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# Title: Modelling alternative management scenarios of economic and environmental sustainability of beef finishing systems

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# Abstract:

The livestock industry, and particularly beef production, is recognised as an important source of greenhouse gas (GHG) emissions linked to climate change. The complexity of beef systems means that appropriate GHG mitigating strategies depend on local conditions, requiring tailored entry points to be identified and evaluated. Using Scotland as a case study, here we combine a bio-economic simulation model and farm-level carbon footprinting tool to study 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 (i.e. 18-24 months) pasture-based beef production systems in Scotland were found to achieve a balance between financial returns and environmental performance.

Keywords: Beef production systems; Greenhouse gas; Environmental modelling; Carbon footprint

# 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 14.5% of all human-induced emissions (Gerber et al., 2013; Rojas-Downing et al., 2017). Among the livestock sector, the cattle industry, with over 1.3 billion cattle globally, accounts for 65% of the whole livestock sector's emissions (4.6 Gt $CO_2$-eq) (Gerber et al., 2015, 2013). Beef production attracts more attention than dairy beef since contributing 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 53.9% 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). Besides, 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 to 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 interrelating 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 since 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 that is the precise reason why it is important considering issues of 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.

# Materials and Methods

## Model description

### 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 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 that calculated 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 the 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 on 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 is assuming poor utilisation of the forage production area, which is typical for beef systems keeping animals housed for the whole finishing duration. 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 on the Supplementary Material.

## 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.

## 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 on GSBM and the results produced were then introduced to AgRE Calc to provide estimates of emissions intensity for animals within the finishing systems (Figure 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 breakdown every system to 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 connection channel between the two models as well as automate the footprinting process. Data collected from the amalgamation of the two models, provided the basis for comparison of different durations and types of finish, identifying sustainable methods of beef production in Scotland.

Subsequently, results from the GSBM simulation model were adopted as input values in 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 together 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 comprised 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.

## 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 2).

The system 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 ~~employed as a basis for modelling the Scottish finishing systems~~ assumed that all animals were treated in the same way prior to entering the system and were randomly assigned across alternative growth path management regimes (Hyslop et al., 2016), so excluding this stage from the calculation of lifecycle emissions intensity does not affect the relative ranking of the different systems. In addition, by excluding this part from the model, the variations on economic and environmental performance of finishing systems become independent from calves' performance early in life, affected by mothers' body conditions during weaning, and could now 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, a number of 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.

# Scope of the Study

## Factors

### Finishing duration

Several factors have been identified as having a key impact on the emissions intensity of production; the duration of the finishing period is one such variable. 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 that 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 on a monthly time step to systems' financial and environmental performance.

## Finishing type and diet

Global beef production systems demonstrate additional complexity, due to the fact that 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 distinct 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). <u>The effects of type (housing/pasture) and diet (concentrates/grass) had on a system's 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 were grazing on perennial ryegrass swards</u>

Diet is a key driver of the carbon footprint and the amount of GHGs emitted from beef cattle, particularity on the finishing stage (Beauchemin et al., 2010). During the finishing stage, feeding treatments for substituting roughage with concentrates results 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). <u>Nutritional strategies to decrease cattle emissions</u> ~~The rate of supplementation~~ usually depend~~s~~ on interactions between 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).

## Gender selection

Differences in animal performance between steers and heifers have been shown, 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, studies found notable differences in animal performance between genders in terms of emission intensities, with steers producing lower emissions than heifers (McAuliffe et al., 2018). The model includes both steer and heifer systems for the simulation, in an effort to capture the magnitude of gender effect on beef finishing systems in Scotland. Simulation results enabled a comparison between genders, to identify differences in performances for each finishing age.

## Farm profitability in relation to greenhouse gas emissions

For examining 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 system was the medium finishing at 18 months for steers and the short finishing at 16 month systems for heifers. For the short duration systems, 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 3).

# Results

## Effects of finishing duration

~~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 (Figure 4).~~ In Figure 4, the relative contribution of different sources to the absolute GHG emissions of heifer finishing systems are presented. 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 land and crops category, a trend for an increasingly large contribution over time was noted, while the opposite tendency resulted for emissions from livestock enteric fermentation on finishing systems. The feeding and bedding category contributed more on 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.

## Effects of finishing type and diet

~~The effects of type (housing/pasture) and diet (concentrates/grass) had on a system's 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 were grazing on permanent perennial ryegrass swards~~. Analysis revealed a strong relationship between LWG (kg $day^{-1}$) and emissions intensity was revealed ($CO_2$-eq kg $LWG^{-1}$) for each treatment (Figure 5). ~~Analysis showed that~~ 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).

## Effects of gender

Results for total GHG emissions produced on systems simulated to finish exclusively either steers or heifers are reported in Figure 6 (Supplementary Table 1 in Supplementary Material). For the two short duration systems at 16 and 17 months, the steer systems scored slightly higher on emissions intensity than heifer systems in both cases. 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.

## Effects of farm profitability in relation to greenhouse gas emissions

~~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~~. Figure 7a shows the relationship between the land and crops emissions with profitability. Especially, for the medium and long duration systems, the emissions from land and crops were higher as the cost-effectiveness was decreasing. As a result, the longer duration less profitable systems recorded higher land and crops emissions. Figure 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 steer 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 7c, the relationship between the carbon footprint evaluation, measured with the total GHG emissions, and the cost-effectiveness analysis of the evaluated systems considering the financial aspect of the rural producer, expressed by the net margin of an enterprise is shown. Here, after grouping results on 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.

# Discussion

## 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 similar growth rate. Results from this study were compared with similar findings from McAuliffe et al., (2018). Slight differences between emissions intensities were noted, with lower values were reported in this study. These differences could be attributed to animal physiology expressed through different ~~diverse~~ genotypes of cattle measured in each study (i.e. Limousin and Aberdeen Angus two-breed reciprocal crosses ~~Limousin crosses~~ (Kamilaris et al., 2019) in contrast to Charolais x Hereford-Friesian cattle (McAuliffe et al., 2018)), along with the effect produced by variability in grass quality.

Differences were noted between the two genders in terms of emissions intensity for all systems examined. Systems that finished steers were found to have 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. Long period grazing systems appear to have low emissions per animal but score low in profitability with negative net margins for all systems. In contrast, most of the medium and all of the short duration systems appear profitable but show higher emissions intensity. In search of a solution that could satisfy high profitability and sustainable environmental performance, the 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 displaying lower GHG emissions. To be more specific for both steers and heifers', the 18 and 19 month systems appear to belong to a range of "win-win" 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). Especially for Scotland, where opportunities may be found in 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, 2016).

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 ecosystems 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·ha$^{-1}$·yr$^{-1}$ (Conant et al., 2017). Nevertheless, despite the fact that the reported increases to soil organic matter are substantial, 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).

## Limitations of approach and future research

This particular 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 essential to study emissions during the fattening stage particularly in Scotland, as longer finishing strategies are common and often associated with inefficiencies and additional emissions produced (Ogino et al., 2004; Quality Meat Scotland, 2018). ~~Nevertheless, as the cow–calf phase is accountable for approximately 63% of total emissions, irrespective of the production system (Pelletier et al., 2010); linking this stage with the outcomes of this study, which isolated the fattening stage, may alter the current grouping of the results~~.

A significant ~~nother~~ 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 GHG emissions analysis. 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 to the calculation of a range of outputs (Casey and Holden, 2006; Foley et al., 2011).

Future work could focus on ~~employing a different type of modelling to~~ optimizinge results and improvinge identification of "win-win" scenarios. Further analysis and optimisation of the modelling outcomes could result in greater understanding of the underlying connections between profitability and GHG emissions on 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 in 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 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 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., 2018a; 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 et al., 2018b, 2018a).

## 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 the region of Scotland or other regions, 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; hence, suggesting that economic and environmental performances of livestock production systems may not always be positively correlated~~Although emissions intensity for most of concentrate fed beef, pork, and chicken production systems is lower than efficiently produced grass fed beef, results suggest that other aspects should be considered as well, before determining the role of livestock production systems in global food security~~. These insights could guide the decision-making process towards the goal of lowering the GHG emissions of beef industry, whilst maintaining and even increasing farmer's profitability.


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