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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

1 **Introduction**

2 Greenhouse gas (GHG) emissions have gained attention due to their effect on the global climate. The
3 role of GHG emissions in climate change and the urgency to mitigate its adverse effects to avoid
4 further temperature rise, has been highlighted during the United Nations Framework Convention on
5 Climate Change, the Kyoto Protocol and the Paris Agreement (IPCC, 2013). Agricultural activities
6 related to food supply chains are considered to have substantial environmental impact accounting
7 for 26% of all anthropogenic GHG emissions, while non-food agriculture and other drivers of
8 deforestation contribute a further 5% (Frank et al., 2017; Poore and Nemecek, 2018; Tubiello et al.,
9 2015). The livestock sector has been associated with the main gases linked to climate change, i.e.
10 carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) (Steinfeld et al., 2006), and its
11 emissions represent an estimated footprint of 7.1 gigatonnes (Gt) CO₂-eq per annum, or 14.5% of all
12 human-induced emissions (Gerber et al., 2013; Rojas-Downing et al., 2017). Among the livestock
13 sector, the cattle industry, with over 1.3 billion cattle globally, accounts for 65% of the whole
14 livestock sector's emissions (4.6 Gt CO₂-eq) (Gerber et al., 2015, 2013). Beef production attracts
15 more attention than dairy beef since contributing around 41% of the total sector emissions (2.9 Gt
16 CO₂-eq) (Gerber et al., 2015, 2013; Poore and Nemecek, 2018). Additionally, beef cattle are
17 considered responsible for 53.9% of the global enteric CH₄ emissions and are currently the largest
18 contributor of manure NH₃ emissions, accounting for 41% of all animal sectors (Wang et al., 2018).

19 Nonetheless, beef is a valuable commodity, as it provides high-quality protein to consumers and
20 consistent income to producers (FAO, 2011). Global food security trends showed an increase in the
21 absolute number of undernourished people in the world to 821 million in 2017, following a growing
22 trend over the last years, returning the share of people suffering from hunger to levels recorded a
23 decade ago (FAO, 2018). Meat is an important source of high value protein and micronutrients; thus,
24 inclusion of even small quantities on a diet could improve the nutritional status of undernourished

25 populations, by addressing micro- and macronutrient deficiencies, particularly of children, pregnant
26 and lactating women (Biesalski, 2005; FAO, 2011; Scollan et al., 2006). Besides, global demand for
27 beef as a protein source is increasing, driven mainly by the expected population growth, the rapid
28 pace of economic development and the “westernisation” of diets in Asian and surrounding countries
29 (Alexander et al., 2015; Godfray et al., 2010; Smith et al., 2018).

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

45 Post-2020 climate change related policies adopted after the Paris Agreement (Hof et al., 2017; Rogelj
46 et al., 2016) employed a methodology based on the Intergovernmental Panel on Climate Change
47 (IPCC) guidelines for quantifying and reporting national greenhouse gas emissions (IPCC, 2013,
48 2006). Since beef systems are complex systems, with interrelating components like soils, crops,
49 feeds, animals and manures, optimal GHG mitigating strategies will depend on local conditions

50 requiring explicit individual management approaches to identify specific entry points and evaluate
51 mitigation opportunities (Del Prado et al., 2013). Models and predictive tools have been developed
52 since to estimate GHG emissions from livestock systems (Del Prado et al., 2013), based on process
53 simulation modelling (Schils et al., 2007), emission factor calculation (Amani and Schiefer, 2011) and
54 life cycle assessments (LCA) (Cowie et al., 2012; de Boer et al., 2011; de Vries and de Boer, 2010).
55 Several attempts, either empirical or mechanistic (Jose et al., 2016; Kebreab et al., 2008), to predict
56 beef cattle GHG emissions, were based on research with cattle in temperate climates (Ellis et al.,
57 2009; Escobar-Bahamondes et al., 2017; IPCC, 2006; Kebreab et al., 2006; Yan et al., 2009). A key
58 barrier to mitigate emissions from beef production systems is regional and local variation in
59 conditions and production practices, leading to a complicated and problematic process of capturing
60 an optimum value (Opio et al., 2013).

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

71 Here we investigate the environmental impact of a range of beef finishing systems, as well as the
72 trade-offs generated between mitigating emissions and increasing farm profitability, using Scotland
73 as a case study. We combine a bio-economic simulation model (Grange Scottish Beef Model) and a
74 farm-level GHG footprinting tool (AgRE Calc) focused on temperate grassland-based beef systems.

75 Environmental and economic scenarios were explored to enhance understanding of current systems
76 and explore strategies to address both low profitability and potential GHG mitigation. The novelty of
77 this study lies in the way it utilised and combined two distinct models to develop a common
78 methodology for investigating GHG emissions and profitability in beef farms, offering insights by
79 analysing various scenarios for the beef finishing stage.

80 **Materials and Methods**

81 **Model description**

82 **Grange Scottish Beef Model**

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

93 Production systems modelled were based on the “Lifetime growth pattern and beef eating quality”
94 (“Growth Path”) project that represented systems typical of commercial practice for the UK and
95 Scottish farms, previously reported by AHDB Beef & Lamb (Hyslop et al., 2016). During the study, all
96 animals representative of the Limousin crossbred beef cattle genotype experienced three different
97 treatments that led to three distinct “growth-paths” (Hyslop et al., 2016). The six production options
98 modelled represent the short, medium and long finishing treatments along with two genders (steers

99 and heifers), reproducing the continuous experimental design of the Growth Path trial. Scenarios
100 involving finishing either male or female animals on a range of finishing ages for each of three
101 distinct treatments, whereby cattle were slaughtered at intervals of 16-17, 18-24 and 25-35 months
102 of age ('short', 'medium' and 'long' durations respectively). Land area was set to 120 ha, typical for a
103 beef finishing farm in Scotland. Likewise, the inorganic nitrogen input on the grazing area was fixed
104 at 175 kg N/ha across the different systems. All livestock were purchased as yearlings at 12 months
105 of age and the number of animals was matched to land area and forage production. For the shorter
106 duration finishing systems, only one silage cut harvest date was modelled, on 29th May. The one cut
107 silage system is assuming poor utilisation of the forage production area, which is typical for beef
108 systems keeping animals housed for the whole finishing duration. In contrast, for the medium and
109 longer pasture-based systems, two silage cuts were assumed with 6 weeks of regrowth. An extended
110 summary of the GSBM containing additional information regarding the creation, evaluation and
111 validation processes is included on the Supplementary Material.

112 **AgRE Calc**

113 The Agricultural Resource Efficiency Calculator (AgRE Calc) was developed as part of the Scottish
114 Government's Farming for a Better Climate initiative by the consulting division of Scotland's Rural
115 College (SRUC) and has been previously described by Sykes et al. (2017). The carbon footprint tool
116 was developed in alignment with IPCC (2006) Tier I and II methodology and is PAS2050 certified
117 (IPCC, 2006; Sykes et al., 2017). AgRE Calc employed IPCC (2006) Tier II methodology to estimate
118 emissions stemming from livestock and manure management, whilst IPCC (2006) Tier I methodology
119 is used to calculate N₂O emissions from fertiliser applications and crop residues (IPCC, 2006). The
120 model considers embedded emissions from the production of fertilisers, which were calculated using
121 emission factors (EFs) from (Kool et al., 2012), while embedded emissions for imported feed and
122 bedding were calculated according to Vellinga et al., (2013). Emissions from electricity and fossil
123 fuels were estimated using emission factors from DEFRA/DECC (2011) Conversion Factors for

124 Company Reporting (Sykes et al., 2017). Results include an analysis detailing separate emission types
125 and sources.

126 **The synthesis of the Grange Scottish Beef Model and AgRE Calc**

127 The bio-economic model (GSBM) and farm-level carbon footprinting tool (AgRE Calc) were combined
128 to simulate typical beef production systems in Scotland. Scenarios that replicate current production
129 systems were developed on GSBM and the results produced were then introduced to AgRE Calc to
130 provide estimates of emissions intensity for animals within the finishing systems (Figure 1). One of
131 the key challenges during the process of linking and coordinating the two models was to establish a
132 common time step that could be used for recording results. By taking advantage of the flexible
133 design of GSBM, it was possible to breakdown every system to a monthly basis and then generate
134 the carbon footprint through AgRE Calc on the same basis. This level of detail, assessing dietary and
135 performance parameters at the herd level for a monthly time-step, allowed the carbon footprint
136 results for different finishing durations to form a statistically comparable dataset. Furthermore,
137 Microsoft Visual Basic for Applications (VBA) was used to optimise the connection channel between
138 the two models as well as automate the footprinting process. Data collected from the amalgamation
139 of the two models, provided the basis for comparison of different durations and types of finish,
140 identifying sustainable methods of beef production in Scotland.

141 Subsequently, results from the GSBM simulation model were adopted as input values in AgRE Calc to
142 calculate the GHG emissions of different beef finishing systems. To examine the impacts of factors
143 such as fattening duration, type and gender selection on emissions intensity, broader categories that
144 included emissions with interconnected sources were established. Five groups were identified; land
145 and crops (N₂O, CO₂ and embedded), enteric emissions (CH₄), manure (CH₄ and N₂O), feed and
146 bedding (embedded) and fuel and electricity use (CO₂ and embedded). Land and crops represented
147 primarily N₂O emissions, grouping together emissions from crop residues, fertiliser application
148 (organic and inorganic) or (manure from farm and synthetic), lime and urea, as well as embedded

149 emissions from fertilizer and lime. Enteric methane included the methane emissions from livestock's
150 enteric fermentation process. The manure category comprised of methane emitted during the
151 anaerobic decomposition of organic matter while in storage and nitrous oxide emitted during
152 storage and soil application. Finally, the feed and bedding category included the embedded
153 emissions from feed and bedding, while fuel and electricity considered CO₂ and embedded emissions
154 from diesel, electricity and other fuel, as well as the embedded emissions from transporting and
155 disposing of carcasses.

156 **System boundary**

157 This study focuses on the fattening stage of beef production, comparing different systems and
158 management practices. A “gate-to-gate” approach was adopted, where the main costs concerning
159 the post-weaning period of cattle production until slaughtering the animals were included in the
160 model (Berton et al., 2016; Mahath et al., 2019; Ogino et al., 2004). The finishing phase was defined
161 as beginning with the purchase of yearling cattle (either 10 or 12 months old) and ending with the
162 marketing of finished animals (16 to 35 months of age). The beef finishing cycle also included
163 activities like pasture management, feed (silage) production, feed transport, animal management,
164 and cattle waste treatment (Figure 2).

165 The system examined here did not include the cow-calf phase, even though it is recognised to have
166 the main impact on the total carbon footprint associated with beef production, regardless of the
167 finishing strategy (Pelletier et al., 2010). One cow will produce one calf per year; thus for every
168 animal entering the finishing stage a mature cow, along with replacement heifers and bulls, is
169 retained. This aspect doubles the resource requirements and emissions per live-weight kg of beef
170 produced in the system (Phetteplace et al., 2001). The study ~~employed as a basis for modelling the~~
171 ~~Scottish finishing systems~~ assumed that all animals were treated in the same way prior to entering
172 the system and were randomly assigned across alternative growth path management regimes
173 (Hyslop et al., 2016), so excluding this stage from the calculation of lifecycle emissions intensity does

174 not affect the relative ranking of the different systems. In addition, by excluding this part from the
175 model, the variations on economic and environmental performance of finishing systems become
176 independent from calves' performance early in life, affected by mothers' body conditions during
177 weaning, and could now be fully attributed to management strategies (McAuliffe et al., 2018). The
178 aim was to further explore factors during the beef finishing stage, such as finish duration, diet, and
179 gender, which have been identified as significant determinants of emissions intensity (Ogino et al.,
180 2004). As such, a number of factors were studied through scenarios designed to provide a
181 comprehensive assessment of beef finishing systems in Scotland, with an emphasis on identifying
182 key features that contribute to emissions mitigation.

183 **Scope of the Study**

184 **Factors**

185 **Finishing duration**

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

197 provided insights into the effects of duration on a monthly time step to systems' financial and
198 environmental performance.

199 **Finishing type and diet**

200 Global beef production systems demonstrate additional complexity, due to the fact that many
201 systems, particularly in the northern hemisphere's temperate zones, display a highly seasonal nature
202 (Opio et al., 2013). In temperate climates, it is common for animals to be housed during the colder
203 or wetter part of the year (Beauchemin et al., 2010; Casey and Holden, 2006). This seasonal
204 movement between housed and grass-based situations represents a distinct change in diet and
205 activity levels and is distinct from the feedlot-based diet treatments. These changes in diet regimes
206 affect animal performance and impact the carbon footprint of finishing systems (Pelletier et al.,
207 2010). The effects of type (housing/pasture) and diet (concentrates/grass) had on a system's total
208 GHG emissions were explored and reported on a monthly basis. When the animals were housed,
209 they were fed mainly concentrate-based diets, while when out on pasture, they were grazing on
210 perennial ryegrass swards

211 Diet is a key driver of the carbon footprint and the amount of GHGs emitted from beef cattle,
212 particularly on the finishing stage (Beauchemin et al., 2010). During the finishing stage, feeding
213 treatments for substituting roughage with concentrates results in reduced enteric methane (CH₄)
214 production by lowering the pH of the rumen and switching fibre for starch (Knapp et al., 2014).
215 However, producing concentrates for feed is also emissions intensive, resulting in potential trade-
216 offs between enteric CH₄ and land-based N₂O emissions (Hünerberg et al., 2014). Nutritional
217 strategies to decrease cattle emissions ~~The rate of supplementation~~ usually depends on interactions
218 between production of enteric CH₄, rates of liveweight gain (LWG), and emissions generated in the
219 production, as well as processing and transport of concentrates, leading to uncertainty regarding the
220 most efficient approach to finishing beef cattle (Beauchemin et al., 2008). It is also evident that
221 feeding approaches could achieve a reduction of methane emissions, especially when combined

222 with genetic and management approaches (15-30%) (Knapp et al., 2014). Simulation results enabled
223 the investigation and comparison of scenarios involving both feedlot- (“short”) and pasture-based
224 (“medium” and “long”) diets use through different finishing systems (Hyslop et al., 2016).

225 **Gender selection**

226 Differences in animal performance between steers and heifers have been shown, with steers
227 consuming more feed, growing faster, and more efficiently than heifers, resulting in contrasting
228 carcass outputs per area farmed (Koknaroglu et al., 2005; Steen and Kilpatrick, 1995). However,
229 studies found notable differences in animal performance between genders in terms of emission
230 intensities, with steers producing lower emissions than heifers (McAuliffe et al., 2018). The model
231 includes both steer and heifer systems for the simulation, in an effort to capture the magnitude of
232 gender effect on beef finishing systems in Scotland. Simulation results enabled a comparison
233 between genders, to identify differences in performances for each finishing age.

234 **Farm profitability in relation to greenhouse gas emissions**

235 For examining the essential relationship between an enterprise’s cost-effectiveness and carbon
236 footprint performance, financial results previously generated from the GSBM for the corresponding
237 beef finishing systems were employed (Kamilaris et al., 2019). An analysis of the profitability of each
238 system was performed alongside each system’s total emissions, and the two main GHG emission
239 categories, namely the land and crops as well as the enteric emissions groups. Lower financial
240 returns were evident for the longer finishing systems, with the largest losses reported for the 35
241 month finishing system. The most profitable system was the medium finishing at 18 months for
242 steers and the short finishing at 16 month systems for heifers. For the short duration systems, diet
243 was set to include only silage and concentrates; thus, the model assumed that these types of
244 systems could sustain a great number of animals, representing larger intensive feedlot-type beef
245 finishing enterprises. Overall, the systems that generated profit were the short and most of the
246 medium duration finishing systems for both steers and heifers (Figure 3).

247 Results

248 Effects of finishing duration

249 ~~To examine the effect of varying finishing periods on emission intensity, the relative contribution of~~
250 ~~different sources to the absolute GHG emissions of systems are presented for heifer finishing~~
251 ~~systems (Figure 4). In Figure 4, the relative contribution of different sources to the absolute GHG~~
252 ~~emissions of heifer finishing systems are presented.~~ In all systems examined, the dominant emission
253 source was enteric fermentation. Common trends occur for different systems, particularly in terms
254 of the relevant contribution of land and crops as well as enteric methane emissions to the total of
255 systems' GHG emissions. For land and crops category, a trend for an increasingly large contribution
256 over time was noted, while the opposite tendency resulted for emissions from livestock enteric
257 fermentation on finishing systems. The feeding and bedding category contributed more on short
258 duration systems (16-17 months), as these represented more intensive methods of production,
259 compared to the medium (18-24 months) and long duration finishing systems (25-35 months),
260 where the relative contribution was reduced. Manure emissions remained relatively stable for all
261 systems over time, while the fuel and electricity category increased with duration.

262 Effects of finishing type and diet

263 ~~The effects of type (housing/pasture) and diet (concentrates/grass) had on a system's total GHG~~
264 ~~emissions were explored and reported on a monthly basis. When the animals were housed, they~~
265 ~~were fed mainly concentrate based diets, while when out on pasture, they were grazing on~~
266 ~~permanent perennial ryegrass swards. Analysis revealed a~~ strong relationship between LWG (kg day⁻¹)
267 and emissions intensity was revealed (CO₂-eq kg LWG⁻¹) for each treatment (Figure 5). ~~Analysis~~
268 ~~showed that~~ It was evident that when LWG was low, which is typical for cattle during grazing
269 periods, high levels of GHG emissions were observed. On the contrary, for high levels of growth,
270 livestock systems with housed cattle had fewer total emissions. Furthermore, for LWG, around one
271 kg per day, the gap in emissions intensity between housed and grazing systems effectively closed. It

272 is key to focus on systems that facilitate animals achieving a relatively high LWG while on pasture as
273 the environmental impact was significantly lower than similar cases with low LWG. Results
274 generated can be related to experimental data obtained by other UK studies, by employing the
275 linear regressions produced (McAuliffe et al., 2018).

276 **Effects of gender**

277 Results for total GHG emissions produced on systems simulated to finish exclusively either steers or
278 heifers are reported in Figure 6 (Supplementary Table 1 in Supplementary Material). For the two
279 short duration systems at 16 and 17 months, the steer systems scored slightly higher on emissions
280 intensity than heifer systems in both cases. For the remaining systems of medium and long duration,
281 a shift was observed with heifer systems surpassing the steer systems in terms of total GHG
282 emissions. Finishing female animals on less intensive systems, from 18 to 35 months appeared to be
283 less environmentally efficient than the corresponding fattening systems that were simulated to
284 finish steers.

285 **Effects of farm profitability in relation to greenhouse gas emissions**

286 ~~An analysis of the profitability of each system was performed alongside each system's total~~
287 ~~emissions, and the two main GHG emission categories, namely the land and crops as well as the~~
288 ~~enteric emissions groups.~~ Figure 7a shows the relationship between the land and crops emissions
289 with profitability. Especially, for the medium and long duration systems, the emissions from land and
290 crops were higher as the cost-effectiveness was decreasing. As a result, the longer duration less
291 profitable systems recorded higher land and crops emissions. Figure 7b shows the association
292 between emissions intensity from cattle enteric methane emissions and the farm's net margins for
293 every system. Two distinct groups appeared on this figure, for both steer and heifers, one included
294 the long duration systems and the other the medium and the short duration systems. The medium
295 and short duration systems performed better on profitability but showed increased enteric methane
296 emissions compared to long duration systems. Finally, in Figure 7c, the relationship between the

297 carbon footprint evaluation, measured with the total GHG emissions, and the cost-effectiveness
298 analysis of the evaluated systems considering the financial aspect of the rural producer, expressed
299 by the net margin of an enterprise is shown. Here, after grouping results on different systems (short,
300 medium, long), a negative relationship was revealed for each category of finishing systems (e.g.
301 “short”, “medium”, “long”), where lower emissions were associated with higher profitability.

302 **Discussion**

303 **General discussion**

304 The long extensive systems (“long”) have a greater environmental impact when compared to both
305 intensive housing systems (“short”) and medium duration grazing-based approaches (“medium”).
306 These findings were in accordance with other studies on livestock systems emissions, which
307 reported shorter finishing periods could reduce emissions (Cardoso et al., 2016; Casey and Holden,
308 2006). This outcome was driven mainly by the greater land and crops emissions produced in the
309 longer duration systems, for both steers and heifers. A conclusion linked with findings from recent
310 studies, which confirmed that intensive finishing systems tend to display a lower land use intensity
311 than extensive, pasture-based systems, even after the crop production area for feed was included
312 (Bragaglio et al., 2018; Capper et al., 2012). Forage and concentrate feeding during the finishing
313 stage accelerates growth and allows more beef to be produced per unit grazing area (Swain et al.,
314 2018). Additional reasons include the lower requirements for inorganic N fertiliser in short and
315 medium systems (McAuliffe et al., 2018). In addition, livestock methanogenic emissions from the
316 rumen were the single greatest source of GHG emissions for most of the systems, in consonance
317 with other studies on beef production systems (de Vries et al., 2015). It is worth noting that, in the
318 last three long duration heifer systems (33, 34 and 35 months), emissions from land and crops
319 surpassed those of enteric CH₄.

320 At growth rates around 1 kg per day, animals performed similarly in terms of emissions intensity,
321 regardless of the finishing type and diet. These findings indicate that high-input grass-based systems
322 with quality pastures supporting high growth rates have a low environmental load that is analogous
323 to that for intensive concentrate-based systems with similar growth rate. Results from this study
324 were compared with similar findings from McAuliffe et al., (2018). Slight differences between
325 emissions intensities were noted, with lower values were reported in this study. These differences
326 could be attributed to animal physiology expressed through ~~different diverse~~ genotypes of cattle
327 measured in each study (i.e. Limousin and Aberdeen Angus two-breed reciprocal crosses ~~Limousin~~
328 ~~crosses~~ (Kamilaris et al., 2019) in contrast to Charolais x Hereford-Friesian cattle (McAuliffe et al.,
329 2018)), along with the effect produced by variability in grass quality.

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

342 While investigating the relationship between a farms' profitability and environmental performance,
343 results reveal two distinct groups for both steer and heifer systems; one includes the long finishing
344 period systems and the other the short and medium duration systems. Long period grazing systems

345 appear to have low emissions per animal but score low in profitability with negative net margins for
346 all systems. In contrast, most of the medium and all of the short duration systems appear profitable
347 but show higher emissions intensity. In search of a solution that could satisfy high profitability and
348 sustainable environmental performance, the attention is directed towards those high input grazing
349 medium duration systems that suffice in both categories. Despite, the higher profitability
350 demonstrated from the intensive systems, two medium systems appear to score similarly on
351 profitability and displaying lower GHG emissions. To be more specific for both steers and heifers',
352 the 18 and 19 month systems appear to belong to a range of "win-win" realistic scenarios for both
353 profitable and more environmental-friendly beef production. To further support the case for
354 medium duration grass-based beef finishing systems, studies on alternative beef forage-based
355 systems have reported promising results in terms of their potential as mitigation strategies to
356 balance GHG emissions produced, especially for systems with animals grazing on improved pasture
357 (Kamali et al., 2016) and systems employing adaptive multi-paddock (AMP) grazing (Stanley et al.,
358 2018). Especially for Scotland, where opportunities may be found in finishing systems, where a
359 proportion of grass is included in the diet, resulting in high value products from grass-fed animals
360 that could potentially offer higher returns (AHDB, 2016).

361 Furthermore, wider implications could support the case for medium duration pasture-based beef
362 production systems. Well-preserved grasslands provide ecosystem services and could have a positive
363 effect on long-term soil fertility (Dick et al., 2016; Horrocks et al., 2014). Promoting pasture-based
364 beef production systems may have wider socio-economic implications in terms of increased rural
365 employment as well as valuable ecosystems services. Grass-based systems are closely associated
366 with a range of social and economic benefits like rural tourism, recreation, which alleviates burdens
367 linked with progressively urban lifestyles, and many distinctive features of the rural landscape with
368 historic and aesthetic significance (e.g. patchwork of fields bounded by hedgerows and stone walls,
369 etc.) (Chatterton et al., 2015). The potential for carbon sequestration in grazing lands is significant,
370 but at the same time, the estimates are highly uncertain. Synthesis of evidence suggested that even

371 though responses varied greatly, improving grassland management practices could lead to soil
372 carbon sequestration, by an average of 0.47 Mg C·ha⁻¹·yr⁻¹ (Conant et al., 2017). Nevertheless,
373 despite the fact that the reported increases to soil organic matter are substantial, concerns have
374 been expressed regarding the magnitude of the potential climate change mitigation credited to
375 enhanced soil management (Schlesinger and Amundson, 2018).

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

386 **Limitations of approach and future research**

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

392 ~~Nevertheless, as the cow-calf phase is accountable for approximately 63% of total emissions,~~
393 ~~irrespective of the production system (Pelletier et al., 2010); linking this stage with the outcomes of~~
394 ~~this study, which isolated the fattening stage, may alter the current grouping of the results.~~

395 A ~~significant~~ ~~rather~~ reason for caution when modelling agricultural emissions would be implications
396 induced by a system's inherent variations and uncertainties (Gibbons et al., 2006). For instance,
397 weather, spatial or temporal related uncertainties could reduce the robustness of emission factors,
398 and variation surrounding farm system parameters could influence the GHG emissions calculated
399 from a model (Basset-Mens et al., 2009; Crosson et al., 2011). Although this study is limited in the
400 sense that modelling uncertainty was not explicitly considered, future work could explore ways to
401 incorporate this aspect on the GHG emissions analysis. For example, other studies have developed
402 distributions for uncertain model parameters by utilised Monte Carlo simulation (Basset-Mens et al.,
403 2009; Gibbons et al., 2006), or performed sensitivity analysis on a set of important factors, resulting
404 to the calculation of a range of outputs (Casey and Holden, 2006; Foley et al., 2011).

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

417 A more comprehensive evaluation of other environmental and economic issues related to beef
418 production in beef finishing systems was not possible in this study, because essential data on
419 biodiversity, carbon sequestration, acidification, water footprint and macroeconomic factors of

420 production were not available. Future research should concentrate on collecting data to support an
421 extensive analysis of environmental and economic sustainability performance of Scottish beef
422 finishing systems. Moreover, further research is needed to determine the socio-economic
423 implications of shifting between alternative beef farming systems. Future research should assess the
424 “gate-to-gate” social risks and benefits of Scottish beef finishing systems considering indicators of
425 socio-economic sustainability like demographics, economic activity and community aspects (Pelletier
426 et al., 2018a; Revéret et al., 2015). Working with a social life cycle assessment framework to identify
427 the relevant stakeholder groups (e.g. workers, local community, society, value chain partners) and
428 social themes (e.g. access to resources, fair salary, health and safety, social benefits, equal
429 opportunities, local employment, community engagement) could provide insights, supplementing
430 research done on financial and environmental aspects to inform future policies (Pelletier et al.,
431 2018b, 2018a).

432 **Conclusion**

433 The model synthesis described here to assess scenarios regarding the environmental impact of beef
434 production farms while estimating the possible trade-offs generated between mitigating emissions
435 and increasing farm cost-effectiveness, is supported by the increasing necessity to guide local and
436 European agriculture toward production systems that are environmentally friendly, socially
437 acceptable, and profitable for the farmers. The methodology that allowed a bio-economic
438 production model to be linked with an environmental carbon calculator can be further employed as
439 a tool to guide agricultural policy in the region of Scotland or other regions, by evaluating both
440 environmental and production related scenarios. Environmental friendly beef finishing systems,
441 producing lower emissions were identified when finishing steers on intensive short duration
442 systems. Findings also highlighted profitable prospects for commercial farms adopting medium-
443 period, pasture-based beef production systems. In fact, this study indicated that beef production
444 systems with low carbon footprint entail trade-offs between farm profitability and global

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

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