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Life cycle assessment of pasture-based suckler steer weanling-to-beef production systems: Effect of breed and slaughter age

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ABSTRACT

Demand for beef produced from pasture-based diets is rising as it is perceived to be healthier, animal friendly and good for the environment. Animals reared on a solely grass forage diet, however, have a lower growth rate than cereal-fed animals and consequently are slaughtered at an older age. This study focused on the former by conducting life cycle assessments of beef production systems offering only fresh or conserved grass, and comparing them to a conventional pasture-based beef production system offering concentrate feeding during housing. The four suckler weanling-to-beef production systems simulated were: (i) Steers produced to slaughter entirely on a grass forage diet at 20 months (**GO-20**); (ii) Steers produced to slaughter entirely on a grass forage diet at 24 months (**GO-24**); (iii) Steers produced to slaughter on a grass forage diet with concentrate supplementation during housing (**GC-24**), and (iv) Steers produced to slaughter entirely on a grass forage diet at 28 months (**GO-28**). Two breed types were evaluated: early-maturing and late-maturing (**LM**). The environmental impacts assessed were global warming potential (**GWP**), non-renewable energy (**NRE**), acidification potential (**AP**), eutrophication potential (marine (**MEP**) and freshwater) were expressed per animal, per kg live weight gain (**LWG**), kg carcass weight gain, and kg meat weight gain (**MWG**). The GO-20 production system had the lowest environmental impact across all categories and functional units for both breeds. Extending age at slaughter increased environmental impact across all categories per animal. The LWG response of EM steers to concentrate feed supplementation in GC-24 was greater than the increase in total environmental impact resulting in GC-24 having a lower environmental impact across categories per kg product than GO-24. Concentrate feed supplementation had a similar effect on LM steers with the exception of NRE and AP. The increase in daily LWG in the third grazing season in comparison to the second grazing and housing resulted in GO-28 having lower GWP, NRE, AP, and MEP per kg product than GO-24. Early-maturing steers had lower environmental impact than LM when expressed per kg LWG. However the opposite occurred when impacts were expressed per kg MWG, despite LM steers producing the least LWG. The LM steers compensated for poor LWG performance by having superior carcass traits, which caused the breed to have the lowest environmental impact per kg MWG. The results reaffirms the importance of functional unit and suggests reducing the environmental impact of LWG does not always translate into improvements in the environmental performance of meat.

Implications

Beef produced in pasture-based systems is perceived to be healthier and of higher animal welfare than feedlot systems, however cattle are commonly finished at an older age due to lower growth rates. At a common slaughter age, although the supplementation of concentrate feed increases total environmental impact, when expressed per unit product a dilution effect occurs. To reduce environmental impact and optimise output of grass-fed beef systems, farmers should adopt systems that minimise age at slaughter and match breed types to appropriate diet/finishing practices. Furthermore, industry should focus on functional units that are most representative of the primary product when assessing mitigation strategies.

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Introduction

The global agricultural sector is currently faced with the complex challenge of meeting the growing global food demand while simultaneously adapting to the impact of climate change, contributing to climate change mitigation, and preserving and enhancing the sustainable use of natural resources (FAO, 2018). Livestock production, in particular ruminant systems such as beef production has significant environmental impacts where it has been reported to be responsible for 41% of global livestock greenhouse gas (**GHG**) emissions and the reduction in soil fertility and water quality (McDowell and Hamilton, 2013; de Vries et al., 2015; Goulding, 2016). However, red meat produced from these systems is a high quality source of protein as well as numerous micronutrients such as iron, vitamin A, iodine, zinc, and vitamin B12 which is naturally sourced in animal-based foods (Monahan et al., 2012). To reduce the environmental burden of such food production systems and ensure future long-term food security, it is pivotal that economically viable agricultural systems and management practices that promote the sustainable use of natural resources, and the reduction in pollutants are adopted (McAuliffe et al., 2018; FAO, 2018). This is of particular importance for Ireland where the agricultural sector, which is dominant by ruminant systems, contributes 34% and 98% of national GHG and ammonia (NH_3) emissions (EPA, 2019a; 2019b).

Consumers are increasingly concerned about the quality, nutrient content, and safety of the beef they are consuming, as well as the animal welfare standards and environmental impact of the beef production system (Xue et al., 2010). Beef produced from pasture-based production systems ("grass-fed" beef) has gained increasing attention, particularly in developed countries, as it is perceived to be healthier, and that the production system is animal welfare and environmentally friendly (Monahan et al., 2012; Teague et al., 2016; Henchion et al., 2017). Research has shown that grass-fed beef contains elevated levels of ω-3 fatty acids, conjugated linoleic acids, and α-tocopherol (vitamin E) in comparison to beef fed cereal concentrates (Daley et al., 2010). Pastoral systems can also utilise land that is unsuitable for crop production, converting non-human edible forage into high-value human edible products. Grass-fed beef systems also provide ecosystem services such as the preservation and enhancement of biodiversity, conservation of cultural landscape, and contribute to the socio-economic activity in rural areas, in particular marginal areas (Bragaglio et al., 2018).

On-farm measurements of key sources of environmental burden are possible (e.g., wind tunnel measurements of nitrous oxide (N_2O) emissions from synthetic fertiliser application), but it is impractical to measure the total environmental burden of all activities related to a product at each life stage. Furthermore on-farm measurements are expensive, laborious, and time-consuming to complete, hence key sources of environmental burden are not always recorded alongside production system trials. Whole-farm models have been developed to address this by using mathematical equations to replicate the processes and complex interactions which occur within livestock production systems. Life cycle assessment (**LCA**) is a methodology (ISO, 2006a and 2006b) widely used to model the environmental performance of agricultural systems and products (de Vries et al., 2015). Agricultural LCAs commonly take a holistic view of production systems up to the point the product leaves the farm (cradle to farm gate), encompassing all processes and interactions that occur on-farm and that are embodied in farm inputs. Although there are limitations with this approach, such as inconsistency in modelling carbon dioxide (CO_2) losses from soil or land, the LCA methodology is considered the most robust and comprehensive approach to calculate environmental impacts and assess mitigation strategies (Crosson et al., 2011).

There is a paucity of LCA studies that have examined the environmental impact of rearing and finishing suckler-bred male cattle on a solely grass forage diet. Increasing average daily live weight gain (**LWG**) and the subsequent reduction in finishing age has been identified for decreasing GHG emissions and pollutants from pasture-based beef systems (McAuliffe et al., 2018). In countries with temperate climates such as Ireland, recommended production systems often focus on finishing steers at 24 months of age on a grass forage diet, with concentrate supplementation during housing periods (Drennan and McGee, 2009). Previously, feedlot systems have been shown to have lower GHG intensity than pasture-based systems (Pelletier et al., 2010; Capper, 2012), however they are predominantly based on cereal products partially suitable for human consumption. While grass-fed beef production systems reduce or remove the environmental impacts embodied in concentrate feed, the use of synthetic fertilisers to increase grass production can generate substantial GHG emissions and other pollutants. Furthermore, removing concentrate feed reduces LWG and produces lighter carcass weights at a given slaughter age (Regan et al., 2018). To achieve similar carcass weight output to those outlined in recommended production systems, the slaughter age of cattle in grass-fed systems needs to increase, thus potentially increasing environmental impact. Alternatively, animals in grass-fed systems could be finished earlier at a lighter weight prior to the indoor finishing period, thus omitting the enviromental impact embodied in the associated manure management and conserved grass forage.

The predominant genotype in the suckler herd in Ireland (ICBF, 2017) can be described as late maturing (**LM**). Finishing LM steers at an acceptable fat cover in grass fed systems can be challenging, as early-maturing (**EM**) breeds have a greater propensity for fat deposition and therefore may be more suitable for grass fed systems than LM breeds (Keane, 2011). The objective of this study was to determine, on a life cycle basis, the effect of breed type (EM vs. LM), finishing age (20, 24, and 28 months) and concentrate feeding (GO-24 vs. GC-24) on the environmental impact of grass fed (fresh and conserved) weanling-to-beef production systems.

Material and methods

Description of farm systems

This LCA study was conducted using data collated from a farm systems experiment undertaken at the Teagasc, Animal & Grassland Research and Innovation Centre, Grange (longitude 6° 40′ W; Latitude 53° 30′ N; Elevation, 92 m above sea level) between October 2015 and July 2017 (Regan et al., 2018; Regan, 2018). The objectives of this experiment were to evaluate the performance, growth, carcass characteristics, and selected meat quality traits of suckler-bred EM and LM steers on contrasting grass-forage weanling-to-beef production systems with and without concentrate supplementation.

Spring-born early-maturing (Aberdeen Angus and Hereford sired) and late-maturing (Limousin and Charolais sired) suckler-bred bull weanlings were purchased and transferred to Grange Research Centre in October at approximately 7.8 months of age. Bull weanlings were castrated four weeks after arrival. The weanlings were then blocked by sire breed and live weight, and randomly assigned to one of eight treatments in a 2 × 4 factorial design. The experimental factors were breed type and productions systems. The breed types investigated were EM and LM. The production systems assessed were:

(i) **GO-20:** Grass silage for the first indoor period followed by 182 days at pasture, target slaughter age 20 months.

(ii) **GO-24**: Grass silage for the first indoor period followed by 182 days at pasture, rehoused and offered grass silage, target slaughter age 24 months.
(iii) **GC-24**: Grass silage plus 0.8 kg concentrate DM for the first indoor period, followed by 182 days at pasture, rehoused and offered grass silage plus 3.2 kg concentrate DM, target slaughter age 24 months (Control);
(iv) **GO-28**: Grass silage for the first indoor period followed by 182 days at pasture, rehoused and offered grass silage for the second indoor period, followed by 112 days at pasture, target slaughter age 28 months.

During the first housing period, all animals were accommodated in slatted housing and offered an ad libitum grass silage diet. For the GC-24 system, concentrate allowance for the first indoor 'winter' period started on the 16 December at a rate of 0.8 kg DM per day (Table S1). Steers were turned out to pasture on 20 April and rotationally grazed perennial ryegrass (*Lolium perenne*) dominant swards in breed specific groups. Synthetic N fertiliser was applied to grazing area at a rate of 200 kg N per ha per year; 125 kg N in the form of urea and 75 kg N in the form of calcium ammonium nitrate (**CAN**). The rate of synthetic P application for the grazing area was 9 and 15 kg P per ha for GC and GO systems, respectively. The synthetic K application rate for the grazing area was 11 and 25 kg K per ha for GC and GO systems, respectively.

Herbage in excess of target pre-grazing herbage mass was removed as baled silage. Mean pre-grazing herbage mass was 2 069 and 1 777 kg DM/ha, for the second and third grazing season, respectively. Two grass silage harvests were taken annually. Land area designated for silage production was closed in March and was harvested on 11 May and again on 23 June. First and second harvest silage area received 100 kg N (urea) and 90 kg N (CAN) per ha, respectively. Slurry produced during housing was recycled onto the silage area. Synthetic phosphorus (P) and potassium (K) fertiliser application rates for the grazing and silage area (0 kg P/ha, 15 kg K/ha) were in line with Teagasc recommendations i.e. accounting for stocking rate and the quantity of nutrient applied in slurry and imported through concentrate feed (Teagasc, 2017).

At the end of the grazing season (19 October), steers in the GO-20 system were slaughtered, and those in the GO-24, GC-24, and GO-28 systems were housed indoors for a 'second' indoor winter period. Concentrate feed was reintroduced to GC-24 steers on 9 November at a rate of 3.2 kg DM per day (Table S1). At the end of the second housing period (14 March), steers in the GO-24 and GC-24 system were slaughtered. Steers in the GO-28 system were returned to pasture for a 'third' 112-day grazing season before slaughter. All steers were slaughtered at a nearby commercial slaughter plant where carcasses were weighed, and carcass conformation and fat scores were graded mechanically according to the EU Beef Carcass Classification Scheme (Commission of the European Communities, 1982), but on a 15 point scale rather than a 5 point scale (i.e. +, 0, or – was added to each class). Cold carcass weight was estimated as 0.98 of hot carcass weight and kill-out proportion was calculated as cold carcass weight expressed relative to slaughter live weight. Table 1 provides an overview of the systems, live weight performance, and post-slaughter carcass traits.

Goal and scope

Life cycle assessment was applied in accordance with the principles and requirements specified by the International Organisation for Standardization 14040 and 14044 standards (ISO, 2006a and 2006b). The standard phases of the method are (i) goal and scope, (ii) life cycle inventory, (iii) impact assessment, and (iv) interpretation. The aim was firstly to develop a new whole-farm model that evaluates both the technical and environmental performance of weanling-to-beef systems, and secondly determine if there is an environmental advantage in finishing suckler weanlings entirely from grass forage in comparison to a conventional pasture-based system incorporating concentrate supplementation.

A cradle-to-farm gate system boundary was adopted where all processes within the farm gate boundary and embodied in farm inputs (fertiliser, concentrate feed) are accounted for (where possible) up to the point when the product leaves the farm. Environmental impacts embodied in capital goods (i.e. farm infrastructure and machinery) and medicines were not included in the LCA due to lack of data availability. The cow-calf phase was not within the scope of the experiments conducted by Regan et al. (2018) as they represent a 'purchased' weanling-to-beef system. As no data was available for the cow-calf phase of weanlings used in the experiments the cow-calf phase was excluded from the analysis. Hence, the functional units used to report the environmental impact of such production systems were based on the weight gained while on farm (slaughter weight minus purchase weight); kg **LWG**, kg carcass weight gain (**CWG**), and kg meat weight gain (**MWG**) (Table 2). These functional units are collectively referred to as "kg product". An additional functional unit,

Table 1
Description of production systems, live weight performance and post slaughter measurements for early- and late-maturing steers produced to slaughter entirely on a grass forage diet at 20 months (GO-20), entirely on a grass forage diet at 24 months (GO-24), on a grass forage diet with concentrate supplementation during housing (GC-24), and entirely on a grass forage diet at 28 months (GO-28).

	Breed Type							
	Early maturing (EM)				Late-maturing (LM)			
Production System	GO-20	GO-24	GC-24	GO-28	GO-20	GO-24	GC-24	GO-28
Total area (ha)	26	26	26	26	26	26	26	26
Animal purchased[1]	119	94	98	62	123	106	97	66
Live weight (kg)								
Arrival weight (22 Oct)	310	310	295	312	327	323	321	326
Initial live weight (16 Dec)	342	336	331	337	347	345	351	350
Turn-out to pasture (20 Apr)	360	362	384	368	374	375	404	380
Housing second winter (19 Oct)	–	525	530	505	–	488	529	489
Turn-out to pasture (14 Mar)	–	–	–	564	–	–	–	545
Slaughter	528	596	663	708	527	558	649	690
Post-slaughter measurements								
Carcass weight (kg)	280	314	361	381	295	319	375	397
Kill-out proportion (g/kg)	531	527	543	538	560	569	576	576
Carcass conformation score (1–15)	5.75	5.72	6.88	7.83	7.47	8.12	8.94	9.11
Carcass fat score (1–15)	6.06	8.5	9.88	10.11	4.12	6.12	8.00	7.88

[1] Animals purchased each year.

Table 2
Feed intake and net output of early-maturing and late-maturing steers produced to slaughter entirely on a grass forage diet at 20 months (GO-20), entirely on a grass forage diet at 24 months (GO-24) on a grass forage diet with concentrate supplementation during housing (GC-24), and entirely on a grass forage diet at 28 months (GO-28).

	Breed Type							
	Early-Maturing				Late-Maturing			
Production System	GO-20	GO-24	GC-24	GO-28	GO-20	GO-24	GC-24	GO-28
Feed intake[1] (kg DM)								
Grass	1 500	1 475	1 406	2 708	1 435	1 236	1 399	2 510
Grass silage	625	1 616	1 558	1 597	654	1 574	1 622	1 590
Concentrate	–	–	494	–	–	–	494	–
Net output (kg)[2]								
Live weight gain	24 310	34 045	5 1815	40 620	22 780	32 984	45 710	40 037
Carcass weight gain	12 908	17 942	28 135	21 854	12 757	18 768	26 329	23 061
Meat weight gain	9 006	11 510	18 509	14 754	10 248	14 444	19 490	17 188

[1] Feed intake, arrival to sale.
[2] Net output (kg), produced on farm (finish weight – purchase weight).

animal, was used to determine environmental impact of finishing an animal in each production system. To calculate MWG, an equation derived by Conroy et al. (2010) was used to calculate the proportion of red meat in each carcass:

$$(1)\ Meat\ \ propotion\ \ (\text{g/kgCW}) = 698 + 11.82CS - 9.56FS$$

where *CS*, carcass conformation score (1–15); *FS*, carcass fat score (scale 1–15). To calculate the meat proportion of a purchased weanling animal a fat score of 2.0 was assumed.

The intensification of agricultural systems has led to greater use of synthetic fertilisers and subsequently the loading of limiting nutrients to waterbodies, which has resulted in the degradation of water quality and aquatic ecosystems in some areas through cultural eutrophication (McDowell and Hamilton, 2013). The application of acidifying fertilisers and the deposition of acidifying pollutants emitted from agricultural systems not only hampers future production through reduced soil pH and fertility, but can also degrade surrounding ecosystems (Goulding, 2016). Focusing on a single facet of the environment e.g., water, may have adverse consequences for other important environmental compartments. Thus, one of the goals of this LCA study was to determine major environmental impacts of proposed grass-fed weanling-to-beef production systems. The environmental impact categories assessed were consistent with those identified by the European Commission (2018) and included global warming potential (**GWP**), acidification potential (**AP**), marine eutrophication potential (**MEP**), freshwater eutrophication potential (**FEP**), and non-renewable energy (**NRE**).

The intensification of agricultural systems has led to greater use of synthetic fertilisers and subsequently the loading of limiting nutrients to waterbodies resulting in the degradation of water quality and aquatic ecosystems through cultural eutrophication (McDowell and Hamilton, 2013). The application of acidifying fertilisers and the deposition acidifying pollutants emitted from agricultural systems not only hampers future production through reduced soil pH and fertility but can also degrade surrounding ecosystems (Goulding, 2016). The goal of this LCA study was therefore to determine the environmental impact of proposed grass-fed weanling-to-beef production systems. To prevent environmental impact trade-offs multiple impact categories were investigated. The environmental impact categories selected were GWP, AP, MEP, FEP, and NRE.

Life cycle inventory

A whole-farm, dynamic, deterministic, simulation model was deployed to carry out the inventory analysis. The model was parameterised using production data from the current production system (Regan et al., 2018; Regan, 2018) (Table 1). Animals were classified into three life stages: calf (0–12 months of age), yearling (13–24 months of age), and two years old (25–36 months of age). Purchased animals were sorted into their representative grouping on the date they entered the system. The model assumes that the production system is replicated each year where the same quantity of weanlings are purchased at the same weight on the same date of each year. Therefore, if the production system exceeds 365 days, the model simulation will include animals purchased in the previous year and those purchased during the production system for the next cycle.

Within animal group, the model begins on day of animal purchase. For example, the model will commence at day 280 in the calf (0–12 months) life stage for weanling purchased at 280-day old. Based on the sale date provided, the animal then leaves the system. Animal age and performance (Table 1) is based on an average animal within a group with no variation assumed. The methodology used in the animal nutrition and feed supply sub-models of the Grange Beef System Model (Crosson et al., 2006), a bio economical model designed to identify financially optimal suckler beef production systems in Ireland, was adopted to simulate energy intake requirements and DM intake of stock on farm. DM intake of 10.3 and 12.4 g per kg live weight were recorded and applied for the first (GO-20, GO-24, and GO-28) and second (GO-24 and GO-28) indoor housing periods for GO systems, respectively. Substitution rates of 0.26 and 0.19 kg grass silage DM per kg concentrate DM were recorded and applied for EM and LM steers, respectively. DM intake during grazing was not recorded, it was therefore calculated based on the energy requirement of an animal to achieve a specified LWG, and the energy content of feed offered (O'Mara et al., 1997). The animal nutrition and feed supply sub-models were amalgamated with the Beef Greenhouse Gas Emissions Model (BEEFGEM), a whole farm GHG emission model designed to simulate direct and indirect GHG emission from pastoral suckler beef production systems (Foley et al., 2011). The inventory of BEEFGEM was expanded to encompass all pollutants and resource uses that contribute to impact categories investigated. In addition the new version of BEEFGEM, was changed to operate on a daily time step instead of monthly and covers the period animals are on farm rather than a single year.

Sources of on-farm CO_2 emissions in the model were lime application, combustion of fossil fuels, and the application of urea-based fertilisers. Resources used that were not recorded during the experiments (i.e. electricity and contractor diesel usage) was estimated using data collected during the system research experiment in Grange were used along with secondary data sources (Nemecek and Kägi, 2007; Dillon et al., 2018). Methane (CH_4) is released by methanogens during the digestion of feed in the rumen (enteric fermentation (Johnson and Johnson, 1995). As the diets in all systems were >75% high-quality forage, the IPCC Tier 2 enteric CH_4 emission factor 6.3% of gross energy intake was used (IPCC, 2019). An equation developed by Yan et al. (2000) was used to calculate CH_4 emissions from enteric fermentation during housing.

Methane emissions from manure storage and manure deposition during grazing were calculated using IPCC Tier 2 emissions algorithms (Western Europe, Cool Moist Temperate climate) (IPCC, 2019) (Table S2). Direct N_2O emissions are largely generated from synthetic N fertiliser application, deposition of dung and urine onto pasture, and manure management in pasture-based ruminant production systems. Nitrous oxide emissions from fertiliser application have been reported to vary greatly depending on the form of N applied as well as climatic and environmental conditions. Hence, country specific N_2O emission factors developed by Harty et al. (2016) for N fertilisers were applied. Emissions of N_2O from the deposition of excreta onto pasture depend on climatic and environmental conditions; therefore, Krol et al. (2016) derived country specific N_2O emission factors were used. Nitrous oxide emissions from manure storage and application were estimated using IPCC (2019) methodology (Table S2).

Re-deposition of volatilised NH_3 contributes to indirect N_2O emissions, and the acidification and eutrophication of terrestrial and aquatic ecosystems (Forrestal et al., 2016). Urea-based N fertilisers are more susceptible to NH_3 volatilisation than NO_3-based fertilisers. When applied in unfavourable conditions (dry, warm weather), a significant proportion of urea N is lost as NH_3 during the hydrolysis of urea. Therefore, emission factors from the national informative inventory report were used (EPA, 2019a). As recommended, a Tier 2 N mass flow approach (Webb and Misselbrook, 2004) was adopted to calculate NH_3 emissions from manure management (EPA, 2019a) (Table S2).

Nitrate (NO_3^-) leaching from manure application, deposition of manure onto pasture, and synthetic N fertiliser application was estimated as a function of kg N applied using country specific factors specified in the Irish inventory report (EPA, 2019b). Indirect N_2O emissions from NH_3 re-deposition and NO_3^- leaching were estimated according to the IPCC (2019) methodology. Potential losses of P from leaching and runoff were calculated using the methodology developed by Nemecek and Kägi (2007).

National reports and literature resources were used to calculate GHG emissions and non-renewable energy usage embodied in farm imports (Nemecek and Kägi 2007; SEAI, 2019; EPA, 2019b). The LCA database, ecoinvent (2010), was used to determine the remaining pollutants embodied in farm imports (Table S3).

Life cycle impact assessment (LCIA)

This study used the methods recommended in the European Commission (2018) Product Environmental Footprint Category Rules (PEFCR) to calculate impact categories. Accordingly, IPCC (2013) characterisation factors and the accumulated exceedance approach (Posch et al., 2008) were applied to calculate GWP, and AP, respectively. Methane characterisation factors were corrected in accordance with Munoz and Schmidt (2016). Similarly, the ReCiPe 2016 methodology (Huijbregts et al., 2016) was used to calculate eutrophication potential under two subcategories, freshwater eutrophication (g P eq) and marine eutrophication (g N eq). Non-renewable energy-use (NRE) refers to the quantity of finite fossil fuel consumed from on and off-farm activities and was expressed in terms of mega joules.

Sensitivity analysis

To determine the full environmental impact of beef produced from the production systems investigated by Regan et al. (2018), the cow-calf phase of the production cycle must be accounted for. Therefore, a cow-calf model was developed using the LCA methodology reported in the LCI and integrated into the BEEFGEM model. The LCA of the cow-calf phase was conducted over the calving interval period. Animals were categorised into three animal groups: suckler cow, weanling, and replacement heifer. As the cow-calf phase was not within the scope of the experiments conducted by Regan et al. (2018), the LCA model was parameterised using national statistics and reports (Table 3). The same functional units were used to report the environmental impact of the cow-calf and weanling to beef stages. The weight gained by replacement animals was included in the cow-calf stage.

Uncertainty analysis

Fluxes of pollutants from agricultural systems are inherently uncertain, influenced by spatial and temporal factors. Stochastic simulation was therefore adopted to partially account for the inherent uncertainty in key model parameters that influence the environmental impact categories investigated. The minimum, maximum, and most likely values of key parameters were sourced from the studies or reports from which they were obtained (Table 4). Key parameters were identified after carrying out a deterministic simulation of production systems. Palisade @Risk 7.5 software was used to assign a probability distribution to each key variable. A series of Monte-Carlo simulations were subsequently conducted where all parameters were simulated simultaneously. Monte Carlo simulations were conducted (10 000 iterations) for both the cow-calf and weanling-to-finish phase.

Results

Environmental impact and resource use (**LCIA**) of the production systems are detailed in Table 3. The environmental impact of EM steers was lower than LM across all impact categories and production systems when expressed per kg LWG; however, because of superior kill-out proportion and carcass conformation score, and a lower fat score, MWG was greater for LM steers than EM (Table 2). Consequently, LM steers had a lower environmental impact than EM across all impact categories and production systems when expressed per kg MWG (Table 5).

Within breed maturity, environmental impact per animal increased as age at slaughter increased (GO-20 vs. GO-24 vs. GO-28), and also from the inclusion of concentrate feed (GO-24 vs. GC-24) (Table 5). Consequently, within the GO production systems,

Table 3
National average beef calving statistics and synthetic fertiliser application rates for four pasture-based suckler beef production systems.

Item	Average	Source
Calving statistics		
Calving date	25-Feb	Regan et al. (2018)
Weanling sale date	22-Oct	Regan et al. (2018)
Calving Interval (days)[1]	397	ICBF (2019)
Replacement rate (%)[1]	17.9	ICBF (2019)
Age at first calving (days)[1]	900	ICBF (2019)
Calves per cow per year[1]	0.86	ICBF (2019)
Mortality rate at birth (%)	1.1	ICBF (2019)
28 day calf mortality rate (%)	2.67	ICBF (2019)
Grassland management		
Grass utilised per ha (Tonnes DM/ha)	6.2	Teagasc, 2020
Fertiliser application (Grazing), kg N per ha[2]	50	Dillon et al. (2018)
Fertiliser application (Grazing), kg P per ha	4	Dillon et al. (2018)
Fertiliser application (Grazing), kg K per ha	9	Dillon et al. (2018)
Fertiliser application (Silage), kg N per ha[2]	89	Dillon et al. (2018)
Fertiliser application (Silage), kg P per ha	11	Dillon et al. (2018)
Fertiliser application (Silage), kg K per ha	30	Dillon et al. (2018)

[1] Three year average (2017–2019).
[2] 88.2% calcium ammonium nitrate (CAN) based fertiliser, 11.8% urea based fertiliser.

Table 4
Distribution of parameters used in the stochastic analysis of the environmental impact of the pasture-based suckler weanling-to-beef production systems.

Parameter	Unit	Distribution	SD	Minimum	Most likely	Maximum	Source
Enteric fermentation	GEI%	Normal	0.612		6.3		IPCC (2019)
Fertiliser (CAN)	kg N_2O-N/kg N applied	PERT		0.0081	0.0149	0.0381	Harty et al. (2016)
Fertiliser (Urea)	kg N_2O-N/kg N applied	PERT		0.0010	0.0025	0.0049	Harty et al. (2016)
Fertiliser (CAN)	kg NH_3-N/kg N applied	PERT		0.0000	0.0080	0.0200	EPA (2019a)
Fertiliser (Urea)	kg NH_3-N/kg N applied	PERT		0.0300	0.1550	0.4300	EPA (2019a)
Grazing (Dung)	kg N_2O-N/kg N applied	PERT		0.0000	0.0031	0.0148	Krol et al. (2016)
Grazing (Urine)	kg N_2O-N/kg N applied	PERT		0.0030	0.0118	0.0481	Krol et al. (2016)
Liquid manure housing	kgNH_3-N/kg TAN	Normal	14.41		27.7000		Misselbrook et al. (2016)
Liquid manure application	kg N_2O-N/kg N applied	PERT		0.0030	0.0067	0.0225	Bourdin et al. 2014
N applied susceptible to leaching	kg NO_3-N/kg N applied	PERT		0.0500	0.1000	0.1500	EPA (2019b)

GEI = Gross energy intake; CAN = Calcium ammonium nitrate; PERT = Program evaluation and review technique; TAN = Total ammonical nitrogen.

GO-28 had the greatest environmental impact per animal for all impact categories. Although the third grazing season in the GO-28 system resulted in additional GHG emissions, other pollutants (e.g. NH_3), and NRE usage, superior LWG during the third grazing season in comparison to the second grazing and second housing had a dilution effect on the environmental impact. Due to poor performance of steers in GO-24 in comparison to GC-24 and GO-28, the GO-24 system had the greatest GWP, MEP, and NRE for both breeds when expressed per kg LWG, CWG and MWG. Steers finished in GO-28 had the greatest FEP for all functional units.

The response in animal growth and carcass traits to concentrate supplementation resulted in EM steers having a lower environmental impact across categories per kg LWG, CWG, and MWG in comparison to GO-24. Likewise, LM steers in GC-24 had lower GWP, MEP, and FEP per kg LWG, CWG, and MWG in comparison to GO-24, however similar NRE and AP were reported. Steers finished in the GO-24 and GC-24 systems had greater AP per kg LWG, CWG and MWG than GO-28. Additionally, steers finished in GC-24 had greater AP to those finished in GO-28 when expressed per animal. The GO-20 system had the lowest GWP, NRE, AP, and MEP for all functional units investigated for both breeds as a result of younger slaughter age reducing CH_4 emissions from enteric fermentation along with the absence of GHG emissions, pollutants, and NRE usage associated with concentrate feed and a second housing period.

Global warming potential

Methane was the dominant GHG, accounting for 61.8–64.5% of total GHG emissions in CO_2-equivalents across both breed types and the four production systems (Tables 6 and 7). Enteric fermentation was the main GHG emission source contributing approximately 90% of total CH_4 losses and emitting 12.94 to 19.59 kg CO_2eq per kg MWG in LM GO-20 and EM GO-24, respectively. Manure storage emitted the majority of the remaining CH_4 with minor emissions from the deposition of excreta onto pasture.

Nitrous oxide was the second largest GHG from the beef systems investigated, accounting for 19.4–22.6% of total GHG emissions (Tables 6 and 7). The application of synthetic N fertiliser was the main N_2O emission source for all production systems emitting 1.68–2.80 kg CO_2eq/kg MWG in LM GC-24 and EM GO-24, respectively. For GO-20 and GO-28 the deposition of excreta onto pastures, and manure management were the next largest contributors of direct N_2O. Manure management emitted a greater quantity of direct N_2O than the deposition of excreta onto pasture for steers finished at 24 months due to a greater number of housing days than grazing days.

Carbon dioxide contributed 13.7–18.7% of total GHG emissions (Tables 6 and 7). In contrast to CH_4 and N_2O emissions, CO_2 was predominantly emitted off-farm. Production of synthetic fertilisers was the main source of CO_2 for GO production systems emitting

Table 5
Effect of breed type (EM, early-maturing and LM, late-maturing), slaughter age, and concentrate supplementation on the global warming potential (GWP), non-renewable energy use (NRE), acidification potential (AP), freshwater eutrophication potential (FEP) and marine eutrophication potential (MEP) of steers produced to slaughter entirely on a grass forage diet at 20 months (GO-20), entirely on a grass forage diet at 24 months (GO-24), on a grass forage diet with concentrate supplementation during housing (GC-24), and entirely on a grass forage diet at 28 months (GO-28).

	GWP (kg CO_2 eq)		NRE (MJ)		AP (mol H + eq)		FEP (g P eq)		MEP (g N eq)	
Item	EM	LM	EM	LM	EM	LM	EM	LM	EM	LM
GO-20										
Per animal	1 974	1 969	3 995	3 989	20	20	134	143	22 736	22 674
Per kg live weight gain	9.1	9.8	18.3	19.9	0.1	0.1	0.6	0.7	104	113
Per kg carcass weight gain	17.1	17.6	34.5	35.6	0.2	0.2	1.2	1.3	196	202
Per kg meat weight gain	24.4	21.9	49.5	44.3	0.2	0.2	1.7	1.6	282	252
GO-24										
Per animal	3 382	3 003	6 890	6 137	43	39	178	153	42 853	38 554
Per kg live weight gain	11.8	12.8	24.1	26.1	0.15	0.17	0.6	0.7	150	164
Per kg carcass weight gain	22.4	22.5	45.7	45.9	0.29	0.29	1.2	1.1	284	288
Per kg meat weight gain	35.0	29.2	71.3	59.6	0.45	0.38	1.8	1.5	443	375
GC-24										
Per animal	3 952	4 038	8 188	8 308	54	55	187	190	46 826	47 751
Per kg live weight gain	10.7	12.3	22.3	25.3	0.15	0.17	0.5	0.6	127	146
Per kg carcass weight gain	19.8	21.4	41.0	44.0	0.27	0.29	0.9	1.0	234	253
Per kg meat weight gain	30.1	28.9	62.3	59.4	0.41	0.39	1.4	1.4	356	341
GO-28										
Per animal	4 261	4 065	8 528	8 180	45.7	44.1	258.2	261.8	49 473	47 405
Per kg live weight gain	10.8	11.2	21.5	22.5	0.1	0.1	0.7	0.7	125	130
Per kg carcass weight gain	20.0	19.4	40.0	39.0	0.2	0.2	1.2	1.2	232	226
Per kg meat weight gain	29.6	26.0	59.3	52.3	0.3	0.3	1.8	1.7	344	303

Table 6
Contribution analysis (expressed as kg CO_2eq per kg MWG) for greenhouse gas emissions from early-maturing (EM) steers produced to slaughter entirely on a grass forage diet at 20 months (GO-20), entirely on a grass forage diet at 24 months (GO-24) on a grass forage diet with concentrate supplementation during housing (GC-24), and entirely on a grass forage diet at 28 months (GO-28).

	GO-20			GO-24			GC-24			GO-28		
Early-maturing breed type (EM)	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
Enteric fermentation	–	14.47	–	–	19.59	–	–	16.26	–	–	17.36	–
Manure housing and storage	–	0.96	0.12	–	2.88	0.33	–	2.24	0.26	–	1.54	0.18
Manure spreading	–	–	0.54	–	–	1.55	–	–	1.20	–	–	0.83
Manure during grazing	–	0.07	1.51	–	0.04	0.92	–	0.03	0.57	–	0.19	1.44
Fertiliser application	0.58	–	2.10	0.75	–	2.80	0.47	–	1.74	0.68	–	2.48
NH_3 emissions	–	–	0.58	–	–	1.11	–	–	0.80	–	–	0.75
NO_3 leaching	–	–	0.55	–	–	0.68	–	–	0.45	–	–	0.63
Concentrate production	–	–	–	–	–	–	2.55	0.03	0.73	–	–	–
Fertiliser production	1.66	0.03	0.13	2.19	0.04	0.17	1.35	0.02	0.11	1.96	0.03	0.15
Fuel production	0.99	–	0.00	1.60	–	0.00	1.04	–	0.00	1.17	–	0.00
Electricity production	0.15	0.00	0.00	0.32	0.00	0.00	0.21	0.00	0.00	0.24	0.00	0.00
Total	3.38	15.54	5.52	4.87	22.56	7.55	5.62	18.59	5.86	4.05	19.12	6.45

MWG = meat weight gain.

Table 7
Contribution analysis (expressed as kg CO_2eq per kg MWG) for greenhouse gas emissions from late-maturing (LM) steers produced to slaughter entirely on a grass forage diet at 20 months (GO-20), entirely on a grass forage diet at 24 months (GO-24) on a grass forage diet with concentrate supplementation during housing (GC-24), and entirely on a grass forage diet at 28 months (GO-28).

Late-maturing breed type (LM)	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
Enteric fermentation	–	12.94	–	–	16.21	–	–	15.67	–	–	15.19	–
Manure housing and storage	–	0.91	0.11	–	2.51	0.29	–	2.17	0.25	–	1.39	0.16
Manure spreading	–	–	0.50	–	–	1.35	–	–	1.16	–	–	0.75
Manure during grazing	–	0.06	1.31	–	0.03	0.69	–	0.03	0.53	–	0.17	1.23
Fertiliser application	0.51	–	1.87	0.62	–	2.34	0.45	–	1.68	0.60	–	2.17
NH_3 emissions	–	–	0.52	–	–	0.95	–	–	0.78	–	–	0.67
NO_3 leaching	–	–	0.49	–	–	0.56	–	–	0.43	–	–	0.55
Concentrate production	–	–	–	–	–	–	2.39	0.03	0.68	–	–	–
Fertiliser production	1.49	0.03	0.11	1.82	0.03	0.14	1.30	0.02	0.10	1.73	0.03	0.13
Fuel production	0.89	–	0.00	1.34	–	0.00	1.00	–	0.00	1.03	–	0.00
Electricity production	0.13	0.00	0.00	0.29	0.00	0.00	0.20	0.00	0.00	0.22	0.00	0.00
Total	3.02	13.94	4.91	4.07	18.79	6.33	5.34	17.92	5.61	3.57	16.78	5.67

MWG = meat weight gain.

1.30–2.19 kg CO_2eq/MWG in LM GC-24 and EM GO-24, respectively. Other CO_2 emission sources included the use of fossil fuels, urea fertiliser application and electricity generation. Carbon dioxide emission from concentrate production surpassed fertiliser manufacture in the GC-24 production systems, which increased the GC-24 systems total CO_2 emissions.

Acidification potential

Ammonia was the dominant acidifying pollutant and released on average 0.20, 0.37, and 0.25 mol H^+ eq/kg MWG for GO-20, GO-24, and GO-28 production systems (Tables 8 and 9). On-farm NH_3 emissions from manure management was the main source followed by synthetic fertiliser application and deposition of excreta onto pasture. Ammonia emissions were 54% lower per animal and kg MWG for steers finished off grass in their second grazing season (GO-20) in comparison to steers rehoused for a second period in GO-24, respectively. Nitrogen oxide (NO_x) emissions from synthetic fertilisers, manure management and deposition of manure during grazing were minor contributors to total AP of GO production systems (0.04 mol H^+ eq/kg MWG). The import of concentrate feed into GC-24 production systems increased total NO_x emissions (0.08 mol H^+eq/kg MWG for both breeds). As a result, GC-24 system had the greatest AP per animal. Sulphur dioxide (SO_2) was a minor contributor to total AP.

Eutrophication potential

Nitrate leaching and NH_3 emissions were responsible for over 90% of total MEP for GO production systems, with NO_x emissions accounting for the remaining MEP (Tables 8 and 9). Ammonia was the dominant MEP pollutant for all production systems. On- and off-farm NH_3 sources and contributions stated in AP also apply to MEP. Nitrate leaching was the second most important source of MEP, particularly for GO-20 (43.4%) and GO-28 (40.3%) where steers spent a greater amount of time at pasture than indoors in comparison to the 24 months systems. Synthetic fertiliser application released the greatest amount of MEP pollutants from the GO-20, and GO-28 production systems, accounting on average 126 and 146 g N eq per kg MWG, respectively (Tables 8 and 9). Manure management and excreta deposited during grazing were also key contributors to MEP. Due to steers finished in the GO-24 and GC-24 systems spending a greater quantity of days indoors than at grazing, and because a greater proportion of N excreted is lost as NH_3 during housing than at grazing, manure management was the dominant source of MEP pollutants accounting for 206 and 168 g N eq per kg MWG, respectively. Other key contributors to MEP were fertiliser application and excreta deposition at grazing. Concentrate feed production was a main source for the GC-24 system.

Synthetic fertiliser application and production was the main sources of FEP pollutants for the GO-20, GO-24, and GO-28 produc-

Table 8
Contribution analysis (expressed per kg MWG) for acidification potential (AP) (mol H^+eq), marine eutrophication potential (MEP) (g N eq), freshwater eutrophication potential (FEP) (g P eq), and non-renewable energy use (NRE) (MJ) from early-maturing (EM) steers produced to slaughter entirely on a grass forage diet at 20 months (GO-20), entirely on a grass forage diet at 24 months (GO-24) on a grass forage diet with concentrate supplementation during housing (GC-24), and entirely on a grass forage diet at 28 months (GO-28).

	GO-20				GO-24				GC-24				GO-28			
Sources	AP	MEP	FEP	NRE	AP	MEP	FEP	NRE	AP	MEP	FEP	NRE	AP	MEP	FEP	NRE
Manure storage	0.05	36.4	–	–	0.15	104.7	–	–	0.12	81.5	–	–	0.08	56.0	–	–
Manure spreading	0.04	40.0	0.46	–	0.12	115.3	0.94	–	0.09	89.7	0.70	–	0.06	61.6	0.62	–
Grazing	0.03	64.9	0.49	–	0.02	39.3	0.25	–	0.01	24.4	0.14	–	0.03	61.3	0.44	–
Fertiliser application	0.10	133.0	0.20	–	0.13	173.5	0.16	–	0.08	108.1	0.05	–	0.12	156.4	0.19	–
Fertiliser production	0.01	4.7	0.51	32.4	0.01	6.2	0.49	42.2	0.01	3.8	0.17	25.9	0.01	5.5	0.55	39.9
Concentrate production	–	–	–	–	–	–	–	–	0.09	46.0	0.36	17.5	–	–	–	–
Fuel use emissions	0.01	2.5	0.00	14.6	0.01	4.1	0.00	23.6	0.01	2.7	0.00	15.4	0.01	3.0	0.00	18.2
Electricity production	0.00	0.1	0.00	2.5	0.00	0.1	0.00	5.4	0.00	0.1	0.00	3.5	0.00	0.1	0.00	4.2
Pollutant																
NH_3	83.1	50.0	–	–	87.8	60.8	–		70.8	55.6	–	–	84.9	53.6	–	–
NO_X	14.5	6.4	–	–	10.4	5.2	–		27.6	15.9	–	–	12.9	6.0	–	–
NO_3	–	43.6	–	–	–	34.0	–		–	28.5	–	–	–	40.4	–	–
SO_2	2.4	–	–	–	1.8	–	–		1.6	–	–	–	2.2	–	–	–
PO_4	–	–	30.8	–	–	–	26.8		–	–	37.5	–	–	–	30.5	–
P	–	–	69.2	–	–	–	73.2		–	–	62.5	–	–	–	69.5	–

MWG = meat weight gain.

Table 9
Contribution analysis (expressed per kg MWG) for acidification potential (AP) (mol H^+eq), marine eutrophication potential (MEP) (g N eq), freshwater eutrophication potential (FEP) (g P eq), and non-renewable energy use (NRE) (MJ) from late-maturing (LM) steers produced to slaughter entirely on a grass forage diet at 20 months (GO-20), entirely on a grass forage diet at 24 months (GO-24) on a grass forage diet with concentrate supplementation during housing (GC-24), and entirely on a grass forage diet at 28 months (GO-28).

	GO-20				GO-24				GC-24				GO-28			
Sources	AP	MEP	FEP	NRE	AP	MEP	FEP	NRE	AP	MEP	FEP	NRE	AP	MEP	FEP	NRE
Manure storage	0.05	34.2	–	–	0.13	91.5	–	–	0.12	78.7	–	–	0.07	50.8	–	–
Manure spreading	0.04	37.6	0.42	–	0.10	100.7	0.78	–	0.09	86.6	0.68	–	0.06	55.9	0.54	–
Grazing	0.03	56.2	0.41	–	0.02	29.8	0.19	–	0.01	22.8	0.13	–	0.03	52.5	0.36	–
Fertiliser application	0.09	117.5	0.20	–	0.11	143.9	0.12	–	0.08	103.9	0.05	–	0.10	136.7	0.20	–
Fertiliser production	0.01	4.2	0.55	29.0	0.01	5.1	0.39	35.1	0.01	3.7	0.16	24.9	0.01	4.8	0.59	33.6
Concentrate production	–	–	–	–	–	–	–	–	0.08	43.1	0.34	16.4	–	–	–	–
Fuel use emissions	0.01	2.3	0.00	13.1	0.01	3.4	0.00	19.7	0.01	2.6	0.00	14.8	0.01	2.6	0.00	15.2
Electricity production	0.00	0.0	0.00	2.2	0.00	0.1	0.00	4.9	0.00	0.1	0.00	3.3	0.00	0.1	0.00	3.6
Pollutant																
NH_3	83.3	50.6	–	–	88.1	61.5	–	–	71.2	55.9	–	–	85.0	54.0	–	–
NO_X	14.3	6.3	–	–	10.1	5.2	–	–	27.2	15.6	–	–	12.8	5.9	–	–
NO_3	–	43.1	–	–	–	33.4	–	–	–	28.5	–	–	–	40.1	–	–
SO_2	2.4	–	–	–	1.8	–	–	–	1.6	–	–	–	2.2	–	–	–
PO_4	–	–	34.9	–	–	–	26.5	–	–	–	37.1	–	–	–	34.9	–
P	–	–	65.1	–	–	–	73.5	–	–	–	62.9	–	–	–	65.1	–

MWG = meat weight gain.

tion system releasing 0.73, 0.58, and 0.76 g P eq/kg MWG, respectively. In contrast, manure application was the main source of FEP pollutants for the GC-24 system (0.48 g P eq/kg MWG) due to the partial substitution of P fertiliser application rate with P imported onto farm in concentrate feed. As with previous impact categories, the response in animal performance with the introduction concentrate feed exceeded the increase in FEP pollutants embodied in concentrate feed thus resulting in lower FEP per kg LWG, CWG and MWG in comparison to GO-24. Steers finished in the GC-24 system however had greater FEP per animal in comparison to GO-24.

Non-renewable energy use

Non-renewable energy was predominantly consumed off farm, where 65.4%, 59.0%, and 64.1% was used during synthetic fertiliser production for GO-20, GO-24, and GO-28 production systems, respectively (Tables 8 and 9). Other off-farm inputs that consumed NRE were electricity and fossil fuel production. Fossil fuel consumption was the sole on-farm activity that consumed NRE. Synthetic fertiliser production was also the main consumer of NRE in GC-24. Additional NRE was consumed by this system during the production of the concentrate feed. Accordingly, despite a lower NRE per kg product, NRE per animal for GC-24 was greater than the GO-24 system (Table 5). Like the AP and MEP results, the third grazing season for GO-28 increased resource use and consequently NRE per animal. For the GO-20 system, the pattern was also similar to other environmental impacts, in that the absence of a second housing period led to lower NRE embodied in electricity usage and less conserved forage relative to systems with older finishing ages.

Sensitivity analysis

The environmental impact of the complete beef production cycle (cow-calf phase and weanling-to-finish phase) of the four proposed systems are reported in Table 10. Similar trends reported for the environmental impact of the weanling-to-finishing phase where identified for the complete beef production cycle. The GO-20 system had the lowest environmental impact across impact categories investigated for both breed types. The inclusion of the environmental impact cow-calf phase increased the GWP by 0.2–2.5 kg CO_2 eq, 0.7–5.0 kg CO_2 eq, and 0.5–7.0 kg CO_2 eq per kg LWG, CWG and MWG, respectively. Due to lower synthetic N fertiliser and

Table 10
Effect of breed type (EM, early-maturing and LM, late-maturing), slaughter age, and concentrate supplementation on the global warming potential (GWP), non-renewable energy use (NRE), acidification potential (AP), freshwater eutrophication potential (FEP) and marine eutrophication potential (MEP) of the cow-calf phase and a complete suckler-to-beef cycle.

	GWP (kg CO_2eq		NRE (MJ)		AP (H + eq)		FEP (g P eq)		MEP (g N eq)	
Item	EM	LM	EM	LM	EM	LM	EM	LM	EM	LM
GO-20[1]										
Per kg live weight gain	11.6	11.8	20.2	20.5	0.09	0.09	0.81	0.84	104	106
Per kg carcass weight gain	22.1	21.6	38.4	37.4	0.17	0.16	1.54	1.54	198	193
Per kg meat weight gain	31.3	28.9	54.3	49.9	0.24	0.22	2.18	2.05	280	258
GO-24[2]										
Per kg live weight gain	12.6	13.0	22.6	23.0	0.12	0.12	0.79	0.81	126	128
Per kg carcass weight gain	24.1	23.2	43.3	41.2	0.22	0.21	1.52	1.46	240	228
Per kg meat weight gain	35.5	31.5	63.7	55.9	0.33	0.29	2.23	1.98	354	309
GC-24[3]										
Per kg live weight gain	12.0	12.7	22.1	23.1	0.12	0.13	0.71	0.75	118	124
Per kg carcass weight gain	22.5	22.5	41.1	40.8	0.22	0.22	1.33	1.34	219	218
Per kg meat weight gain	32.9	30.9	60.2	56.1	0.33	0.30	1.95	1.84	320	300
GO-28[4]										
Per kg live weight gain	11.9	12.1	21.4	21.6	0.10	0.10	0.78	0.82	115	116
Per kg carcass weight gain	22.3	21.3	40.1	38.2	0.19	0.18	1.47	1.45	216	205
Per kg meat weight gain	32.2	29.2	57.9	52.3	0.28	0.25	2.12	1.98	312	281

[1] GO-20 = Weanlings produced to slaughter entirely on a grass forage diet at 20 months.
[2] GO-24 = Weanlings produced to slaughter entirely on a grass forage diet at 24 months.
[3] GC-24 = Weanlings produced to slaughter at 24 months on a grass forage diet with concentrate supplementation during housing.
[4] G0-28 = Weanling produced to slaughter entirely on a grass forage diet at 28 months.

proportion of N fertiliser applied in the form of urea, AP, MEP and NRE during the cow-calf phase were lower than the weanling-to-finish phase for the GO-24, GC-24, and GO-28 systems. As a result total AP reduced by 0–0.05 mol H^+eq, 0.01–0.08 mol H^+eq, and 0.02–0.12 mol H^+eq per kg LWG, CWG and MWG, respectively. Total MEP reduced by 0–4.1 g N eq, 0–6.7 g N eq, and 0–10.1 g N e q per kg LWG, CWG and MWG, respectively. The inclusion of the cow calf phase increased NRE, AP and MEP per kg product for the GO-20 system due to lower NH_3 and NO_3 emissions as a result of the omission of the second housing season. Due to higher P fertiliser application rates FEP increased by 0.1–0.2 g P eq, 0.2–0.4 g P eq, and 0.3–0.6 g P eq per kg LWG, CWG, and MWG, respectively.

Uncertainty analysis

Based on parameter selected for the sensitivity analysis, the environmental impact categories of interested were GWP, AP, and MEP. The mean and 95% confidence interval of the GWP, AP, and MEP per kg LWG, kg CWG, and kg MWG for EM and LM steers finished in the four production systems is reported in Tables 11 and 12. Early mature steers finished in the GO-20 system had the lowest GWP per kg LWG (9.3 kg CO_2eq, 2.5th and 97.5th percentiles (2.5th–7.5th); 8.3–10.5 kg CO_2eq) while LM steers finished in the GO-20 system had the lowest GWP per kg MWG (22.6 kg CO_2eq, 2.5th–97.5th; 20.1–25.2 kg CO_2eq). Enteric fermentation, N_2O from urine deposition during grazing, and N_2O from CAN fertiliser application were reported to contribute 27.0–50.9%, 16.5–30.7%, and 15.5–51.0% to the simulated variance for GWP, respectively. Similarly, EM and LM steers finished in the GO-20 system reported the lowest AP per kg LWG (0.09 mol H^+eq, 2.5th–97.5th; 0.06–0.13 mol H^+eq) and kg MWG (0.23 mol H^+eq, 2.5th–97.5th; 0.16–0.31 mol H^+eq), respectively. Ammonia emissions from fertiliser application, animal housing, and manure excreted at pasture contributed 51.7–79.1%, 13.2–55.82% and 1.0–7.3% to the simulated variance of AP, respectively. For MEP, EM and LM steers finished in the GO-20 system reported the lowest per kg LWG (107 g N eq, 2.5th–97.5th; 82–135 g N eq) and kg MWG (259 g N eq, 2.5th–97.5th; 200–323 g N eq), respectively. Ammonia emissions from fertiliser application, animal housing, and nitrate leaching contributed 34.2–47.4%, 5.95–33.4% and 31.7–42.5% to the simulated variance of MEP, respectively. Steers finished in the GO-24 system had the greatest GWP, AP, and MEP per kg LWG, CWG, and MWG.

Discussion

With the increase in demand for beef globally, it is critical that economically viable and environmentally sustainable management practices are identified and applied to minimise environmental impact of the beef sector. There has been renewed interest in grass-fed beef, particularly in developed countries where it has added value amongst producers and consumers. Grass-fed beef is perceived to be healthier, better for the environmental, and provide higher standards for animal welfare (Teague et al., 2016; Henchion et al., 2017). A new LCA model was developed to determine the environmental performance of grass-fed beef, and used to examine the effect of breed type and age at finish on the impacts of suckler-bred steer weanling-to-beef production systems.

The objective of the study by Regan et al. (2018) was to compare the post-weaning performance, growth and carcass characteristics of suckler-bred steers i.e. the weanling-to-beef phase of pasture-based suckler beef production systems. The current study therefore applied the same system boundary. Likewise, previous LCA studies evaluating suckler beef systems also excluded the pre-weaning suckling phase (McAuliffe et al., 2018; Stanley et al., 2018; Heflin et al., 2019). It is possible to estimate emissions of the cow-calf phase, however as animals were randomly assigned to the different treatments within breed, factors relating to the suckler cow that would influence the calf performance during the suckling phase are also randomised. Therefore, the differences in the whole-life environmental impact between the systems investigated are associated with the weanling-to-beef phase. It has been established however that the maintenance of the suckler cow is a dominant source of environmental impact from suckler beef systems (De Vries et al., 2015). Using national statistics the cow calf phase was simulated in the sensitivity analysis to calculate the total environmental impact of beef produced from systems investigated.

Table 11
Global warming potential (GWP), acidification potential (AP), and marine eutrophication potential (MEP) for early-maturing steers produced to slaughter entirely on a grass forage diet at 20 months (GO-20), entirely on a grass forage diet at 24 months (GO-24) on a grass forage diet with concentrate supplementation during housing (GC-24), and entirely on a grass forage diet at 28 months (GO-28) expressed per kg live weight gain (LWG), carcass weight gain (CWG), and meat weight gain (MWG).

		GWP (kg CO_2eq)			AP (mol H^+ eq)			MEP (g N eq)		
Item		LWG	CWG	MWG	LWG	CWG	MWG	LWG	CWG	MWG
GO-20	Mean	9.3	17.6	25.2	0.1	0.2	0.3	107	202	289
	Min	7.3	13.8	19.7	0.0	0.1	0.1	68	129	184
	Max	11.7	22.0	31.5	0.1	0.3	0.4	156	294	421
	2.5th	8.3	15.6	22.3	0.1	0.1	0.2	82	154	222
	97.5th	10.5	19.7	28.3	0.1	0.2	0.3	135	253	363
GO-24	Mean	11.9	22.7	35.3	0.2	0.3	0.4	153	291	453
	Min	10.7	20.3	31.7	0.1	0.1	0.2	94	179	279
	Max	13.6	25.8	40.2	0.2	0.4	0.7	218	415	646
	2.5th	11.2	21.2	33.1	0.1	0.2	0.3	119	227	353
	97.5th	12.8	24.3	37.8	0.2	0.4	0.6	188	358	558
GC-24	Mean	10.8	19.9	30.2	0.1	0.3	0.4	129	239	363
	Min	9.9	18.3	27.8	0.1	0.1	0.2	84	155	235
	Max	12.0	22.2	33.7	0.2	0.4	0.6	178	329	500
	2.5th	10.3	19.0	28.8	0.1	0.2	0.3	105	194	294
	97.5th	11.3	20.9	31.7	0.2	0.3	0.5	155	285	433
GO-28	Mean	11.0	20.5	30.4	0.1	0.2	0.3	128	238	353
	Min	9.2	17.1	25.3	0.1	0.1	0.2	78	146	216
	Max	13.0	24.2	35.8	0.2	0.4	0.5	184	342	507
	2.5th	10.0	18.6	27.5	0.1	0.2	0.2	98	183	271
	97.5th	12.2	22.6	33.5	0.2	0.3	0.4	160	297	440

Table 12
Global warming potential (GWP), acidification potential (AP), and marine eutrophication potential (MEP) for late-maturing steers produced to slaughter entirely on a grass forage diet at 20 months (GO-20), entirely on a grass forage diet at 24 months (GO-24) on a grass forage diet with concentrate supplementation during housing (GC-24), and entirely on a grass forage diet at 28 months (GO-28) expressed per kg live weight gain (LWG), carcass weight gain (CWG), and meat weight gain (MWG).

		GWP (kg CO_2eq)			AP (mol H^+ eq)			MEP (g N eq)		
Item		LWG	CWG	MWG	LWG	CWG	MWG	LWG	CWG	MWG
GO-20	Mean	10.1	18.1	22.6	0.1	0.2	0.2	116	208	259
	Min	8.1	14.5	18.1	0.1	0.1	0.1	72	129	161
	Max	12.9	23.1	28.8	0.2	0.3	0.4	167	299	372
	2.5th	9.0	16.1	20.1	0.1	0.1	0.2	90	161	200
	97.5th	11.3	20.3	25.2	0.1	0.2	0.3	145	260	323
GO-24	Mean	12.9	22.6	29.4	0.2	0.3	0.4	168	295	383
	Min	11.6	20.3	26.4	0.1	0.1	0.2	108	189	246
	Max	14.6	25.6	33.3	0.3	0.5	0.6	235	414	537
	2.5th	12.1	21.3	27.7	0.1	0.2	0.3	131	230	299
	97.5th	13.7	24.1	31.4	0.2	0.4	0.5	205	361	469
GC-24	Mean	12.4	21.5	29.0	0.2	0.3	0.4	148	257	348
	Min	11.3	19.7	26.6	0.1	0.2	0.2	98	170	229
	Max	13.5	23.4	31.6	0.2	0.4	0.6	198	345	466
	2.5th	11.8	20.5	27.7	0.1	0.2	0.3	121	210	283
	97.5th	13.0	22.5	30.4	0.2	0.4	0.5	177	307	415
GO-28	Mean	11.4	19.9	26.6	0.1	0.2	0.3	134	232	311
	Min	9.6	16.6	22.3	0.1	0.1	0.2	83	144	194
	Max	13.9	24.1	32.4	0.2	0.3	0.4	191	332	446
	2.5th	10.4	18.0	24.2	0.1	0.2	0.2	103	180	241
	97.5th	12.6	21.9	29.3	0.2	0.3	0.4	166	289	388

Effect of age at slaughter, breed and concentrate supplementation on environmental impact of suckler weanling-to-finish systems

This study's findings indicated that steers finished at 20 months on high nutritive value grazed grass had the lowest environmental impact across all impact categories and functional units examined. Extending the GO-20 system to finishing steers at 24 months by housing and offering high nutritive value grass silage, or further by finishing steers at 28 months during a third grazing season, increased the environmental impact per animal across all categories investigated. While GO-28 system was found to have the greatest environmental impact per animal, excluding FEP, the increase in daily LWG in the third grazing season resulted in the GO-28 system having lower environmental impact per kg product than the GO-24 system. This finding is in agreement with McAuliffe et al. (2018) who quantified GHG emissions from temperate pasture-based steer finishing systems in the UK and reported a strong negative correlation between GHG intensity per kg LWG and daily LWG. Additionally, Heflin et al. (2019) reported finishing cattle on high quality diets, in intensively managed feedlot systems, in the shortest time possible reduced GHG intensity of LWG in comparison to cattle in pasture-based systems. Though the current study did not investigate a feedlot system, the principle of finishing steers within the shortest time possible to minimise environmental impact per kg product remains, where it is evident that increasing age at slaughter from 20 months to 24 and 28 months increases other environmental impact across all categories.

Late-maturing breed cattle have superior kill-out proportion, heavier carcasses, greater muscle conformation, lower fat score and thus greater carcass lean meat proportion than EM breeds at the same age (Drennan et al., 2005; Keane, 2011). At a similar slaughter live weight, LM steers should therefore have a lower environmental impact per kg MWG. Carcass weight rather than LW has been highlighted to be a more accurate estimate of animal performance in pasture-based beef production systems, due to the large influence of breed and diet on factors such as gut fill, hide proportion and offal fat, and consequently kill-out proportion (Keane, 2011). This was evident in the current study, whereby EM steers were heavier at slaughter than LM, but due to an inferior kill-out proportion they had lighter carcasses. This was reflected in the results where although EM steers had the lowest environmental impact per kg LWG for all the production systems, when expressed per kg CWG, the differences in breed type were less apparent.

Carcass conformation and fat scores have been identified as relatively accurate predictors of carcass meat, fat, and bone proportions (Conroy et al., 2010). As producing meat is the primary objective of beef cattle production, it is reasonable to assume that MWG is a superior measurement of animal performance than LWG and CWG. Congruous with findings from the current study, Pesonen et al. (2013) reported that carcasses from LM steers had a greater meat yield than EM steers. Consequently, in the current study LM steers had a lower environmental impact than EM steers per kg MWG for all production systems categories investigated. Based on these findings, selecting a breed type or management practice to reduce environmental impact based on kg LWG could in fact have a detrimental effect as opposed to selection based on kg MWG, the primary product.

In this study, the LM steers finished at 20 months off grass did not achieve the minimum commercially acceptable carcass fat score (6 on a 1–15 scale), which could potentially deter the adoption of the GO-20 systems for LM breeds, unless animals with a genetic predisposition for subcutaneous fat deposition are selected. Overall, the GO-20 system may be more appropriate for EM breed types as they are fatter than LM breed types at the same age; Regan et al. (2018) reported a difference in carcass fat score of 2-units on a 15-point scale in favour of EM over LM within each production system. Those authors highlighted that for a production system to optimise output it is important that producers match cattle breeds or genotypes to appropriate diets/finishing practices.

When comparing the GC-24 and GO-24 systems it is evident that supplementation of concentrate feed increased all environmental impact categories when expressed per animal. The increase in daily LWG and subsequently total LWG associated with concentrate feed supplementation surpassed the increase in total system environmental impact. The EM steers finished in the GC-24 system therefore had lower environmental impact across all impact categories per kg LWG, CWG, and MWG than those finished in the GO-24 system. Similarly, LM steers finished in the GC-24 system tended to have lower environmental impact per kg LWG, CWG, and MWG than those finished in the GO-24 system, with the exception of NRE and AP, which were similar. Consequently, there is a role for strategic concentrate supplementation within pasture-based beef production systems. It is noteworthy that the influence of concentrate feed on the environmental impact of beef systems is also dependent on the ingredient composition of the concentrate ration (e.g. cereals vs. by-products) offered, and thus the associated transport, land use change etc. involved in its production.

Life cycle assessment comparison

While whole-farm or life cycle modelling has been identified as the most robust method to determine the environmental performance of agricultural production systems (Schils et al., 2007), inconsistencies in methodologies compromises the efficacy of comparing of LCA studies (Crosson et al., 2011). In addition, a systematic review of impact categories used in livestock LCA studies reported that 98% of publications include "climate change" and that 28% of publications focused solely on this one category (McClelland et al., 2018). To obtain a more holistic view of the environmental impact of livestock systems and to account for trade-offs which may occur between "climate change" and other environmental impacts, multiple impact categories should be reported. Considering this issue, a cradle-to-farm gate boundary was set and environmental impact was reported using five impact categories and multiple functional units.

Global warming potential

Few LCA studies have investigated the environmental impact of pasture-based weanling-to-beef production systems. Heflin et al. (2019) evaluated the GHG intensity of multiple finishing strategies in the Southern High Plains region in America, and reported steers finished on native pastures and feed lot systems emitted 26.5 kg and 4.8–8.1 kg CO_2eq per kg LWG, respectively. Similarly, Stanley et al. (2018) reported males finished in feedlot systems to have a lower GHG intensity (8.43 kg CO_2eq /kg LWG) in comparison to males finished in a pasture-based system (16.23 kg CO_2eq/kg LWG). The GHG intensity of the production systems examined in the current study were lower than the systems investigated by Heflin et al. (2019) and Stanley et al. (2018). Differences between studies are partially attributable to different LCA methodologies but also due to differences in management practices. Steers in the pasture-based system reported by Stanley et al. (2018) entered the farm at 362 kg, spent 200 days in an adaptive multi-paddock grazing system, and finished at approximately 20 months of age weighing 528 kg. In contrast, steers in the native pasture system reported by Heflin et al. (2019) entered the farm at 250 kg and required 700 days to achieve 500 kg slaughter weight. Comparing the results of the current study and Stanley et al. (2018) to Heflin et al. (2019) highlights the importance of providing high nutritive value pasture to reduce age at slaughter and subsequently the associated environmental impact.

It is widely reported that cereal-based intensive beef finishing systems have a lower GHG intensity than pasture-based finishing systems. For pasture-based systems, both Herron et al. (2019) and Foley et al. (2011) reported suckler-bred bulls finished on a high-concentrate diet at 16 months to have a lower GHG intensity to that of suckler bred steers finished predominately on forage at 24 months. Lupo et al. (2013) (23 vs. 32 kg CO_2eq /kg CW) and Capper (2012) (16, 18.8 vs. 26.8 kg CO_2eq /kg CW) also reported feedlot finishing systems to have a lower GHG intensity per kg product than pasture-based beef finishing systems. The difference in GHG intensity is partially attributed to high concentrate feed diets increasing growth rates and reducing age at finish (Heflin et al., 2019) as well as the aforementioned feedlot systems using bulls or steers with 'growth-enhancing technology' (Capper, 2012), both of which are more efficient than the 'natural' steers used in pasture based systems.

Feedlot systems that use cereal grains rather than by-products, however, have a poorer human edible feed efficiency ratio than pasture-based systems; Wilkinson (2011) reported human edible protein efficiency ratios of 0.92 and 3.0 for upland suckler beef systems and "cereal" based beef systems, respectively. Pasture-based finishing systems mainly convert forage, a natural non-human edible protein source, into high value animal product without compromising food security (McAuliffe et al., 2018). Additionally, the rearing of livestock in a regenerated managed agro-ecosystem, such as the rotational grazing system used in our study, improves soil C sequestration and ecological function, and enhances biodiversity (Teague et al., 2016; Provenza et al., 2019). Capper (2012) argues however that if all beef is to be produced in grass-fed systems, land area for beef production will have to significantly increase thus increasing competition for land suitable for arable production systems that produce readily available human edible products.

Eutrophication potential

To develop a broader understanding of the environmental impact of a product, multiple impact categories should be reported. Accordingly, the EU PEFCR guidelines for product environmental footprint (PEF) were followed. As the PEF is a relatively new methodology, limited studies reported AP using the AE approach and EP under two sub-categories, freshwater and marine. Tsutsumi et al. (2018) found lower eutrophication potential per kg carcass weight for organic (20.3 gPO_4) and non-organic (17.8 gPO_4) beef systems compared to conventional Japanese feedlot beef systems (37.5 gPO_4). Similarly, Lupo et al. (2013) reported their extensive "grass-fed" system to have lower MEP and FEP in comparison to feedlot and background/feedlot systems. The FEP and MEP values for the post suckling phases of the "grass-fed" systems in that study were notably lower than those of the current study. Lupo et al. (2013) however did not specify any N or P fertiliser application onto pasture, and also reported manure to contribute 83% and 82% of MEP and FEP, respectively. In contrast, synthetic fertiliser contributed 40.3–49.0% and 40.3–47.7% of MEP and FEP for the GO systems in the current study, respectively. Similarly, the "grass-fed" system in Pelletier et al. (2010) was fertilised by manure only; however the "grass-fed" system was reported to have greater EP per kg CW than the feedlot background feedlot systems simulated. This inconsistency in results is attributed to variation in production system and methodology. In the current study, total FEP and MEP increased with age of slaughter for the GO systems due to greater lifetime consumption and resource usage.

Acidification potential

As with the current study, Tichenor et al. (2017) reported AP in terms of mol H^+ eq, but applied American characterisation factors develop by Norris (2003). In contrast, country specific characterisation factors provided by Posch et al. (2008) were adopted in the current study as acidifying pollutants can have varying consequence on atmospheric conditions and ecosystems depending on the sensitivity of the environment. Regardless, Tichenor et al. (2017) also reported that the majority of AP from grass-fed systems was due to NH_3 emissions, primarily from manure. As with other impact categories, AP per animal increased with age of slaughter for GO systems. The GO-20 system had the lowest AP for all functional units, as steers were finished at grass prior to second housing, thus omitting managed manure related pollutants. Despite having the greatest AP per animal, GO-28 had lower AP per kg product than both GO-24 and GC-24. This is due to the combination of lower NH_3 emissions per kg LWG during the grazing season than the housing season and the significant increase in LWG during the third grazing. Lupo et al. (2013) similarly reported the "grass-fed" system to have lower AP per kg CW than the intensive backgrounding/feedlot systems. Post weaning grazing in the "grass-fed" system was a minor contributor to AP, whereas in contrast the intensive indoor finishing phase of the backgrounding/feedlot systems was identified as a significant contributor to AP. The results of the current study and those discussed above suggest that finishing cattle at pasture reduces AP per kg product.

Non-renewable energy use

In agreement with a number of beef LCA studies, forage production (fertiliser production included) was the main contributor to NRE use for all systems simulated (Capper, 2012; Berton et al., 2016; Pelletier et al., 2010). The "grass-fed" systems reported by Wiedemann et al. (2015) had lower NRE usage (18.24 MJ/kg red meat) in comparison to feedlot systems (24.00–32.5 MJ/ kg red meat). These values are notably lower than the NRE usage found in the current study. This disparity is likely to be attributed to the high synthetic fertiliser usage in the systems simulated in the current study. In contrast to Wiedemann et al. (2015), Capper (2012) reported their "grass-fed" system to consume greater quanitity of NRE per kg CW (12.5 MJ) than conventional (8.8 MJ) and natural (no growth enhancer) (10.3 MJ) feedlot systems. This is interesting as it is perceived that grass finishing systems use less NRE than intensive cereal-based finishing systems. In reality, relatively high stocked pasture-based production systems utilise large quantities of NRE embodied in synthetic fertilisers and combustion of fossil fuels by machinery for pasture management, forage harvesting and feeding. Grass-fed beef producers should therefore aim to finish cattle early. Finishing cattle at a younger slaughter age has many environmental benefits, but our research shows the optimum slaughtering age is dependent on breed and cannot be applied using a "one size fits all" approach.

This is one of few studies that investigated the environmental impact of grass-fed beef production systems, and to the best of our knowledge the only study that determined the effect of slaughter age and breed type. Further research should be conducted to identify management practices that reduce the environmental impact of the preceding suckling-to-weanling phase to ensure all phases of suckler beef production are considered and investigated. This should be conducted using a common harmonised LCA approach.

Conclusion

For the GO systems, environmental impact per animal increased with slaughter age for both breeds. The GO-20 system subsequently had the lowest environmental impact across all functional units and systems investigated. The LWG response to concentrate supplementation in GC-24 was greater than the increase in total environmental impact. As a result, EM steers finished in the GC-24 system had a lower environmental impact across all categories per kg product than GO-24. Similarly, LM steers finished in the GC-24 system had a lower environmental impact across all categories per kg product than GO-24 with the exclusion of NRE and AP which were similar for both systems. Across systems, EM steers had a lower environmental impact than LM when expressed per kg LWG, but the opposite occurred when expressed per kg MWG; LM steers had lower environmental impact. As meat yield can be easily and relatively accurately predicted from carcass classification scores, MWG should be the metric of choice.

Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.animal.2021.100247.

Ethical approval

Not applicable.

Data and model availability statement

The data was not deposited in an official repository. Data is available upon request.

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Declaration of interest

None

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