beef production farms while estimating the possible trade-offs generated between mitigating emissions and increasing farm cost-effectiveness, is supported by the increasing necessity to guide local and European agriculture toward production systems that are environmentally friendly, socially acceptable, and profitable for the farmers. The methodology that allowed a bio-economic production model to be linked with an environmental carbon calculator can be further employed as a tool to guide agricultural policy in regions such as Scotland, by evaluating both environmental and production-related scenarios. Environmental friendly beef finishing systems, producing lower emissions were identified when finishing steers on intensive short-duration systems. Findings also highlighted profitable prospects for commercial farms adopting medium-period, pasture-based beef production systems. In fact, this study indicated that beef production systems with low carbon footprint entail trade-offs between farm profitability and global environmental issues, suggesting that economic and environmental performance of livestock production systems may not always be positively correlated. These insights could guide the decision-making process towards the goal of lowering the GHG emissions of the beef industry, whilst maintaining and even increasing farmer's profitability.

Chapter 6: Modelling policy impact assessment on the implications of the United Kingdom leaving the European Union on Scottish beef production systems

6.1 Introduction

Cattle production is considered the main agricultural sector in Scotland, with beef farms generating the highest proportion of all agricultural revenue from the sale of animals for meat production (Scottish Government, 2018b; Vosough Ahmadi et al., 2015). Scotland has one of the highest ratio of beef to dairy cows, as well as a high proportion of cattle fattening farms compared to other European countries, which indicates that the performance of the agricultural sector is dependent on beef finishing farms and may consequently be vulnerable if these enterprises face economic challenges (Ihle et al., 2017). Still, the majority of the producers rely significantly on Common Agricultural Policy (CAP) support payments provided by the European Union (EU) to sustain their farming activities, prompting concerns for the overall viability and sustainability of the agri-business sector and the rural social structure (AHDB, 2016b; Vosough Ahmadi et al., 2015).

The CAP is a unique agricultural policy that was established in 1962 and has since been a key driver of structural changes in agriculture for the EU member states (Raggi et al., 2013; Van Berkel et al., 2011; Zagata and Sutherland, 2015). This strategy defined a set of rules between the member states governing the international trade agreements, the flow of commodities, while also providing financial support in an attempt to regulate all aspects of agricultural production

(Matthews et al., 2013, 2006; Turner and Daily, 2008). Over the years, CAP has undergone various policy reforms, as initially, the aim was to satisfy the prerequisites of a growing population during the 'productivism' era (Downing et al., 2014; Patton et al., 2008). Accordingly, policies were focused on maximising the quantity of agricultural output by offering farmers guaranteed prices for their produce and subsidies based on the amount of production, as well as setting tariffs to restrict competition, and promoting exports (Downing et al., 2014; Matthews et al., 2013; Meert et al., 2005; Sutherland, 2010). This continued up until 1992 when the 'MacSherry' reforms marked the dawn of a 'post-productivism' era, which shifted the emphasis from quantity to both quality of production and the environmental protection, while at the same time attempting to reduce trade distortions (Skogstad and Verdun, 2009).

Following, the 'Agenda 2000' reforms, the CAP was divided into two 'Pillars'; where 'Pillar 1' included the production support (e.g. Direct payments, market support), while rural development measures (e.g. support for farming in Less Favoured Areas (LFAs)), were defined in 'Pillar 2' (Downing et al., 2014; Thomson et al., 2011). Further CAP changes under the 'Fischler' reforms of 2003, replaced direct production support with the Single Farm Payment (SFP) that was not linked to production (decoupling of payments) (Downing et al., 2014; Scottish Government, 2009). In 2008, the 'Health Check' alterations, mostly refined the 2003 modifications of the CAP (Ciaian et al., 2014; Downing et al., 2014). The latest 'CAP reform 2014-2020', allowed the Member States to customise the implementation of the Single Farm Payment, switching between modes of subsidising on historical basis or area basis (Downing et al., 2014; European Union Committee, 2017).

In 2017, the United Kingdom (UK) formally entered negotiations for leaving the union, scheduled to be finalised by 2019 and will come into effect the following year (BREXIT) (Springmann and Freund, 2018). For more than half a century, the economies of the Member States have developed strong connections that have led to an established complex network of trade dependencies and supply chains, which underpin their financial and social security. Consequently, removing the common institutions and regulations is expected to lead to changes across all sectors of the British economy, building uncertainty regarding the post-Brexit economic landscape (AHDB, 2016b; Springmann and Freund, 2018).

It is anticipated that the British exit from the EU the CAP (Brexit) will have fundamental implications for the UK's agricultural sector (European Union Committee, 2017; Hubbard et al., 2018). This policy change is expected to be the greatest change in British and Scottish agricultural policy since 1973 when the United Kingdom joined the European Economic Community (European Commission, 2013b). Recent studies highlight the fact that Scotland stands out as the most vulnerable region to the possible Brexit scenarios implications on the agricultural sector (Harvey et al., 2019). Amongst the most affected enterprises for the UK and Scotland are expected to be the beef and sheep farms, largely because of their established reliance on subsidies under the present CAP and the dependence on trade relations with the EU and the Rest of the World (Feng et al., 2017; Harvey et al., 2019; Hubbard et al., 2018; Shrestha et al., 2018).

Nevertheless, opportunities for the UK and Scottish beef exports exist by exploring non-EU markets with previously limited access; especially markets for premium products, while taking advantage of the regional pasture-based production systems (AHDB, 2016b; European Union Committee, 2017).

Farming systems are considered complex and diverse eco-systems, displaying variations in size, scope, speciality, intensity, and orientation, which influence the resources, limitations, and goals of each system (Reidsma et al., 2018). Hence, models are typically employed to deal with the complexity of assessing potential impacts of policy alternatives across a range of impact areas as part of the overview of new policies (Antle et al., 2017a, 2017b). Outcomes generated from farm models are considered valuable resources for informing the decision-making process of policy makers (Ciaian et al., 2013; Hertin et al., 2009; Louhichi et al., 2018). Several models have been developed to assess policies for the livestock sector (Benoit and Laignel, 2014; García-Martínez et al., 2011; van de Ven and van Keulen, 2007; Veysset et al., 2005; Vosough Ahmadi et al., 2015).

Here, we developed a farm-level linear optimisation (LP) model for exploring possible ways Brexit might affect the landscape for Scottish beef farms and finishing systems. The objective of this study was to investigate the financial and structural impacts of different post-Brexit scenarios on these specific types of farms. In this study, we employ the model to generate useful information to increase the understanding of approaching socio-economic policy changes that are projected to influence the management of beef production systems in Scotland.

6.2 Materials and Methods

6.2.1 Input data

The farm-level data used for the current study were obtained from a database established and maintained from the Farm Business Survey (FBS) for Scotland, which prior to 2017 was referred to as the Farm Accounts Survey (FAS). The FBS dataset consists of farm accounts data that contains economical and some technical data of a sample of approximately 500 farms. The annual data collection for the FBS database was performed by Scotland’s Rural College (SRUC) on behalf of the Scottish Government. A sample stratified by farm type and size was recruited and data are collected directly through regular farm visits and detailed auditing of each business’s records. The data covered physical, financial, and economic information for the farm business on production, resources, income, and balance sheets (RESAS, 2018). Subsequently, the undisclosed farm accounts were handled by the Scottish Government for analysis and publication mainly via the Rural and Environment Science and Analytical Services (RESAS, 2018).

In this study, annual farm accounts for the year 2016 were used as input for the model. The selected dataset consists of a physical description and performance data at the enterprise-level of specialized beef farms in Scotland (n=111), with a proportion being Less Favoured Area (LFA) land. In addition, several farms (n=74) included to a lesser degree sheep farming as production activity. Farm-specific data related to the sample of 111 farms, including land area, number of cattle, net margins, enterprise and farm-level farm payments, were used as input for the model to examine the dependency of these farms on subsidised farm payments based on the current CAP. A summary of the performance and characteristics of these farms are detailed in Table 6.1. The aim was to develop a model for policy impact assessment for the most common beef finishing systems in Scotland; hence, the data that were not available in the farm dataset, such as livestock units and labour requirements, were adopted from the Farm Management Handbook (SAC Consulting, 2017).

Table 6. 1 *Average figures of beef production farms (n=111) characteristics**

Technical Performance				Financial Performance			
	Mean	SD	Median		Mean	SD	Median
Animals (head)				Costs (£)			
Suckler cows	95.28	7.47	77.50	Variable	36,860	1,983	33,809
Yearlings	78.64	6.28	67.50	Fixed	59,411	8,711	40,891
Cattle (18 month)	34.15	3.06	22.60				
Cattle (24 month)	3.83	0.78	1.00				
Land (ha)				Subsidies (£)			
Grassland (ha)	120.95	7.43	102.02	BPS**	45,381	2,881	38,300
Rough Grassland (ha)	57.51	9.54	15.00	LFA land	9,116	719	7,568
Silage (ha)	36.14	1.87	32.40				
Stocking rate (LU/ha)	0.83	0.05	0.80				

*Source: Calculated from FBS 2016 dataset.
**Basic Payment Scheme.

6.2.2 Farm-level model

Optimisation farm-level modelling has been widely employed for policy impact assessments in the context of the EU (Acs et al., 2010; Bartolini et al., 2007; Gohin, 2006; Hennessy et al., 2009; Ridier and Jacquet, 2002; Shalloo et al., 2004; Shrestha et al., 2018). A simple optimisation linear programming (LP) farm-level model, the 'ScotBeefFarm' model, was further developed and configured for the present study. The model was constructed according to a general linear programming model design, i.e.:

Max $z = (p - c) \times x$;

Subject to $A \times x \leq R$ and $x \geq 0$

where z is farm net margin (NM), calculated as revenues minus the costs linked to the farm activities and the fixed costs; x are farm activities; p is a measure of the returns; c are the costs procured for x; A is an input-output technical coefficient for activity x; and R is a limiting farm resource.

The ScotBeefFarm model was developed using the General Algebraic Modeling System (GAMS) and employed the Mixed Integer Programming solver CPLEX. It is a static linear optimization model and it is interfaced with Microsoft Excel input and output data files (Bartolini et al., 2007; Diakité et al., 2019). The model adapts and further develops an earlier model, ScotFarm model (Shrestha et al., 2007; Vosough Ahmadi et al., 2015), combining with production elements taken from the Grange Scottish Beef Model (GSBM) (Kamilaris et al., 2019), a beef production system model described in Chapter 4 of this thesis. The schematic diagram of the ScotBeefFarm model is provided in Figure 6.1, where simulated farm environment and associated activities are illustrated. The key model activities simulate the annual beef farming and production cycle. These functions were constrained by land for housing animals, feed, labour, and animal replacement available on a farm. However, farms were permitted to buy in feeds, animal replacements and hire casual labour if required. Farm net margins comprised of the accumulated revenues collected from the final product of the farm activities minus the variable and fixed costs for inputs, plus the single farm payment.

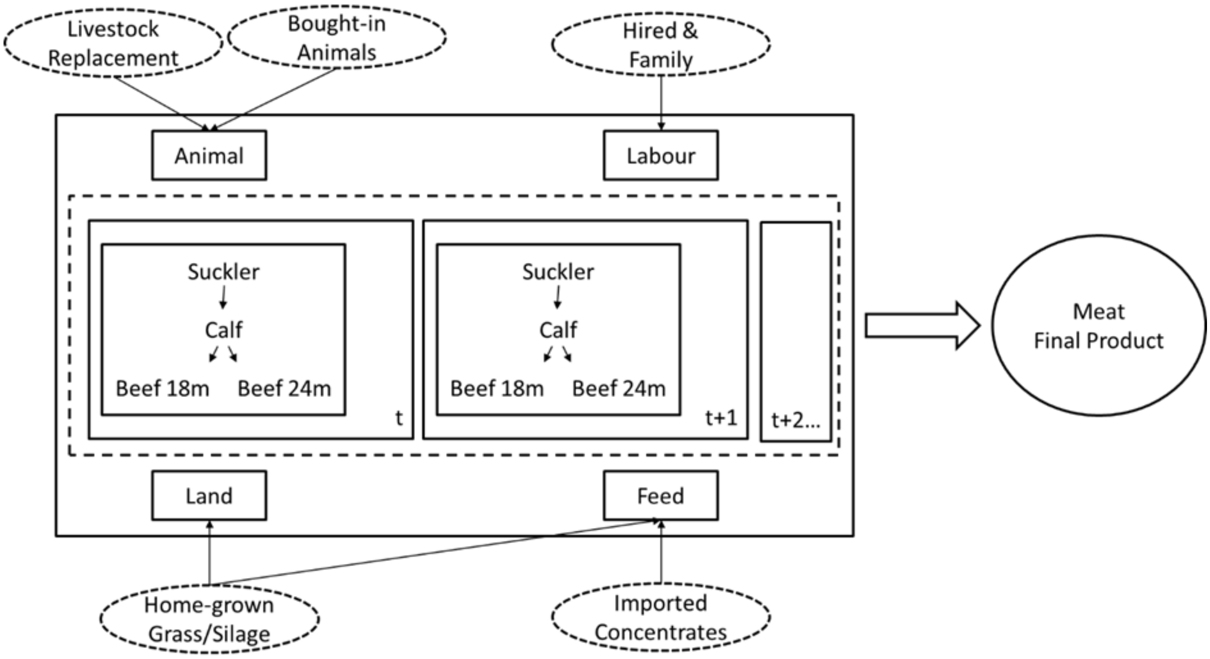

Figure 6. 1 *A schematic diagram of ScotBeefFarm model.*

The model is dynamic and runs within a 10-year timeframe. This way, a farm activity in a particular year was based on the farm activity in the previous year, emphasizing the impact of choices on time. Hence, for example, the number of beef suckler cattle in year 't' for each of the farm types 'f' depended on the number of beef suckler cattle and heifers used as replacements in the previous year 't−1', as well as number of replacements and culled animals in year 't' as indicated in the following equation;

$suckler_t = suckler_{t-1} + heifer_{t-1} + replacement_t - cull_t \ \forall \ f$

The model produces annual farm margins for all 10 years, but the results from the first 3 years and last 3 years were excluded from the final analysis, to minimize the starting and terminal effects of linear programming (Shrestha et al., 2014; Vosough Ahmadi et al., 2015). The ScotBeefFarm model consists of four different conceptual sub-systems, namely the animal, land, feed and financial components. The animal system simulated two production systems typical of commercial practice for the UK and Scottish farms, which were modelled based on the study that was used for the development of the GSBM (Hyslop et al., 2016; Kamilaris et al., 2019). The animals were allocated to pathways depending on the duration of finishing, i.e. short (18-month system) and medium (24-month system) period systems for males and females respectively (Figure 6.2). The animal system consists of seven livestock categories based on age, sex, and finishing duration: suckler cows, male and female calves, male and female beef animals sold on 18 months, and male and female beef animals sold at 24 months of age.

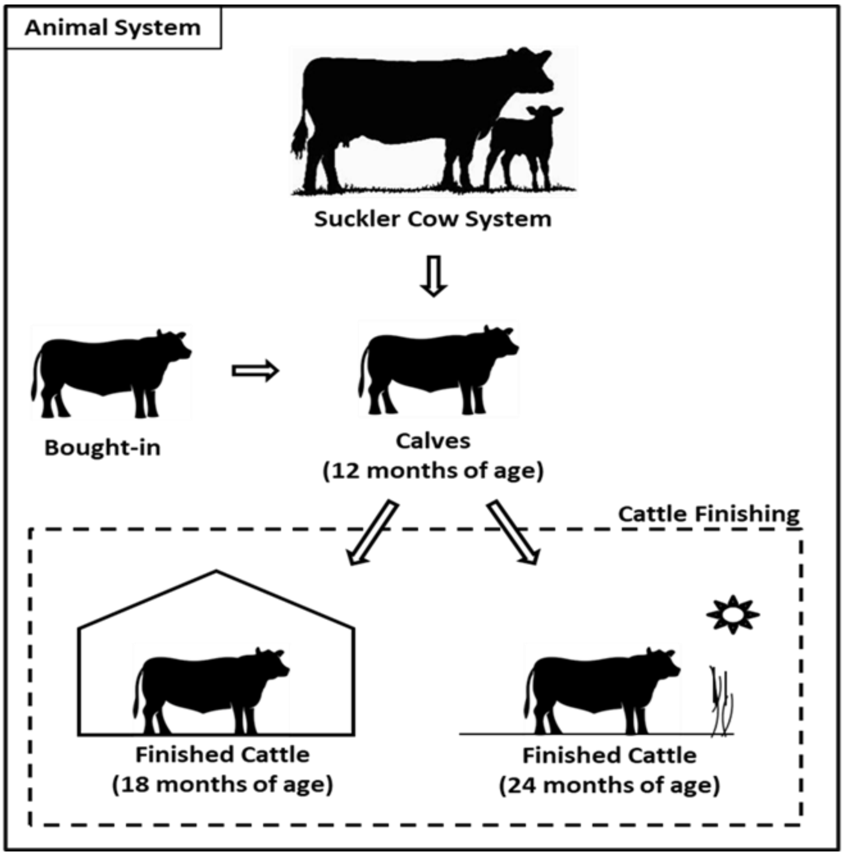

Figure 6. 2 *Representation of animal sub-system developed for the LP model ScotBeefFarm.*

Beef finishing enterprises in the model were allowed to source animals reared in the suckler system, as well as animals (yearlings) that were bought in from outside the farm. The number of the animals purchased was limited by stocking rate and by the average number of animals that each farm could support. Each farm could buy replacement cows at the end of the previous year, dependant on specified culling and replacement rates. All animals in the finishing systems were sold at the end of each annual cycle, whereas a maximum 0.136 of the suckler cows are culled and replaced every year (SAC Consulting, 2017). In addition, the calving rate was set to 0.94 and the calves survival rate to 0.955 (SAC Consulting, 2017). Moreover, the default mortality was assigned a different value for every stage of the production cycle; thus, the mortality rate of growing animals was set at 5% of growing animals, and 2% for animals at the finishing stage, equally distributed over the year (SAC Consulting, 2017). Every step of the model run reflected a decision the farmer must take in a highly complex environment; either increase costs and deliver a more valuable product or sell the animals sooner.

The land component of the ScotBeefFarm model simulated the grazed grass and grass silage production of the farm. The initial grassland area consisted of permanent perennial ryegrass swards, which is characteristic of Scottish systems (Quality Meat Scotland, 2013). The grass growth equations, the expected yield and monthly distribution previously developed for the GSBM were adopted in this case as well, using data originated from field experiments and historic Scottish data (Bell et al., 2016; Kamilaris et al., 2019). A typical grazing season was modelled lasting from March till the end of October, and grass utilization was set at 50% to replicate the performance of a set stocking grazing system for typical Scottish beef farms (Quality Meat Scotland, 2013). The maximum amount of organic nitrogen output was restricted to 170 kg N/ha for the UK, in accordance with the Nitrates Directive (The Scottish Government, 2008). In addition, the stocking rate was based on the amount of land used for grazing, including rough grazing land, so it restricted the number of animals (SAC Consulting, 2017). The GSBM simulated the separation of a number of grass swards, during the peak growth period, for producing grass silage (Kamilaris et al., 2019). The proportion of the grass area required for silage production was based on optimised number of animals on the farm. The amount of feed grown in the farm acted as a constraint for forage intake, while farms were allowed to buy concentrates to make up for the difference. Typical barley-based concentrate ration was assumed for the finishing animals (energy content of 1.15 UFL or UFV/kg DM) (Jarrige et al., 1986; Quality Meat Scotland, 2018b).

Feed available was either home-grown (grass and silage production), or purchased concentrates, while feed availability restricted the number of animals on each farm. The feed component of the ScotBeefFarm model was largely based on results obtained by the GSBM. Growth equations based on liveweight and liveweight gain were adapted to calculate the net energy requirements and animal intake capacity (Kamilaris et al., 2019). The GSBM calculated requirements for animals and the diets designed used grazed grass, grass silage, and concentrates to meet these demands, while all related terms were defined as animal energy requirements and were subject to a maximum intake capacity. Every month, the feed requirements were calculated for each animal on a farm based on type, age, gender, and production level. The amount of nutritional requirements was subsequently multiplied by the number of finishing animals at the farm. For the suckler beef systems, the nutritional requirements were not taken into account; instead, the model included the costs of maintaining (silage diet) suckler system per cow, multiplied by the number of suckler cows at the enterprise. It was also assumed that the nutritional requirements of calves before weaning were incorporated in the values for suckler cows.

The financial element of the ScotBeefFarm model captures the key costs and the prices associated with beef farming in Scotland. Input pricing data from 2016 were collected from the Farm Management Handbook and used for the modelling cycles (SAC Consulting, 2017). Scottish beef prices were taken from the GSBM, where they were calculated as a function of the conformation and fat class of the animal. Variable costs, for example, veterinary and medicine, commission, haulage and levies, were provided by the Farm Business Survey; calculated per animal and multiplied by the number of animals per category. Labour costs were estimated from average labour hours per month for different categories of beef finishing system (Nix and Redman, 2016; SAC Consulting, 2017). In addition, in this chapter, the payments were included in the farm margin linked with the grazing land on farm, as the single farm payment was regarded as an area-based payment.

The outcome of the model provides an optimised farm net margin, the optimal number of animals, a feeding and grazing pattern, annual buying and selling activities, along with the monthly casual labour utilized. The forthcoming Brexit is anticipated to be the policy change that is likely to affect both farm economics and optimum stock numbers. The current study examines the implications of prices of different trade scenarios before and after Brexit while focusing particularly on the optimum financial results and stock numbers.

6.2.3 Model scenarios

Initially, the ScotBeefFarm model ran using the basic average input prices to establish the baseline scenario. This scenario (Baseline) presumes a continuous membership of the EU, unchanged access to the EU Single Market and a steady version of the CAP. The trade relations between the EU and the UK, as well as the CAP, were considered fixed to their prior-Brexit mode, with no expected changes or revisions beyond 2019. As Brexit will have significant implications on UK agricultural commodity markets because of changes to trade flows, alternative Brexit trade scenarios were compared against a Baseline, in an attempt to capture and quantify the impacts of these policy changes the projections. This study employed three alternative post-Brexit trade scenarios reported by the Agri-Food and Biosciences Institute, which used FAPRI, a partial equilibrium model (Davis et al., 2017).

The first scenario simulated a possible free trade agreement (*FreeTrade*) with the EU. This scenario involves the UK establishing a new customs arrangement with the EU, which involves a mutual tariff and quota free access for imports and exports. Tariffs and other trade arrangements for UK imports and exports with the rest of the world countries will be unaffected compared to the Baseline. Also, trade facilitation costs equal to 5% of the product price were integrated within this scenario to reflect extra trade costs of exporting and importing (Matthews, 2016). As a result of the uninterrupted flow of commodities between the UK and the EU-27, allocation of the EU's existing tariff rate quotas (TRQs) commitments does not cause significant market price effects for this scenario (Davis et al., 2017).

The second scenario considers an absence of a trade agreement between the UK and the EU, with the UK assuming automatically a default member position under the World Trade Organisation (WTO) rules for governing global trade (*WTO*). Under this scenario, most favoured nation (MFN) tariffs, which are default trade-restrictive tariffs that WTO members charge one another, will be applied to imports from the EU and the rest of the world beyond TRQs (Harvey et al., 2019). In addition, the EU applies its MFN tariffs to imports from the UK and Scotland. In the specific case of beef imports, the relevant carcass MFN tariffs were used as representative of all products in that category. In the case of exports from the UK to the rest of the world, it was assumed that the UK acquired the current EU's tariff structure to third countries, while the level of TRQs for the UK was simulated based on the average level of imports from the rest of the world in the last five years. Moreover, along with the MFN tariffs, further trade facilitation costs equal to 8% were applied to all trade activities with the EU to capture additional costs associated with less integrated trade arrangements (Davis et al., 2017).

For the third scenario, a one-sided trade liberalisation (*LibTrade*) deal was assumed, with the UK imposing zero tariffs on imports to the UK from both the EU and the rest of the world. While, it is not realistic for all import tariffs to disappear, especially for products where the UK has a significant production interest, this scenario represents an extreme version of trade liberalisation, designed to provide an indication of which sectors would be particularly sensitive to changes in tariffs. Similar to the previous scenario (*WTO*), UK exports faced MFN tariffs applied to both the EU and countries from the rest of the world. Additionally, the 8% trade facilitation costs applied to all trading activities were similar to the WTO scenario (Davis et al., 2017). Each of these scenarios was designed to represent a possible outcome from price implications under different trade agreements after Brexit.

Even though the UK government has guaranteed to keep overall payments to farmers at the same level until 2022, the lack of concrete policy decisions creates uncertainty around the beef sector, which is one of the most reliant on CAP payments (SAC Consulting, 2017). Hence, the model explored each of the AFBI scenarios on Scottish beef finishing farms under assumptions of continued and withdrawn direct CAP support payments to farmers (Figure 6.3). To isolate the effects of prices, six alternative post-Brexit trade scenarios were compared with the Baseline scenario, in which the UK is fully integrated within the Single Market. In addition, for all AFBI post-Brexit scenarios, the expected average rate of price deviations between 2019 (year of the Brexit) and 2026 was reported for beef value, variable costs, and concentrate costs (Table 6.2). The environmental performance of animals during the finishing phase for every farm under different scenarios was studied by employing a greenhouse gas (GHG) coefficient that was previously calculated in Chapter 5. This coefficient corresponds to the amount of GHG emitted by each animal, depending on gender, nutrition level, animal performance on the different finishing systems examined in this study.

Table 6. 2 *Commodities price change (%) from 2019 to 2026**

	With Direct Support				Without Direct Support			
Beef Production	Baseline	WTO	LibTrade	FreeTrade	Baseline	WTO	LibTrade	FreeTrade
Beef prices	17%	37%	-33%	17%	17%	37%	-33%	19%
Variable Costs	8%	7%	7%	7%	8%	7%	7%	8%
Concentrate Prices	-4%	-3%	-5%	-4%	-4%	-1%	-4%	-4%

*Adopted from the report in Davis et al., (2017).

6.3 Results

To examine the economic performance of beef the production sector in Scotland results concerning the profits of each farm under various post-Brexit scenarios were presented in Figure 6.3 and Figure 6.4. Figure 6.3 illustrates Scottish beef farm net profitability under the assumption of retaining existing levels of direct support. Results indicated that the majority of the farms under the Baseline scenario were producing farm profits. Also, when the model simulated the effects of different post-Brexit trade scenarios, the estimated business net profits remained almost unaffected under the *FreeTrade* scenario, while under the *WTO* scenario an average increase of 28% in profitability was noted compared to the baseline performance. Higher returns were attributed mainly to higher prices facilitated by a secure EU market environment, from which the Scottish beef farmers profited. In contrast, signs of financial underperformance, with an average drop of 64% in farm profitability, were reported when the *LibTrade* scenario was simulated. The key reason behind this drop was the disproportionate reduction of taxation in imported products, compared to the high level of taxation policy for exports. In addition, this scenario simulated the effects of the UK market opening to discounted imports, which challenged and consequently lowered the prices the Scottish beef farmers received for their product. However, despite the unfavourable conditions under this scenario, several beef farmers were generating profits due to the continuation of direct governmental support, which accounted for a substantial part of their gains.

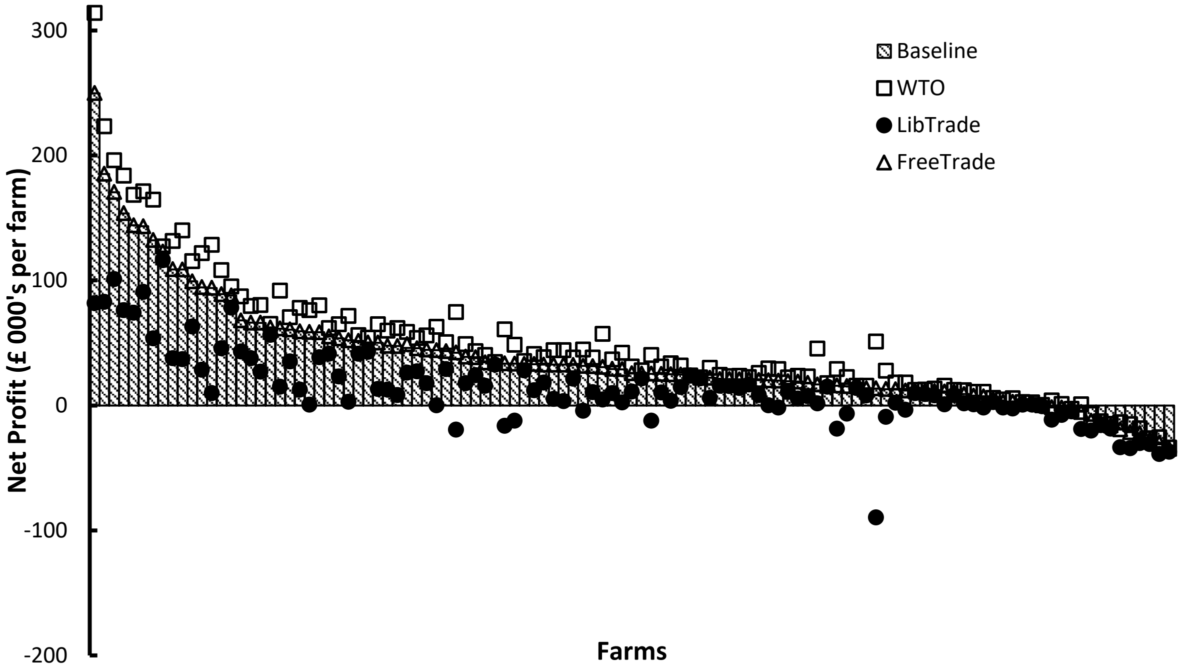

Figure 6. 3 *Estimated farm net profit (<u>with direct support</u>) of beef farms under the baseline scenario and three post-Brexit trade scenarios.*

Figure 6.4 describes the farm profits calculated by the ScotBeefFarm model for individual farms, under the price implications resulted from three alternative trade scenarios, without the direct support scheme payments. Results indicated that under each of the post-Brexit scenario examined almost all of the farms experienced considerable losses in net profitability when the existing level of support was removed. Only a third of beef farms under the *WTO* scenario and 22% under the *FreeTrade* deal remained profitable. Even more discouraging were the outcomes predicted for the beef sector under the *LibTrade* scenario, where all the farms reported negative financial outputs.

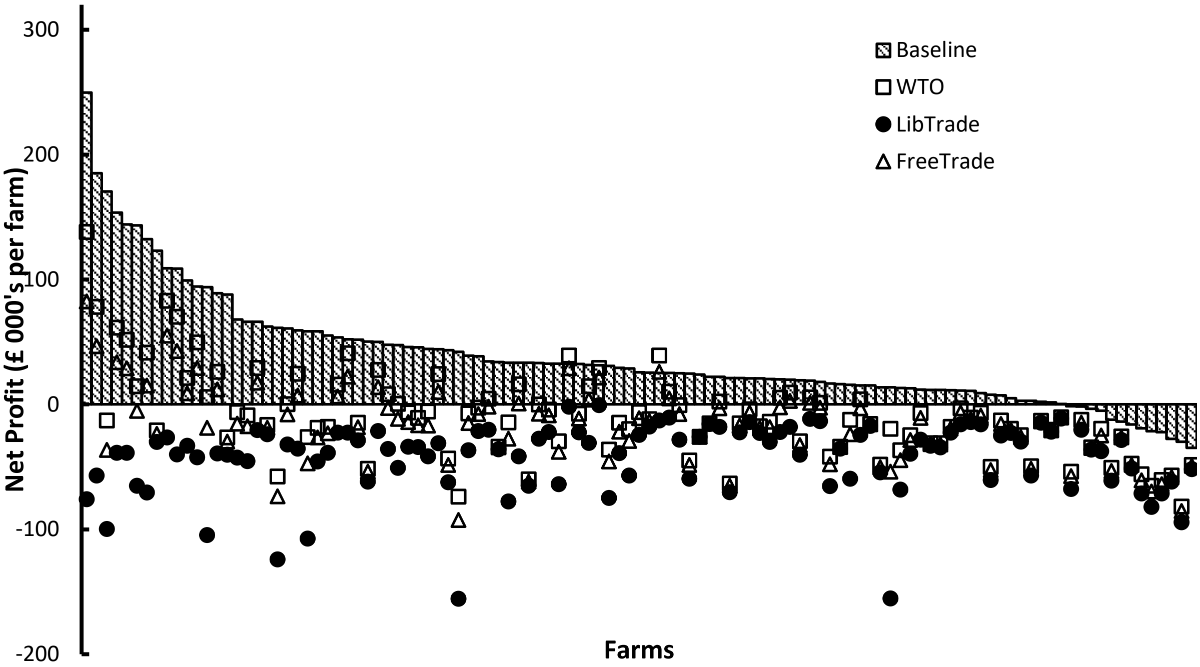

Figure 6. 4 *Estimated farm net profit (*<u>*without direct support*</u>*) of beef farms under the baseline scenario and three post-Brexit trade scenarios.*

For increasing the understanding regarding the post-Brexit impacts on different farm types, the farms were clustered into four quartiles, with Q1 being the highest profit-making, Q2 and Q3 medium profit-making, while Q4 included the lowest profit-making farms, reflecting similar levels of efficiency and managerial abilities (Table 6.3). Outcomes highlighted the fact that the profitability of beef enterprises in Scotland is principally susceptible to tariff free imports to the UK (*LibTrade*) and removal of direct support scheme. Farms from every group reported higher returns under *WTO* scenario, which simulated the effects of the UK having a default member position in WTO, while much lower outcomes were described under the *LibTrade* scenario, even when modelling a steady income from direct support.

Table 6. 3 *Farm Average Net Profit Scenario Results (£)**

		With Direct Support			Without Direct Support		
Quartile	Baseline	WTO	LibTrade	FreeTrade	WTO	LibTrade	FreeTrade
Top (Q1)	98,513	120,591	52,719	98,663	35,189	-16,312	18,446
2nd (Q2)	37,473	49,370	15,742	37,675	- 5,010	-28,607	-10,792
3rd (Q3)	19,554	25,976	4,274	19,613	-19,126	-43,332	-24,126
Bottom (Q4)	-3,569	-853	-17,871	-3,549	-48,870	-80,436	-54,436
All Farms	38,159	48,981	13,801	38,267	-9,367	-42,161	-17,669

*Predicted difference in beef farm net profits for different performance quartiles under post-Brexit scenarios compared to the Baseline

The averaged figures for major farm variables for the highest performing farm group (Q1) and the lowest performing farm groups (Q4) are presented in Table 6.4. Farms in Q1 had on average significantly more grazing land and displayed a higher stocking density, while incurred less variable and feeding costs per animal. The lower quartile farms (Q4) had slightly lower stocking density, while supported considerably fewer animals, hinting a more extensive type of beef farming. In addition, Q1 farms received greater financial aid through direct support and LFA payments, while they were more environmentally friendly, producing lower emissions per animal during the finishing stage.

***Table 6. 4** Differences in farm characteristics between the top and the bottom performance quartile**

Farm Input Variable	Top (Q1) Average	Bottom (Q4) Average
Animals (average number)	219.62	26.54
Grassland (ha)	173.28	84.26
Rough Grassland (ha)	119.69	26.10
Silage Area (ha)	51.97	25.43
Stocking density (LU/ha)	0.95	0.69
Variable Costs (£/animal)	71.22	132.07
Feed Costs (£/animal)	64.36	95.02
Direct Support Payments (£)	77,217	26,347
LFA Payments (£)	16,385	4,788
Emissions (kg CO_2-eq animal^{-1})*	131.59	195.50

*Refers only to emissions produced during the finishing stage of beef production

The impact of the alternative scenarios on the average number of animal categories with (Figure 6.5) and without direct support (Figure 6.6). Most notably, the ScotBeefFarm model projected a 13% increase under the *WTO* scenario and a 43% decrease of the total number of animals under the *LibTrade* scenarios with subsidies (Figure 6.5). The contraction occurred under the *LibTrade* deal was mainly driven by the decrease of the number of animals in the suckler system and the 18-month finishing system for both steers and heifers. In the meantime, under the same policy scenario without providing governmental support, there was a further contraction in all categories of the beef herd by 55%. More specifically, the average number for suckler cows dropped by 88%, for yearlings by 86%, for steers finished at the 18-months system by 24% and for heifers finished at the same system by 33%. Whereas, the categories for steers and heifers finished at 24-months systems, experienced smaller decreases by 5% and 6%, respectively (Figure 6.6).

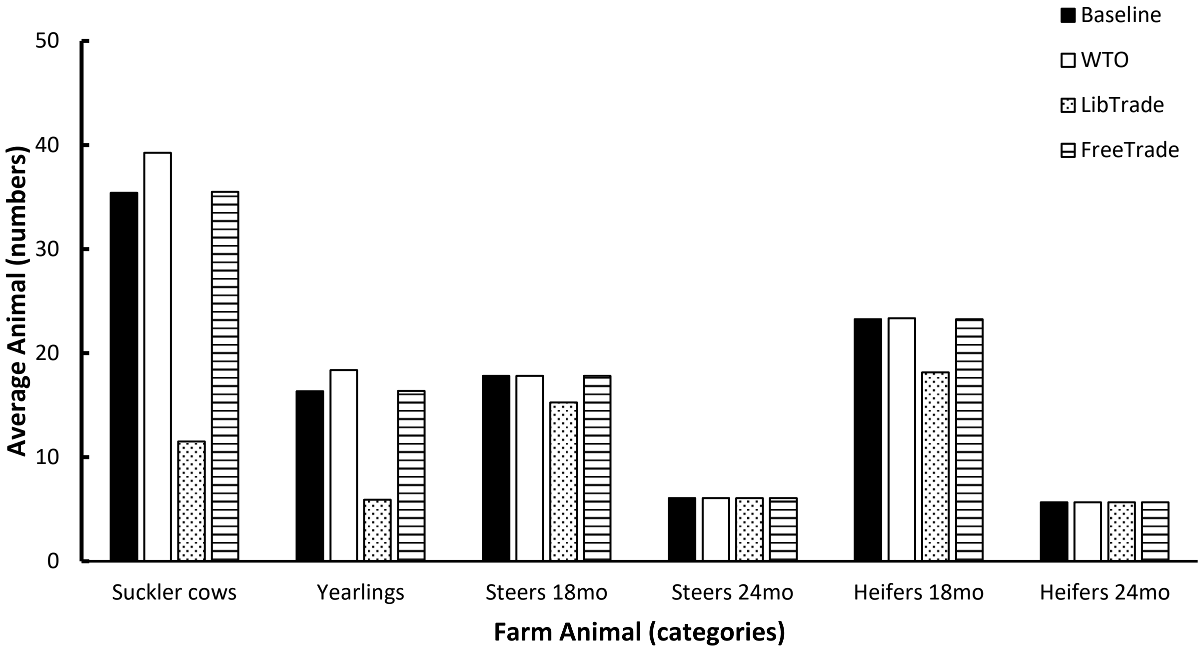

Figure 6. 5 *Estimated farm livestock numbers (<u>with direct support</u>) for beef farms under the baseline scenario and three post-Brexit trade scenarios.*

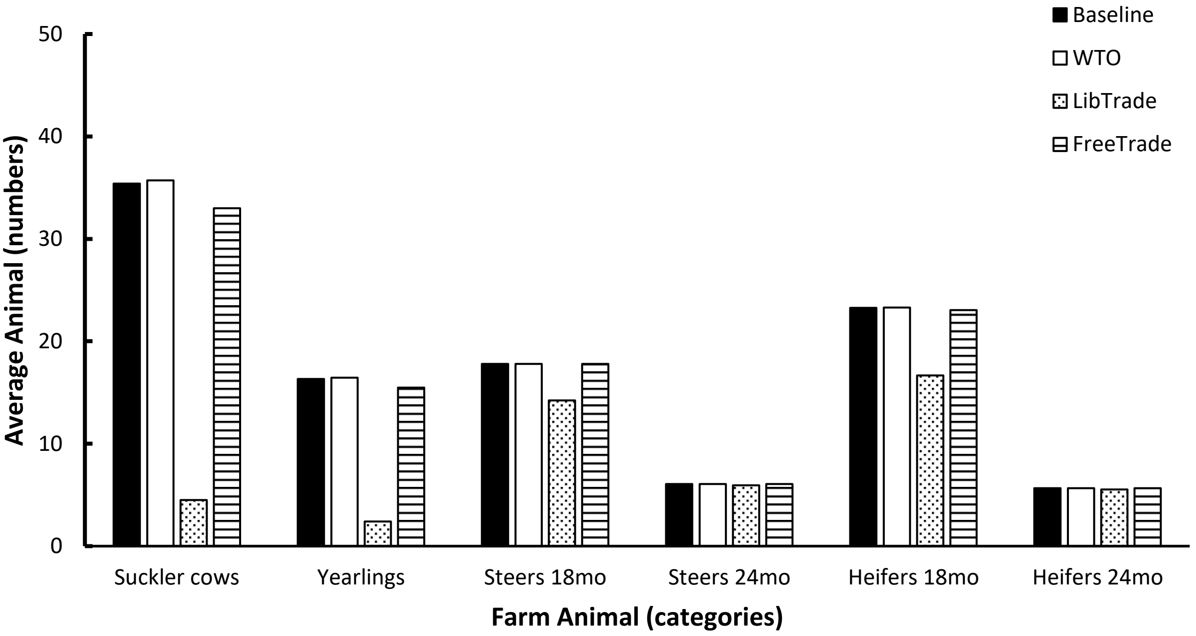

Figure 6. 6 *Estimated farm livestock numbers (<u>without direct support</u>) for beef farms under the baseline scenario and three post-Brexit trade scenarios.*

6.4 Discussion

6.4.1 General Discussion

This study examines price implications as a result of two factors that are considered crucial when defining the consequences of the UK leaving the EU for the beef production in Scotland; namely, the trade agreements and the changes in domestic agricultural policy. It should be noted that the modelled impacts were based on several assumptions; hence, simulations cannot accurately represent the actual impacts for individual farms. Furthermore, comparing the observed data from the original database against model solutions could further validate the model and reveal its particular strengths and weaknesses. However, the exact calculations of several economic parameters in the database were unknown and therefore could not be used in a comparison. Still, the outcomes derived from the model were considered suitable for recognising general trends, indicating areas where low gains and pressure for structural adjustment were likely to have more impact. Also, the model results were found to be consistent with other studies that employed similar principles and scenarios (Harvey et al., 2019; Shrestha et al., 2018).

The impact of different prices resulting from alternative trade agreements on the beef sector will be proportionate to the degree of trade competitiveness (e.g. relative tariffs imposed) and trade openness achieved through the negotiations between the UK with the EU and countries from the rest of the word. The *LibTrade* scenario had a negative impact on farm profitability when compared to the baseline and other post-Brexit scenarios. This outcome could be attributed to a significant drop in beef prices as a consequence of UK setting zero tariffs on imports from both the EU and the rest of the world, while exports from the UK still faced trading partner's MFN tariffs (Feng et al., 2017). The impact of the *WTO* scenario was positive when the Pillar-1 simulation support was maintained, while the scenario that involved the *FreeTrade* arrangement had no significant impact compared to the baseline. These findings were in accordance with other studies that employed similar models to examine the effects of these particular scenarios on different UK agriculture sectors (Davis et al., 2017; Feng et al., 2017; Harvey et al., 2019; Shrestha et al., 2018).

However, model results showed that a change in farm subsidy payments was critical and caused a negative effect on farm gains under all post-Brexit scenarios, while a great number of farms stopped generating profit. This indicated that changes in farm payments were more vital to the financial performance of the majority of beef farms than alternative tariff rates and trade agreements. These findings underpin concerns over the viability of beef farming after Brexit, based on the fact that the majority of beef producers rely on support payments provided by the EU to sustain their farming activities (AHDB, 2016b; Vosough Ahmadi et al., 2015). Another interesting outcome was the variability observed regarding the magnitude of the effects of different prices originating from post-Brexit trade deals on different farm types. The top-performing farms (Q1) suffered the greatest losses under the *LibTrade*, *FreeTrade* and *WTO* scenarios without receiving direct support. Results showed that these farms (Q1) were more vulnerable to the deduction of governmental economic support, probably because of the difference in farm size translated into receiving a proportionally higher amount of direct support payments than smaller farms in other lower quartiles (Harvey et al., 2019).

Outcomes indicated differences between the average numbers of animals on each farm reflecting price implications under alternative post-Brexit trade agreements when compared to a baseline. The most considerable effect was the contraction in the animal number produced under the *LibTrade* scenario without providing direct payments to the beef farms. Under this hypothetical scenario, almost 30% of the enterprises that previously retained suckler cows in the baseline scenarios would completely de-stock their entire herd from the farms, highlighting the inefficient nature of beef production in Scotland without support from the government. In general, the decrease in stock number on beef farms, as result of political and economic shocks may have involuntary consequences for the farm environment as well as animal health and welfare (Stott et al., 2003; Vosough Ahmadi et al., 2015).

Given the magnitude of projected income reductions, it becomes evident that the pressure for structural change will be significant. However, the ScotBeefFarm model has been constructed to restrict every other production possibility, confining solutions only to activities currently observed for the given individual beef farm. In particular, the structural changes imposed by the low and non-existent in some cases profitability when direct payment scheme was removed reveals an underlying pressure for major adjustments for beef farmers. Hence, this particular push may lead farmers to search for alternative income sources, leading to prospects like diversifying their current farm activities, or increasing present levels of beef production efficiency, or even abandoning the farming activity. Also, regarding the environmental performance of beef farms, with results only reported for the finishing phase, reductions in animal numbers under *LibTrade* scenario without direct support, would indicate the potential to alleviating environmental pressures, with less GHG emissions and less overgrazing effects in burdened areas. Nevertheless, the emissions reduction for this scenario would not affect animal emission efficiency, and given the fact that the demand for beef remains unchanged, the global net GHG production would remain the same, and the impact of this scenario would be minimal.

6.4.2 Limitations of Approach and Future Research

The approach employed for designing the ScotBeefFarm model followed the principles of LP, hence, the projected model results have been restricted to portray only the optimal outcomes in contrast to the actual ones (Binfield and Hennessy, 2001). Also, the modelling framework assumes that all farmers behave in a manner that would facilitate profit maximisation, while this may not always be the case in real enterprises (Burbi et al., 2016; Moran et al., 2013). The assumption of perfect rationality is a common weakness of optimisation modelling, with various studies highlighting the differences in the behaviour of optimising agents and real-life farm managers, along with the need of further research in the area (Appel and Balmann, 2018). Besides, the model hypothesised that all farms within a farm category are the same, when in reality they will differ in structure, financial and biophysical characteristics (Moran et al., 2013). This study also assumed that all the resources in every farm were used at an optimal level when the case is that they might be constrained by the variability in farmers' skills or geophysical barriers (Shrestha et al., 2007).

Further limitations of the current approach excluded risk factors from the decision-making process (Glenk et al., 2017). An extension of the model could, therefore, incorporate an element of risk, for example through the development of probabilistic outcomes (e.g. Markov chains) for yield effects and costs over the years (Nielsen et al., 2004). It should also be noted that the fixed costs in the model were kept steady through the model cycles, as well as the cost for labour included did not differentiate between skilled and unskilled (Vosough Ahmadi et al., 2015). Further work could expand the existing model to allow fixed costs to change and assign different prices to corresponding types of available labour. Another reason for caution is that the effects on farm profitability caused by price implications under different trade agreements could be dwarfed by exchange rate movements, by possible changes in labour market conditions and by other non-tariff barriers (Harvey et al., 2019; Hubbard et al., 2018).

Future work could also focus on measuring the knock-on effects of the potential variations in the agricultural sector that would most likely have far-reaching effects in other sectors, such as the input supply and food processing industries. Investigating the impact of price movements due to trade and domestic policy scenarios to the entire UK food supply chain, particularly consumers, would be a significant, as UK food prices will depend not only on the tariff schedule put in place in the UK but also the value of the pound in foreign exchange markets (Harvey et al., 2019). Also, a more flexible approach than optimisation modelling could be employed in the future to examine fluctuations of factor prices, for example in land rents and labour costs because of the possible changes in availability in labour supply, due to restrictions in unskilled labour migration, and its consequences on agricultural wages and rural unemployment rates. Moreover, to accomplish a broader picture of the post-Brexit landscape of Scottish beef production, more research is needed in formulating additional scenarios capable of accurately depicting more diverse trade deals and future policies, because of the high levels of uncertainty surrounding the negotiations the forthcoming exit of the UK from the EU.

6.5 Conclusion

The ScotBeefFarm model described in this study is an LP optimisation model that could be employed as a tool to guide agricultural policy in the region of Scotland or other regions, by evaluating the impact of price changes under different post-Brexit trade agreements and domestic policies on beef farm profitability. It was evident that domestic decisions on direct payment support will potentially have significantly more serious implications on farm profitability than price fluctuations because of alternative trade deals negotiated between the UK, the EU, and the countries from the rest of the world.

The magnitude of the projected reductions in income due to price implications is such that the economic viability of many farms is uncertain under any trade scenario if Pillar 1 support is abolished without some associated increase in other (i.e. Pillar 1-type) support and/or alternative income support measures. This becomes more evident when studying changes in the herd structure, which imply that many livestock farms would simply cease production. These insights could guide the decision-making process aiming to prevent the realisation of scenarios that were shown to have adverse impacts on beef farm profitability and viability in Scotland. Although the exact nature of trading arrangements remains highly uncertain, the outcomes of this study appear worrying regarding the effects of eliminating the current financial support in the whole beef sector.

Chapter 7: General Discussion and Conclusion

7.1 General discussion

Over the next years, beef consumption is forecast to increase at a similar rate to population growth, since per capita consumption at a global level is expected to remain stable (OECD/FAO, 2017). Given the projected population growth rates, which predict a population increase by nearly 2.5 billion by 2050, with 90% of this growth in the developing world, the total beef consumption is still expected to rise by 1.5% yearly (Godfray et al., 2010; Tilman and Clark, 2014). By 2026 both production and the price of beef are expected to increase (OECD/FAO, 2017). Apart from population growth, other major drivers influencing world consumer demand are income per capita and income distribution (Alexander et al., 2015). The latest trends are pointing to an emergent global middle class that has more disposable income to acquire consumer goods, and are open to a western type of diet with higher levels of protein intake (Agriculture and Horticulture Development Board, 2017). This paradigm shift of world diets to a more “westernized” model is expected to increase beef consumed in developing countries by 21% over the coming decade, with 45% of additional beef demand credited to Asian markets; thus, altering existing food supply systems and creating export opportunities for high-value temperate zone meat products (OECD/FAO, 2017; Pingali, 2007).

Producing finished cattle is recognised as a strategic agricultural venture in Scotland, accurately reflecting the land characteristics and capability. Over 85% of Scotland’s agricultural area is suitable only for improved grassland or rough grazing and is classified as a less favoured area (LFA) (Vosough Ahmadi et al., 2015). In the absence of alternative agricultural uses, the land is employed for supporting ruminant livestock production that plays a vital role in sustaining local economies and the environment. Beef farms in Scotland generate the highest proportion of all agricultural output from the sale of animals for meat production (Scottish Government, 2018b; Vosough Ahmadi et al., 2015). The region's economic efficiency displays a strong dependence on the livestock sector compared to the UK as a whole or the average of EU members (ERSA, 2016). Consequently, concerning other European Union member states, Scotland has one of the highest ratio of beef to dairy cows, as well as a high proportion of cattle fattening farms. This fact highlights the reliance of the whole agricultural sector on beef finishing enterprises, hinting at susceptibility to potential economic challenges that these farms might face (Ihle et al., 2017).

However, during the sectoral analysis performed in Chapter 2, several issues of the beef production sector in Scotland were identified. The beef production sector is afflicted by low profitability that in most cases implies negative net margins for the producers. Also, the decreasing number of animals over recent times is leading to shortages in beef production. Further, the excessive fluctuation of the agricultural input prices over the last years combined with the forthcoming changes in the agriculture policy in Scotland, since the United Kingdom is leaving the European Union, resulted in increased uncertainty surrounding the economic viability of the sector. In addition, the climate emergency led Scotland to adopt legislation proposing a new target of net-zero emissions by 2045, which implies that beef enterprises must decrease their carbon footprint and greenhouse gas emissions while maintaining financial viability.

The ability of simulation models to investigate the implications that arise in complex systems, similar to those on beef finishing farms, without a large investment in infrastructural resources, makes them an attractive option in research (Pang et al., 1999a). Previous studies have employed simulation models to conduct whole-farm analysis in both dairy (Dillon et al., 2005) and beef systems (Crosson et al., 2006b, 2006a; Pang et al., 1999a). These models can provide a framework for evaluation of farm performance in terms of both technical and economic outputs and so are capable of robustly evaluating the impacts of alternative systems performance on farm profitability. Simulation models have been developed to extend the current level of knowledge in beef finishing systems by investigating their behaviour under various production, environmental and policy related scenarios (Plà, 2007).

In Chapter 3 the relevant literature concerning agricultural systems and mathematical modelling was reviewed, focusing mainly on models relevant to beef production farming systems. More specific, several models have been developed that simulate beef cattle growth and carcass composition (Hoch and Agabriel, 2004; Kilpatrick and Steen, 1999), feed intake and animal performance (Rotz et al., 2005), and feeding strategies (Bonesmo and Randby, 2010). While simulation models illustrate possible consequences of alternative decisions, optimisation models provide an objective function of profit that is maximised according to production alternatives (Stygar and Makulska, 2010). To investigate the numerous implications of policies on enterprises and farming systems, optimisation models (Veysset et al., 2005) and linear programming models (García-Martínez et al., 2011) have been previously employed. These models enable the broad investigation of alternative systems performance; however, the need arises for livestock simulation and optimisation modelling approaches based on region-specific robust datasets that will be efficiently pre-parameterized for conditions indicative of the system examined (Antle et al., 2017a).

By constructing models capable of simulating and optimising multi-year animal performance, the impacts of alternative management strategies can be robustly evaluated. The resulting variation in beef systems economic and environmental efficiency during the finishing phase, such as animal growth rate deviations and carcass price differentiation, could further be used to configure farm bio-economic models which to enable robust economic evaluation of alternative systems performance because of the management approach applied on farm.

The specific objectives of the studies described in this thesis were:

i) To investigate the factors affecting the physical and financial performance of beef production, to both regional and enterprise-level in Scotland, and develop comprehensive scenarios to examine the effect of variability in technical factors, policy environment and market conditions on farm profitability.

ii) To redevelop an existing bio-economic whole-farm model to construct a simulation model of the beef finishing stage of cattle production using the data generated from research specific for the region of Scotland and evaluate the effect of alternative management strategies on cost-effectiveness and efficiency of Scottish beef farm systems.

iii) To combine the aforementioned bio-economic simulation model and a farm-level GHG measuring tool to investigate the environmental effects of a wide range of temperate climate-based beef systems. The trade-offs originated from the mitigating emissions and increasing farm profitability were also explored for Scottish farms.

iv) To investigate the potential impact of Britain leaving the European Union on the structure and financial performance of beef finishing farms and consequently establish its implications on technical and economic output using a farm-level linear optimisation model.

Given the paucity of published models that quantify the individual and cumulative effects of management on the profitability of beef farms in Scotland, the study described in Chapter 4 aimed to develop a model to enable evaluation of alternative finishing management strategies over various scenarios. A bio-economic model to simulate Scottish conditions for beef finishing systems was developed by adjusting and re-parameterizing an existing framework of the whole-farm model the Grange Dairy Beef Systems Model (GDBSM) (Ashfield et al., 2013). The GDBSM is a static bio-economic model with feed and animal inventory calculated on a monthly time-step with outputs displayed in terms of technical (land use and animal live weight gain) and economic (costs and profit margins) results. A new model, the Grange Scottish Beef Model (GSBM), was designed to depict the Scottish environment and was informed using databases and results from experiments that have taken place in the region. The structure of typical livestock systems, animal performance, and nutrition were modelled in line with the results acquired from the "Lifetime growth pattern and beef eating quality" ("Growth Path") project, led by AHDB Beef & Lamb (Hyslop et al., 2016). Animal feed supply was based on a forage system calculating grazed grass and grass silage production of the farm, which was modelled following a field experiment and historic data from South-West Scotland (Bell et al., 2016). Beef carcass prices were modelled after gathering and analysing data from the Scottish Farmer publications, while stochastic modelling was employed to consider the seasonal and yearly fluctuation of prices (The Scottish Farmer, 2018). Further pricing data were gathered from diverse sources including Farm Management Handbook (2016), websites, publications from Scottish Government and personal communication with SAC Consultants (AHDB Beef & Lamb, 2018; Ashworth, 2009; ERSA, 2016; Hyslop et al., 2016; SAC Consulting, 2017; Scottish Government, 2014; The Scottish Government, 2015a, 2015b, 2008).

Farm performance was investigated by configuring a 120 hectare beef finishing farm as the base resource from which to simulate the effect of different finishing durations ('short', 'medium' and 'long'). In this farm, 175 kg of nitrogen were applied per hectare, with all livestock purchased in spring as yearlings, selling as finished cattle straight to abattoirs, at a range of monthly intervals

(Chapter 4). Scenarios based on varying aspects that affect financial outcomes were developed to examine the resilience of Scottish beef production systems. More specific, scenarios concerned finishing duration (French et al., 2001), choice of animal gender (Koknaroglu et al., 2005), feed efficiency (Cantalapiedra-Hijar et al., 2018), within-herd variation (Jenkins et al., 1991) and provision of governmental subsidies (Dwyer and Williams, 2018). Outputs in the form of differences and changes in enterprise net margin were displayed on a yearly basis. Opportunities to improve the profitability of beef production systems arise when focusing on finishing mainly steers in pasture-based medium duration systems. The prevalent beef production systems in Scotland, slaughtering at 24 months for both steers and heifers (Quality Meat Scotland, 2018a), were found to have 39% and 33% chances of recording losses, despite adding basic grants. All systems turn out to be highly dependent on direct payments from the EU and given the approaching departure of the UK from the EU, policy mechanisms should be conceived to protect the Scottish livestock sector from severe economic shocks.

The study in Chapter 5 aimed to evaluate the environmental performance of beef finishing systems typical for Scotland. The bio-economic model GSBM, which was developed in Chapter 4, was integrated with the already established carbon calculator AgRE Calc (Sykes et al., 2017) to measure the profitability and GHG emissions of typical Scottish beef production systems and subsequently explore strategies to address both low profitability and potential GHG mitigation. The common time step established between the two models enabled the examination of each system monthly, increasing the level of detail when evaluating performance parameters. The methodology developed in Chapter 5 facilitated the transfer of results from the GSBM simulation model as input values in AgRE Calc to calculate the GHG emissions of different beef finishing systems. The processes of evaluating a farms' carbon footprint and connecting the two models were optimised using Microsoft Visual Basic for Applications (VBA). The carbon footprint measures for different finishing durations composed a statistically comparable dataset, which supported the investigation of alternative durations and types of finish, to identify sustainable methods of beef production in Scotland. In terms of developing scenarios, numerous factors were identified affecting the emission intensity of beef production systems. Scenarios concerning the study of alternative finishing durations (Pelletier et al., 2010), types (Opio et al., 2013), diets (Beauchemin et al., 2010) and genders (McAuliffe et al., 2018) were examined, along with the vital relationship between an enterprise's cost-effectiveness and carbon footprint performance. Outcomes indicated that greater environmental impacts were produced in the longer grass-based production systems, especially the ones finishing heifers. While, for animal growth rates around 1 kg per day, high-quality pasture-based systems that support high growth demonstrated similar environmental performance as intensive concentrate-based systems, regardless of the finishing type and diet. Furthermore, the longer period grazing systems scored high on emissions per animal and low in profitability, while shorter duration systems performed better in cost-effectiveness, but had lower emissions intensity scores. However, high input grazing medium duration systems demonstrate the potential to satisfy increased profitability and sustainable environmental performance.

Considering the economic and political significance of the UK leaving the EU, it was decided to develop a farm-level linear optimisation (LP) model in Chapter 6, for investigating possible effects the Brexit might have on Scottish beef farms and finishing systems. The simple optimisation LP model 'ScotBeefFarm' was developed on the General Algebraic Modeling System (GAMS) (Diakité et al., 2019), and the data employed for the model were obtained from the Farm Business Survey (FBS) for Scotland (RESAS, 2018). The dataset consisted of 111 specialized beef production enterprises in Scotland and the production systems were based on the typical Scottish systems identified in previous chapters for the development of the GSBM (Chapter 4 & Chapter 5). The main constraints placed in the models were land for housing animals, feed, labour, and animal replacement available on a farm. Three alternative post-Brexit scenarios simulating alternative trade agreements concerning the Scottish agricultural sector were examined (Davis et al., 2017). Scenarios considered possible negotiation outcomes such as a free trade agreement with the EU, a unilateral trade liberation deal, or an absence of a trade agreement between the UK and the EU, each under assumptions of continued and withdrawn direct CAP support payments to farmers. Outcomes were reported in farm net margins comprised of the accumulated revenues collected from the final product of the farm activities minus the variable costs for inputs. Results revealed the magnitude of the financial losses depending on the production systems, as well as the underlying structural changes. It was shown that the impact of alternative trade agreements will be proportionate to the degree of trade competitiveness and openness negotiated while devising a mechanism to maintain the levels of financial support previously provided by the EU would define the viability of the beef sector in Scotland. Additionally, the consequences of the impending Brexit to agriculture could prove to have an irreversible damaging effect on beef production, with many enterprises being particularly susceptible due to their high reliance on governmental financial aid received for sustaining their farming activities. Such information is useful to both producers and policy makers alike as a blueprint to guide future prophylactic measures to protect against the alarming economic impacts that Brexit may have on Scotland's beef production sector.

7.2 Main concluding remarks

Managing beef production's aspects that are under the farmer's control, such as finishing duration, gender selection of stock, and nutrition is considered a key feature of an agricultural enterprise. Models can be used to better comprehend drivers of profitability in beef finishing systems and to identify opportunities for profitable and sustainable beef production. Estimating the impact of these factors by employing alternative scenarios, could provide valuable indicators of a farm's overall profitability and environmental performance. Additional inclusion of data from future studies about the examined factors as well as others less researched will greatly enhance the predictive capacity going forward.

Several opportunities exist to advance profitable, sustainable and more environment-friendly beef production in Scotland, for both cereal- and forage-based systems. Findings from the work presented in this thesis suggest that alternative management strategies such as aiming for a younger age profile at slaughtering, both in intensive housing systems and medium duration grazing-based approaches, were more cost-effective and had a reduced carbon footprint when compared with longer extensive systems. This was attributed mainly to higher feeding and input costs, as well as lower land use intensity for the shorter duration finishing systems. Additional evidence indicates that, regardless of the finishing type and diet, at a relatively high growth rate, animals performed similarly in terms of emissions intensity. Hence, demonstrating that for quality grass-based systems, which support high growth rates, the environmental load could be equivalent to that of intensive feedlot systems with similar growth rates.

Further possibilities for improving both profitability and environmental performance were found to lie in production systems that finish steers instead of heifers. In general, livestock systems finishing exclusively male cattle as steers have considerably lower emissions intensity, as well as generating more profit for the farmer. The financial differences can be generally explained by the fact that continental steers have the tendency to grow faster and produce heavier carcases, while heifers deposit fat tissue fast influencing negatively their carcass profile, value and methane emissions.

The profitability of beef production can be significantly improved when finishing cattle that were selected through breeding programmes focused on improving the trait of feed efficiency. Especially, when applied complementary with selection within the same breed or herd, it could have an effective long-term impact on genetic change for particular aims. In addition, cattle bred for feed efficiency were found to reduce environmental impact due to less manure production and fewer methane emissions.

In terms of evaluating the technical and economic performance of Scottish beef finishing systems, scenarios, where a system's performance may appear to be promising when applying average values, may lack flexibility when investigated using stochastic analysis. For the most common steer and heifer production systems in Scotland, the probability of an enterprise generating positive net margins without adding the subsidies is less than 10%. Findings indicate that both steer and heifer systems are highly dependent on European Union Common Agricultural Policy payments.

Finally, the effects of Britain leaving the European Union are projected to be significant for UK agricultural producers, exporters, and consumers. The existing trade and subsidy arrangements influencing the livestock and food market in the UK are currently in flux. Studying relative trade scenarios revealed that the removal of direct payments has significant implications for the beef sector as a whole, as subsidies are a crucial component of farm business income across the UK. The consequences could include land use changes and herd restructuring, threatening the viability of typical Scottish beef production systems.

7.3 Strengths and weaknesses of approaches

Models are not able to fully characterise a real system entirely and they will have undergone a process of constant improvement (Gradiz et al., 2007). Furthermore, when developing a general model there will be a trade-off between a more practical approach for less accuracy and precision (Hirooka et al., 1998). In addition, when modelling agricultural systems and emissions, weather, spatial, or temporal related uncertainties could reduce the robustness of farm system parameters that could influence the precision of model's calculations (Basset-Mens et al., 2009; Gibbons et al., 2006). A suitable technique proposed for an appropriate representation of beef production models is the development of a dynamic stochastic approach (Agabriel and Ingrand, 2004; Hoch and Agabriel, 2004). The software utilised in the construction of the dynamic management model can stochastically evaluate parameters such as animal growth or input parameters. However, it was decided that the data-intensive approach required to model certain variables stochastically within the model, would needlessly complicate the understanding of the overall impact of individual management strategies. The models developed utilised Monte Carlo simulation to perform stochastic analysis by accounting only for the variability created by fluctuation in prices. Nevertheless, aspects that could significantly influence the model behaviour are yet to be fully explored and included, for example, variability in animal performance, energy demands, grazed grass, and grass silage yields.

In the simulation of the scenarios selected for Chapter 4 the gender and the duration of the finishing period were identified as major contributory factors to overall farm profitability, as male animals finished as steers in shorter duration systems were proven to be more cost-effective. This was even more evident in Chapter 5 where the same factors had a significant effect on the environmental sustainability of a farm as they recorded a lower carbon footprint as well. Because of the scenarios examined in Chapter 4 and Chapter 5, great potential was identified for more sustainable finishing practices, such as finishing animals in medium duration high-input pasture systems. In addition, the profitability of these systems was further analysed under different policy scenarios to measure the dependency from the EU financial aid and the negative impacts of the forthcoming Brexit.

The UK Government plans to replace CAP by developing a novel post-Brexit agricultural policy, which would follow the principle that public funding through subsidies should be restricted to the provision of public goods, such as environmental improvement (Natural Capital Committee, 2017). Grass-based production systems support the preservation of grasslands and deliver a plethora of environmentally related public benefits, such as enhanced biodiversity, long-term soil fertility, and recreation that improves psychical and mental health (Chatterton et al., 2015; Dick et al., 2016; Horrocks et al., 2014). However, policy approaches oriented in providing public subsidies for environmental improvement will be required to consider delivering directly or indirectly net improvement in farm profitability (Bateman and Balmford, 2018). Hence, the medium duration pasture-based steer systems, which were identified as both more environmentally friendly and profitable, are expected to play a central role in Scotland's post-Brexit agricultural policy. The simulation of alternative finishing season lengths targeted in these systems would allow the investigation of a greater dispersal of slaughter points due to alternative management strategies.

Throughout this thesis, three different modelling approaches were used to investigate the sustainability and performance of beef production systems in Scotland. The GSBM contributed to extending the understanding of complex relationships that regulate beef production systems by gathering information from different sources and building on previous studies on feed efficiency and financial performance. The model produces outcomes that could guide the design of novel systems by examining the profitability of newly designed systems and compare them with the existing ones. Also, it provides a framework for investigating multiple effects of alternative policies, market and production conditions on beef farm profitability by designing and exploring a range of scenarios. While the GSBM is applicable in Scotland and other areas of the temperate climate zone, the core methodology followed was not specific to a particular geographic region and can be employed to simulate beef finishing systems in other contexts and regions. This applies equally to the approach for linking the GSBM with the carbon calculator AgRE Calc, and the process of building the optimisation ScotBeefFarm model. Since the methodology for all modelling approaches in this thesis was not explicit to a specific area, important inputs such as costs, animal performance, and ration composition can be adapted to simulate different regions and examine scenarios concerning beef finishing systems.

A reason for caution would be the paucity of appropriate datasets available while developing the models. Even though the dataset described typical Scottish systems, the figures employed represented only one beef production cycle; hence, plausible effects caused by year-to-year variation were excluded from the models. Due to the lack of appropriate data, several assumptions were made that decrease the available options during model designing and scenario construction. For example, in this study, grazing was excluded from shorter finishing duration systems, while a relatively large number of animals were assumed. Another assumption was that the model simulated the continental breed beef cattle genotype, accounting only for the animal performance of Limousin crossbred cattle that is the most used beef sire in Scotland and the UK. To be able to investigate implications of breed selection on farm profitability and environmental footprint, other breeds with different performance characteristics should be included in the models. Additionally, the implications concerning bull rearing, as well typical production options for dairy breeds, should be further considered as the model would be able to compare the animal performance of the dairy breeds to beef cattle breeds for each treatment and specific environment for more informative scenario analysis (McAuliffe et al., 2018).

Additional ambiguity could be instigated by the fact that for this study it was not possible to evaluate other environmental and economic issues related to beef production in beef finishing systems, because essential data on biodiversity, carbon sequestration, acidification, water footprint, and macroeconomic factors of production were not available. Furthermore, questions for future research were identified but were considered to be out of the scope of the models developed for his thesis. Important topics such as the social dimension of beef production systems, as well as issues concerning animal welfare, for example, the process of castration in steers, were left out of this analysis. Moreover, this particular study was concentrated on impacts linked to the finishing stage of beef production, while excluding from the results economic and environmental effects associated with the cow-calf phase emissions (Pelletier et al., 2010). This study did not consider implications concerning crop and animal integrated systems were not examined, even though the practice of crop-livestock integration has been thought to be a modern management practice in production systems with diverse economic, environmental, ecosystem and social benefits (de Figueiredo et al., 2017).

The models developed throughout the chapters of this thesis offer advancement on the previous bio-economic, environmental and policy impact assessment modelling approaches by linking dynamic simulations of the finishing stage and environmental carbon calculators with a whole farm analysis and optimisation of system performance while exploring policy change impacts. As a result, it fills a gap in scientific knowledge. However, various studies have indicated that to effectively translate findings from mathematical models into novel field practices a framework of decision support tools needs to be created (Newman et al., 2000). While not developed throughout this thesis, the potential of the software utilised to develop such tools implies that future research looking into the possibility of creating a useful application to aid management decisions in beef finishing farms may be warranted.

7.4 Conclusion

Within beef production systems, maintaining the high animal performance or even increasing it thought improved feed efficiency is critical to maximising profitability. There is a wide range of management techniques used to increase profit in a beef finishing enterprise; however, the results from this thesis indicate that finishing continental beef breed animals in high-input pasture-based systems, while achieving high animal growth rates and optimal nutrition should be given priority, as such a strategy will maximise both farm profitability and reduce carbon footprint. Sustainable and profitable prospects for commercial farms adopting medium-period, pasture-based steer production systems were highlighted throughout this study. It is important that while beef producers shift to alternative techniques and adopt more profitable production systems, policy makers legislate accordingly to protect the beef sector form external shocks. The beef sector has been sensitive to policy changes. However, by employing effective governance, the perceived negative impacts of Brexit could be altered to an opportunity for growth.

The findings of this thesis should provide a greater understanding of factors under the control of the farm manager, which can improve the profitability and the GHG emissions of a beef finishing enterprise. It is anticipated that the models developed will be employed to guide agricultural policy in the region of Scotland or other regions, by evaluating environmental, market, and production-related strategies. The level of dependence on the EU's financial aid, along with the effects of carcass and store price volatility on profitability for the most popular fattening systems in Scotland was identified. Other model outcomes suggested that more environmental friendly grass-fed beef could be produced while maintaining and even increasing farmer's profitability. Adoption of systems that would prove more stable and tailored to the region's strengths while decreasing the reliance form governmental financial support should be the aim of the agricultural policy of Scotland in the years that will follow after the UK leaves the union. The addition of a novel dynamic systems model, a bio-economic model linked with a an environmental carbon calculator and a general optimisation model with specific focus on beef production in the region of Scotland will bolster the previous research work carried out on beef cattle in the area and aid in the development of future models for the finishing stage. The possibility now exists, through the different software used in the construction of the models described in the thesis, to develop a more user-friendly decision support tool for use in the beef finishing industry.

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Appendix

Supplementary material for Chapter 4

Table 1

Live-weight gains (kg/d), live weight (kg) and different finishing durations included in the model*

Gender	Steers			Heifers		
Duration	Short	Medium	Long	Short	Medium	Long
Age of slaughter	16-17	18-24	25-35	14-17	18-24	25-35
Starting LW (kg)	390	380	350	265	315	315
Killing out (g/kg)	570	572	558	554	566	570
Conformation Score (1-15)	9.92	10.25	9.50	8.92	9.50	9.75
Fat score (1-15)	7.62	7.50	7.38	5.88	8.12	7.75

*Adopted from (Hyslop et al., 2016)

Table 2

The primary forage equations used in the Grange Scottish Beef Model

Model variables	Equations
Grazed grass yield (kg DM/ha)*	$3917.6+(65.73 \times N)-(0.2109 \times N^2)+(0.000232 \times N^3)$
Fill value grazed grass (CFU/kg DM)**	$95/(-13.9 + 145\ OMD)$
Net energy content of grass silage (UFV/kg DM)**	$1.48\ DMD - 0.294$
Net energy content of grass silage (UFL/kg DM)**	$1.29\ DMD - 0.1166$
Fill value of grass silage (CFU/kg DM)**	$-0.0018\ DMD + 2.65$
Intake capacity of growing animals (CFU kg d^{-1})**	$0.0368 \times W^{0.9}$
Intake capacity of finishing animals (CFU kg d^{-1})**	$0.2087 \times W^{0.6}$

*Adopted from (Bell et al., 2016)

**Taken from (Ashfield et al., 2013)

Table 3

Beef carcass average prices used for investigating Scottish beef finishing scenarios*

Beef prices (£/kg)	Steers	Heifers
U3	368	373
R3	365	366
O+3	356	353
O-3	324	311
U4L	368	373
R4L	367	366
O+4L	359	358
O-4L	328	316
U4H	365	368
R4H	366	364
O+4H	353	352
O-4H	316	307

*Taken from The Scottish Farmer

Table 4

Prices used in the scenarios to demonstrate the application of the Grange Scottish Beef Model

Steer yearling price (p/kg)*	201
Heifer yearling price (p/kg)*	206
Yearling concentrate (£/t)***	160
Finisher concentrate (£/t)***	150
Ammonium nitrate 34.5% (£/t)**	245
Urea (£/t)**	255
P & K compound for grazing 0–10–20 (£/t)***	255
P & K compound for silage 0–7–30 (£/t)***	237
Lime (£/t)**	20
Silage contractor (£/ha)***	154
Slurry spreading (£/m3)***	3.79
Silage value (£/ t DM)***	70

*Taken from (The Scottish Farmer, 2018)

**Taken from (SAC Consulting, 2017)

***Taken from personal interviews with SAC consultants

Table 5

Harvest date, yield and dry matter digestibility for first and second harvest grass silage*

1st Harvest dates	15-May	22-May	29-May	05-Jun	12-Jun	19-Jun
Grass yield (t DM/ha)	3.63	4.45	5.08	6.09	7.00	7.73
DMD (g/kg)	789	771	749	727	697	662
2nd Harvest dates			After 6 weeks of regrowth			
Grass yield (t DM/ha)	3.37	3.25	3.08	2.85	2.57	2.22
DMD (g/kg)	755	751	748	745	741	737

*Adopted from (Ashfield et al., 2013) and modified to better depict Scottish conditions after consulting a panel of beef specialists during a series of workshops and consultations.

Table 6: GSBM finishing treatments for both steers and heifers adopted from (Hyslop et al., 2016).

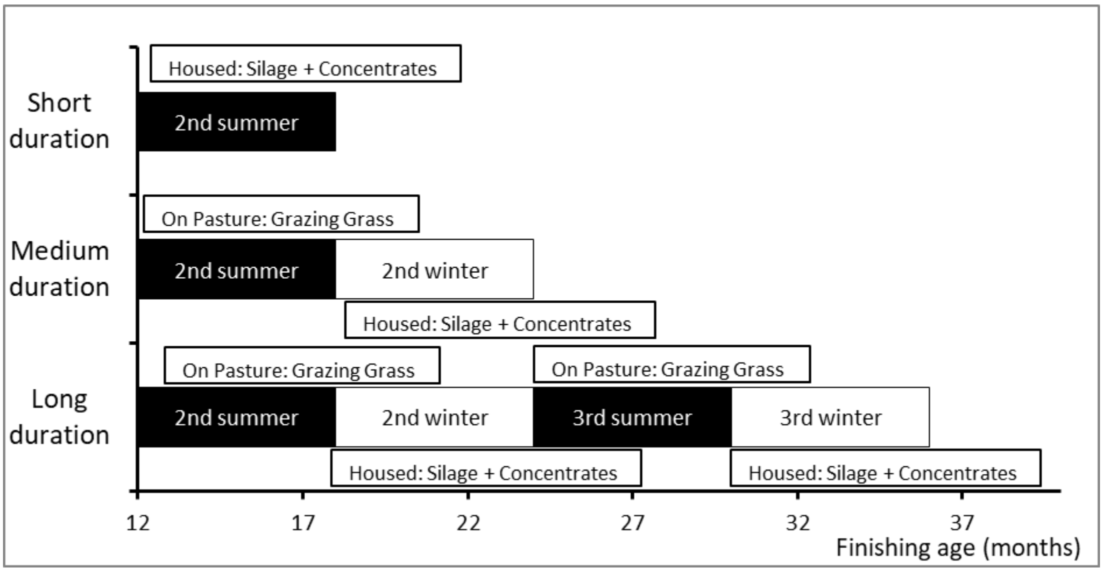


Table 7

Technical and Financial results of Steer systems investigated using the Grange Scottish Beef Model (1)

Steer systems	Short	Short	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Months	16	17	18	19	20	21	22	23	24
Physical results									
Area farmed (ha)	120	120	120	120	120	120	120	120	120
Grazing area (ha)	0	0	95	92	88	85	82	79	76
1st silage harvest (ha)	120	120	25	28	32	35	38	41	44
2nd silage harvest (ha)	0	0	17	19	21	23	25	27	29
Grazed grass (kg DM per animal sold)	0	0	1090	1092	1093	1095	1097	1099	1101
Grass silage (kg DM per animal sold)	581	658	396	464	536	603	680	756	838
Concentrates (kg DM per animal sold)	1468	1786	161	391	639	878	1154	1439	1749
Whole farm Inorganic N(kg N/ha)	125	125	178	179	179	180	180	181	181
Whole farm Organic N (kg N/ha)	244	246	106	118	128	139	150	160	170
Number purchased	884	782	378	368	357	348	338	329	319
Number finished	874	772	374	363	352	342	332	322	312
Liveweight output (kg per hectare)	5067	4764	1804	1868	1925	1972	2017	2056	2092
Carcass output (kg per animal sold)	397	422	331	353	376	395	417	438	460
Carcass output (kg per hectare)	2888	2716	1032	1068	1101	1128	1154	1176	1197
Financial (£ per animal)									
Revenue									
Livestock sales	1514	1581	1237	1318	1371	1421	1476	1484	1547
Livestock purchases	763	763	738	739	739	740	741	741	749
Gross output	752	818	499	579	631	682	735	742	798
Variable costs									

Concentrates	267	324	29	71	116	159	209	260	319
Grazing grassland	0	0	47	48	49	51	52	53	55
Silage	43	49	45	49	54	58	64	69	75
Slurry	15	18	4	8	12	16	19	23	27
Straw	32	38	9	14	20	26	32	38	45
Vet and Med	23	24	23	24	25	26	27	28	30
Reseeding	2	2	4	4	4	4	4	4	4
Marketing and transport	64	64	40	40	40	40	40	40	40
Total variable costs	446	518	201	258	319	379	447	516	597
Fixed costs									
Car, electricity, phone	5	5	11	11	11	12	12	12	13
Hired labour	100	114	50	70	89	109	129	148	170
Machinery operating	9	10	20	21	21	22	23	23	24
Land improvement maintenance	10	11	14	16	18	19	21	23	26
Other	5	5	11	11	12	12	13	13	13
Loan interest	1	1	1	1	1	1	2	2	2
Fixed costs	128	146	107	130	153	176	199	222	247
Depreciation Charges									
Land improvements	0	0	1	1	1	1	1	1	1
Buildings	7	8	17	17	18	18	19	19	20
Machinery	3	3	4	4	5	5	6	6	6
Total Depreciation Charges	10	12	21	22	23	24	25	26	27
Total fixed costs	139	158	129	152	176	200	224	248	275
Gross margin	306	300	298	321	312	302	289	227	201
Net margin	167	142	169	169	136	102	65	-21	-74

Table 8

Technical and Financial results of Steer systems investigated using the Grange Scottish Beef Model (2)

Steer Systems	Long	Long	Long	Long	Long	Long	Long	Long	Long	Long	Long
Months	25	26	27	28	29	30	31	32	33	34	35
Physical results											
Area farmed (ha)	120	120	120	120	120	120	120	120	120	120	120
Grazing area (ha)	75	79	82	85	80	76	73	69	67	64	62
1st silage harvest (ha)	44	41	38	35	40	44	47	51	53	56	58
2nd silage harvest (ha)	29	28	25	24	26	29	32	34	36	37	39
Grazed grass (kg DM per animal sold)	1101	1519	1697	1873	1876	1879	1882	1885	1888	1892	1895
Grass silage (kg DM per animal sold)	838	1056	1058	1060	1235	1409	1594	1784	1914	2060	2204
Concentrates (kg DM per animal sold)	1749	609	610	611	612	613	614	615	616	617	619
Whole farm Inorganic N(kg N/ha)	181	181	180	180	181	181	182	182	182	183	183
Whole farm Organic N (kg N/ha)	170	144	142	141	145	148	150	152	156	159	163

Number purchased	319	238	220	205	197	190	183	176	172	167	163
Number finished	312	232	214	199	191	184	177	170	166	161	157
Liveweight output (kg per hectare)	2092	1134	1050	980	985	988	991	992	1001	1009	1017
Carcass output (kg per animal sold)	460	327	328	330	345	360	375	390	404	419	434
Carcass output (kg per hectare)	1197	633	586	547	550	552	553	553	558	563	567
Financial (£ per animal)											
Revenue											
Livestock sales	1146	1199	1222	1253	1299	1313	1370	1392	1419	1450	1436
Livestock purchases	687	687	687	687	688	688	688	689	689	689	689
Gross output	459	512	535	565	611	625	681	704	731	761	746
Variable costs											
Concentrates	118	118	118	118	140	164	189	216	247	282	318
Grazing grassland	67	74	81	88	90	93	95	98	100	102	104
Silage	97	99	101	104	116	129	143	157	166	177	187
Slurry	20	20	20	20	23	27	31	35	38	42	46
Straw	25	25	25	25	30	35	41	47	53	59	66
Vet and Med	46	47	48	49	50	51	51	52	53	54	55
Reseeding	5	6	6	7	7	7	7	8	8	8	8
Marketing and transport	40	40	40	40	40	40	40	40	40	40	40
Total variable costs	417	428	438	449	497	546	598	652	705	764	824
Fixed costs											
Car, electricity, phone	16	17	19	20	21	22	22	23	24	25	25
Hired labour	136	138	141	143	162	182	201	221	240	260	279
Machinery operating	29	32	35	37	39	40	42	44	45	46	47
Land improvement maintenance	28	30	33	35	37	40	42	45	47	49	52
Other	16	18	19	21	22	22	23	24	25	26	26
Loan interest	2	2	2	2	2	2	2	2	2	2	2
Fixed costs	227	238	248	258	283	308	333	359	383	407	432
Depreciation Charges											
Land improvements	1	1	2	2	2	2	2	2	2	2	2
Buildings	24	27	29	31	32	33	35	36	37	38	39
Machinery	7	8	8	9	9	10	10	11	11	12	12
Total Depreciation Charges	33	36	38	41	43	45	47	49	50	51	53
Total fixed costs	260	273	286	299	326	353	380	407	433	459	485
Gross margin	42	84	97	116	114	79	83	51	26	-3	-78
Net margin	-218	-189	-189	-183	-212	-274	-297	-356	-407	-462	-563

Table 9

Technical and Financial results of Heifer systems investigated using the Grange Scottish Beef Model (1)

Heifer Systems	Short	Short	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Months	16	17	18	19	20	21	22	23	24

Physical results									
Area farmed (ha)	120	120	120	120	120	120	120	120	120
Grazing area (ha)	0	0	94	83	75	68	61	56	52
1st silage harvest (ha)	120	120	26	37	45	52	59	64	68
2nd silage harvest (ha)	0	0	18	25	30	35	39	42	46
Grazed grass (kg DM per animal sold)	0	0	977	979	981	982	984	985	987
Grass silage (kg DM per animal sold)	786	853	383	582	774	953	1157	1334	1522
Concentrates (kg DM per animal sold)	832	1083	97	164	248	331	432	556	692
Whole farm Inorganic N(kg N/ha)	125	125	179	180	181	182	183	184	184
Whole farm Organic N (kg N/ha)	180	190	115	120	125	129	132	136	139
Number purchased	653	603	416	381	352	329	306	289	273
Number finished	645	595	411	376	347	324	301	283	267
Liveweight output (kg per hectare)	2942	2918	1694	1633	1586	1546	1507	1483	1459
Carcass output (kg per animal sold)	303	326	280	295	311	325	340	356	371
Carcass output (kg per hectare)	1630	1617	959	924	898	875	853	839	826
Financial (£ per animal)									
Revenue									
Livestock sales	1157	1235	1051	1105	1141	1173	1214	1241	1310
Livestock purchases	535	536	633	634	634	635	635	636	643
Gross output	622	699	418	471	506	538	579	605	667
Variable costs									
Concentrates	151	197	18	30	45	60	78	101	126
Grazing grassland	0	0	42	45	48	51	55	57	61
Silage	59	64	42	57	71	85	100	113	129
Slurry	15	18	4	8	12	16	19	23	27
Straw	24	28	8	12	17	22	27	32	32
Vet and Med	25	25	25	26	27	28	29	30	32
Reseeding	2	2	3	3	4	4	4	5	5
Marketing and transport	64	64	40	40	40	40	40	40	40
Total variable costs	340	398	182	222	264	304	352	401	453
Fixed costs									
Car, electricity, phone	6	7	10	11	12	12	13	14	15
Hired labour	100	114	50	70	89	109	129	148	170
Machinery operating	12	13	18	20	22	23	25	26	28
Land improvement maintenance	10	11	14	16	18	19	21	23	26
Other	6	7	10	11	12	13	14	15	16
Loan interest	1	1	1	1	1	2	2	2	3
Fixed costs	135	153	103	129	154	178	204	228	257
Depreciation Charges									
Land improvements	1	1	1	1	1	1	1	1	1
Buildings	10	10	15	16	18	19	20	22	23
Machinery	3	4	4	4	5	5	6	7	8
Total Depreciation Charges	14	15	20	22	24	25	28	29	32

Total fixed costs	148	167	123	150	177	204	231	258	289
Gross margin	282	301	236	249	242	234	226	204	214
Net margin	134	134	113	99	65	30	-5	-54	-75

Table 10

Technical and Financial results of Heifer systems investigated using the Grange Scottish Beef Model (2)

Heifer Systems	Long	Long	Long	Long	Long	Long	Long	Long	Long	Long	Long
Months	25	26	27	28	29	30	31	32	33	34	35
Physical results											
Area farmed (ha)	120	120	120	120	120	120	120	120	120	120	120
Grazing area (ha)	76	81	84	87	83	79	76	72	70	68	66
1st silage harvest (ha)	44	39	36	33	37	41	44	48	50	52	54
2nd silage harvest (ha)	29	26	24	22	25	27	29	32	33	35	36
Grazed grass (kg DM per animal sold)	1298	1502	1707	1911	1914	1917	1920	1923	1927	1930	1933
Grass silage (kg DM per animal sold)	978	979	981	983	1140	1297	1464	1634	1750	1881	2011
Concentrates (kg DM per animal sold)	135	135	135	136	253	371	499	632	785	959	1134
Whole farm Inorganic N(kg N/ha)	181	180	180	180	180	181	181	182	182	182	183
Whole farm Organic N (kg N/ha)	152	148	144	142	145	149	152	155	159	163	166
Number purchased	272	245	223	205	198	191	185	179	175	171	167
Number finished	266	239	217	199	192	186	179	173	169	164	160
Liveweight output (kg per hectare)	1050	960	886	825	831	835	839	841	850	858	865
Carcass output (kg per animal sold)	270	275	279	283	296	308	321	333	344	357	369
Carcass output (kg per hectare)	598	547	505	470	474	476	478	480	484	489	493
Financial (£ per animal)											
Revenue											
Livestock sales	964	1020	1047	1084	1121	1135	1176	1198	1217	1246	1259
Livestock purchases	640	640	640	640	641	641	641	642	642	642	642
Gross output	325	380	407	443	480	494	535	556	575	604	617
Variable costs											
Concentrates	26	26	26	26	47	69	91	115	143	174	205
Grazing grassland	64	72	80	88	90	92	95	97	99	101	103
Silage	90	93	95	98	109	121	133	146	154	163	172
Slurry	20	20	20	20	23	27	31	35	38	42	46
Straw	20	20	20	20	25	29	34	39	44	49	55
Vet and Med	30	30	30	30	30	30	30	30	30	30	30
Reseeding	5	5	6	7	7	7	7	8	8	8	8
Marketing and transport	40	40	40	40	40	40	40	40	40	40	40
Total variable costs	295	306	318	328	372	415	462	510	555	607	658
Fixed costs											
Car, electricity, phone	15	17	18	20	21	21	22	23	23	24	25
Hired labour	136	138	141	143	162	182	201	221	240	260	279
Machinery operating	28	31	34	37	39	40	41	43	44	45	46

Land improvement maintenance	28	30	33	35	37	40	42	45	47	49	52
Other	16	17	19	21	22	22	23	24	24	25	26
Loan interest	1	1	1	2	2	2	2	2	2	2	2
Fixed costs	224	235	246	258	283	307	332	357	381	405	429
Depreciation Charges											
Land improvements	1	1	2	2	2	2	2	2	2	2	2
Buildings	23	26	28	31	32	33	34	35	36	37	38
Machinery	7	7	8	8	9	10	10	11	11	11	12
Total Depreciation Charges	31	34	37	41	43	44	46	48	49	50	52
Total fixed costs	255	269	284	298	325	352	378	405	430	456	481
Gross margin	29	74	90	115	108	79	73	47	20	-3	-42
Net margin	-226	-196	-194	-183	-217	-273	-305	-359	-410	-459	-523

Supplementary material for Chapter 5

Summary description of the Grange Scottish Beef Model

The Grange Scottish Beef Model (GSBM) is based on earlier modelling work in Ireland (Ashfield et al., 2013), but obtained its main functions and coefficients from datasets gathered from conducted in Scotland (Bell et al., 2016; Hyslop et al., 2016). The “Lifetime growth pattern and beef eating quality” (“Growth Path”) project (Hyslop et al., 2016) included a wide range of finishing options and was primarily used to design core aspects of the model. The part simulating the different finishing systems in the model was intended to replicate animal treatments from the “Growth path” study. The model initiated the simulation at 12-months of age with animals entering the farm on 1st of May, which is a typical date for spring-born animals in Scotland (Hyslop et al., 2016). Scenarios concerning cattle on short duration systems were the exception as animals were assumed to enter the farm on 1st of March (10-months of age). Details on the three different treatments that led to three distinct “growth-paths" (i.e. short, medium and long), as well as for each gender and finishing duration are presented in Supplementary Figure 1.

Default parameters including starting live-weight and monthly live-weight gains were taken from the same experiment. In addition, the original growth rates were adopted to regulate the animal intake and were used for the calculation of net energy requirements (Supplementary Table 2). The variability measured during this experiment informed the simulation of average initial live-weights. Subsequently, these were calculated at the start of each month and based on the previous month's starting live-weight and live-weight gain. Growth equations were based on liveweight and liveweight gain and were adapted to calculate the net energy requirements and animal intake capacity for GSBM.

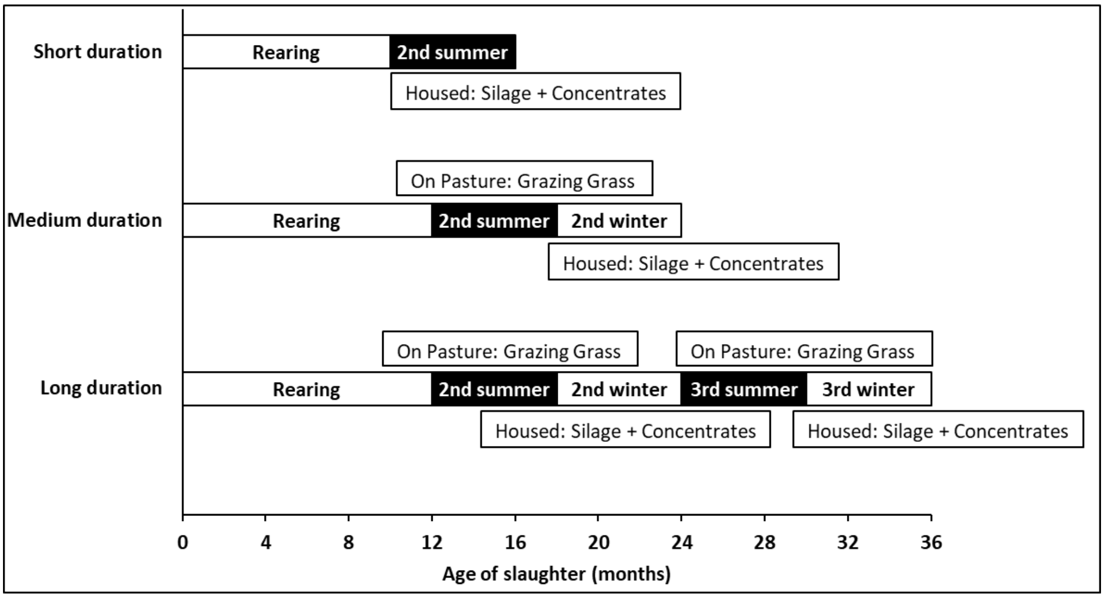
The GSBM calculates animal requirements and designs diets using grazed grass, grass silage and concentrates to meet these demands, while all relevant specifications were described as animal energy requirements and subject to a maximum intake capacity. The modelled land area of grass-based beef systems consists mostly of permanent perennial ryegrass swards, which is characteristic of Scottish systems. Data from a field experiment in South-West Scotland were used to create an equation predicting grass growth from Nitrogen (organic and inorganic) application rates (kg/ha), while the expected yield and monthly distribution of grass growth was based on historic Scottish data (Bell et al., 2016; Kamilaris et al., 2019). Grass silage was produced by isolating some of the grass swards during peak growth periods. Animal nutrition drove the demand for silage, which in turn indicated the proportion of the area required for grass silage. The feed grown in the farm was modelled as a constraint for forage intake, while brought-in concentrates made up for the difference. Typical barley-based concentrate ration were assumed for the finishing animals (energy content of 1.15 UFL or UFV/kg DM).

For grazing animals, the stocking rates were specified as organic nitrogen output per hectare for cattle, with the maximum amount of organic nitrogen output restricted to 170 kg N/ha for the UK in agreement with the Nitrates Directive (The Scottish Government, 2008). The same methodology was applied to slurry production, its nutrient content and available nutrients. The volume of the slurry produced was based on the number of animals, number of days spent indoors, as well as the amount of slurry produced per animal per day. Slurry application was assigned to the grass silage areas with 70% in spring and 30% over the summer, while its nutrient content was considered when calculating chemical fertilizer requirements, which followed values suggested for Scotland in the Technical Note for fertilizer recommendations for grasslands (Sinclair et al., 2013). A number of the main forage equations used in the GSBM are presented in Supplementary Table 3.

The major purpose of GSBM was to simulate the biological operation and economic performance of Scottish beef finishing enterprises. The beef prices used in the model are a function of the conformation and fat class of the animal. The profitability analysis includes variable costs (e.g. concentrate, fertiliser, silage making, veterinary and medicine, reseeding, straw, slurry spreading, market and abattoir costs, transport costs and land rental) and fixed costs (e.g. electricity, car, phone, land improvements maintenance, machinery operating, building maintenance and labour). The main output from the financial sub model is the monthly and annual cash flow and annual profit and loss account. Relevant data to inform these costs were gathered from numerous sources (AHDB Beef & Lamb, 2018; Ashworth, 2009; ERSA, 2016; Hyslop et al., 2016; SAC Consulting, 2017; Scottish Government, 2014; The Scottish Government, 2015a, 2015b, 2008).

From the early stages of the GSBM's design process, several sessions with researchers at Scotland's Rural College and SAC consultants helped identify the suitable biological relationships and validate coefficients employed in the model (Kamilaris et al., 2019). As with many farm systems models, the absence of appropriate independent datasets further complicated the validation process of the GSBM. This led to the selection of an evaluation and validation method by "knowledgeable individuals'', an approach based on the principle of ''face validity'' (Qureshi et al., 1999; Rykiel, 1996; Sargent, 2010).

For this purpose, a validation workshop was organised with thirteen knowledgeable individuals (including beef specialist consultants, grass specialists, professors, farm managers and researchers). Workshop activities aimed to produce appropriate feedback from the beef experts regarding the model's performance and accuracy. Subsequently the comments from the workshop were applied to recalibrate the model and following a series of consultations with beef experts form SAC Consulting, supporting both model verification and model validation processes, they were content that GSBM was simulating beef finishing systems in Scotland satisfactorily (Kamilaris et al., 2019).



<u>Figure 1</u>: GSBM finishing treatments for both steers and heifers adopted from (Hyslop et al., 2016; Kamilaris et al., 2019).

A total of 72 animals, representative of the Limousin crossbred beef cattle genotype, entered the study at 12 months of age (yearlings), with the exception of animals in short duration treatments entering the study two months earlier, and were offered either a mixture of concentrates with forage based finishing diets or grazed diverse quality grasslands. Steers and heifers, being treated under three management regimes, led to three distinct "growth-paths" (Hyslop et al., 2016).

The short duration treatment animals were finished indoors on an intensive silage and concentrate based finishing system and slaughtered at 16-17 months of age.

The medium finishing duration animals were turned out to graze a high quality grass from 12-17 months of age and finished indoors during the subsequent winter feeding period when offered a mixed silage and concentrate finishing diet. They were slaughtered at 18-24 months of age when judged to have achieved commercially acceptable carcass characteristics (target R4L).

The long finishing duration animals were grazed for two summer periods on poor quality, unimproved grassland with the intervening winter period being a store period where the animals were offered forage based diets. The final finishing diet was a mixed silage and concentrate diet offered during their second winter prior to slaughter at 25-36 months of age (Hyslop et al., 2016).

Table 1

Total Greenhouse gas emissions from beef systems simulated to finish either steers or heifers

System	Age of Slaughter	Emissions Intensity (kg CO2-eq/kg LWG)	
		Steers	Heifers
Short	16	7.59	7.33
	17	7.77	7.55
Medium	18	10.22	10.59
	19	10.06	11.22
	20	10.03	11.97
	21	10.08	12.52
	22	10.21	13.11
	23	10.36	13.63
	24	10.56	14.20
Long	25	15.80	19.52
	26	16.79	20.34
	27	17.89	21.29
	28	18.97	22.23
	29	18.75	21.81
	30	18.65	21.56
	31	18.73	21.53
	32	18.86	21.58
	33	18.91	21.56
	34	19.01	21.60
	35	19.19	21.73

Table 2

Live-weight gains (kg/d), live weight (kg), stocking rates and different finishing durations included in the model

Gender	Steers			Heifers		
Duration	Short	Medium	Long	Short	Medium	Long
Age of slaughter	16-17	18-24	25-35	14-17	18-24	25-35
Starting LW (kg)	390	380	350	265	315	315
Slaughter weight range (kg)	652-696	550-766	579-752	506-547	468-628	466-626
Killing out (g/kg)	570	572	558	554	566	570
Stocking rate (LU/ha)	2.02	1.54	0.87	1.52	1.46	0.88

Adopted from (Hyslop et al., 2016; Kamilaris et al., 2019)