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Effects of grass silage-based feeding strategies and carcass weight on performance and environmental impacts of finishing beef on dairy crossbred heifers

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ABSTRACT

When targeting low-carbon feed production and feeding cattle with non-human-edible feeds, in practice, this means maximising the use of forages such as grass. However, there is a gap in knowledge of the environmental impacts when carcass weight increases and/or concentrate is excluded from grass silage (**GS**)-based diet. The objective of this study was to evaluate the effects of two different GS–based diets and three carcass weights on performance and environmental impacts of growing heifers. The experiment was conducted using 84 crossbred heifers (Holstein or Nordic Red × Blonde d'Aquitaine). Two experimental diets were GS alone (**GSA**) and GS supplemented with barley grain (285 g/kg DM; **GSB**). Both diets contained a mineral-vitamin mixture (15 g/kg DM). The heifers were fed total mixed rations *ad libitum*. The animals were slaughtered at three **BW**s, targeting carcass weights of 300 (**LCW**), 325 (**MCW**) or 350 (**HCW**) kg. Life cycle assessment approach was used to compare climate change, eutrophication, and acidification impacts for both feeding treatments across three carcass weights. The experimental treatments had no effects on daily DM intake, but total DM intake was 13% higher for the GSA compared to GSB ($P < 0.001$) and 37% higher for HCW compared to LCW ($P < 0.001$). Barley grain supplementation increased daily energy intake by 14% ($P < 0.001$). Excluding barley grain from the diet decreased carcass gain by 20% ($P < 0.001$). Feed conversion (kg DM/kg carcass gain) declined when barley grain was excluded from the diet ($P < 0.001$). Carcass weight had no effect on growth rate and feed conversion. For GSA, the dressing proportion was 3% ($P < 0.001$) and carcass conformation 11% ($P = 0.018$) lower compared to GSB, but they were not affected by carcass weight. For carcass fat score, feeding × carcass weight quadratic interaction was observed ($P < 0.016$). Compared to GSA, GSB animals were fatter and carcass fat cover was affected to a greater extent by carcass weight. At the same carcass weight, the climate change impact of GSB was 10–11%, eutrophication potential 13–15%, and acidification potential 20–23% lower compared to GSA. Increasing carcass weight raised all impacts by 4–9% per functional unit within both dietary treatments. For all carcass weights, GSB showed consistently lower environmental impacts than GSA. In conclusion, including concentrate in the diet improved performance of the heifers and decreased environmental impacts.

Implications

When targeting low-carbon feed production and feeding cattle with non-human-edible feeds, it means maximising the use of forages. In indoor beef production, feeding heifers with good quality grass silage alone, a reasonable growth can be achieved. However, concentrate in the diet improved performance of the animals. Additionally, climate change impact, eutrophication potential and acidification potential decreased. Increasing carcass weight is one way to increase beef production. However, it increased environmental impacts, the effect being higher when concentrate was excluded from the diet. In conclusion, including concentrate in the diet improved performance of the animals and decreased environmental impacts.

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Introduction

Global population growth increases demand for food, including beef, in the near future (Organisation for Economic Co-operation and Development (OECD) and the Food and Agriculture Organization (FAO) of the United Nations, 2024). Since 2021–2023, beef consumption is projected to grow 11% by 2033 and global consumption is forecast to reach 81 million tonnes (OECD/FAO, 2024). The growth in beef demand is roughly in line with population growth (OECD/FAO, 2024). At the same time as the demand for food production increases, the pressure to reduce environmental impacts is strengthening. Globally, there is a growing trend among consumers to pay more attention to environmental effects, particularly in beef production, which is considered a major source of greenhouse gas emissions in food production (Wilkinson and Lee, 2018). These trends will drive the development of practices that improve resource efficiency and productivity, which is a prerequisite for sustainable beef production (Capper and Bauman, 2013). One way to produce beef in a more environmentally sustainable way could be to improve beef production based on dairy cattle which has been shown to cause less greenhouse gas emissions per produced meat unit compared to suckler cow systems (Nguyen et al., 2010; de Vries et al., 2015; Hietala et al., 2021).

Particularly in Europe, a large proportion of offspring from dairy cows enter beef fattening systems and dairy cows are increasingly being inseminated with beef breed semen (Greenwood, 2021). It is typically used for less superior cows whose offspring are not intended to be used for milk production. This is an opportunity to dairy farms to produce a higher economic value crossbred calves for beef production. In beef production system, crossbred calves improve production efficiency, such as growth rate, feed efficiency and carcass quality, compared to purebred dairy breeds (Huuskonen et al., 2014; Vestergaard et al., 2019; Basiel and Felix, 2022). In addition, improving the feed efficiency is an effective way to reduce the environmental impacts (Leinonen, 2019; Huuskonen, et al., 2023).

Beef production in Finland relies heavily on dairy farming. In 2023, pure dairy breeds and beef on dairy crossbreds comprised 80% of total beef produced. The remaining 20% originated from suckler cow production (Luke, 2025a). Most slaughtered young cattle are bulls, but heifers are also raised for beef production. The beef produced from the dairy branch consist of culled dairy cows (21%) and their pure or crossbred bulls (45%) and heifer calves (14%). (Luke, 2025a). Because of the decrease in the size of the dairy cattle population and no substantial change in beef consumption, there is an undersupply of domestic beef and the gap is foreseen to grow in the future. In 2023, beef self-sufficiency was 90% in Finland (Luke, 2025b).

To compensate for the reduction in numbers of slaughtered animals, slaughterhouse pricing systems favour heavy carcasses and the average carcass weight of dairy and beef on dairy crossbred bulls is currently 362 kg (Luke, 2025a). However, it is biologically inefficient to increase further the carcass weight because due to a shift in the proportion of muscle vs. fat deposition along with increasing age and/or weight. In the early growth stage, muscle growth is dominant, but as the animal matures, fat deposition increases, and maintenance requirements increase. In consequence, feed conversion declines as a result of decreased growth rate and increased DM intake (Lawrence and Fowler, 2002). Thus, new ways must be found to promote beef production to ensure self-sufficiency and meet the increasing global demand for beef. Increasing the number of suckler cows is not a fast enough way, at least in the short term. Furthermore, higher greenhouse gas emissions compared to dairy breed beef system have to be taken into account. One way to increase environmentally more sustainable beef production could be to improve the growing and finishing methods of heifers originated from dairy herds and intended for beef production. Currently, about 80% of these animals are beef on dairy crossbreds, and there is untapped potential in terms of their carcass weights.

From a global perspective, beef should primarily be produced under sustainable production conditions, such as in Finland, where water is not a limiting factor, and climatic conditions favour grass-based production (Lehikoinen et al., 2019). Additionally, in the future, as the demand for food increases, it will be increasingly important to use feeds that are not directly fit for human consumption, and thus are also socially more sustainable. This favours grass-based cattle production because of the ability of cattle to transform feeds not suitable for humans into high-quality food (Godfray et al., 2010). However, in terms of production efficiency, forage dominated diets generally decrease average daily gain of growing and finishing cattle compared to moderate or high concentrate diets and in consequences, less beef is produced during the same rearing period (McGregor et al., 2012; Huuskonen et al., 2023) and environmental impacts increase (Huuskonen et al., 2023). However, when carbon footprint from feed production is considered, the effect is no longer as clear, particularly when feeding is based on grass silage (**GS**) diet (Huhtanen and Huuskonen, 2020). When targeting low-carbon feed production and feeding animals with non-human-edible feeds, in practice, this means maximising the use of forages such as grass. However, there is a gap in knowledge of the impacts when carcass weight increases and/or concentrate is excluded from GS-based diet in growing and finishing heifers.

The first objective of this study was to determine the effects of two concentrate levels and three carcass weights in GS-based feeding on feed intake, growth rate and carcass composition of growing and finishing beef on dairy crossbred heifers. The second objective was to evaluate the effects of these growing and finishing strategies on greenhouse gas emissions and eutrophication and acidification potential as measures of environmental sustainability. It was hypothesised that excluding concentrate from the diet reduces growth rate, impairs feed conversion and decreases carcass fatness of the crossbred heifers. It also was hypothesised that by increasing the carcass weight, growth rate will decrease and feed efficiency will be impaired. Additionally, dressing percentage and carcass conformation will improve, and carcass fatness will increase when carcass weight increases. In terms of environmental impacts, it was hypothesised that excluding concentrate from the diet and increasing carcass weight both will increase environmental impacts.

Material and methods

Animals and housing

A feeding experiment was carried out in the experimental barn of Natural Resources Institute Finland (Luke) in Ruukki, Finland (64°42′ N, 25°00′ E). The experiment started in January 2023 and ended in March 2024. It comprised a total of 84 beef on dairy crossbred heifers and the experiment began simultaneously with all animals. Sire breed for all animals was Blonde d'Aquitaine and dam breed was dairy breed, either Holstein (57 animals) or Nordic Red (27 animals). During the experiment, one heifer (Blonde d'Aquitaine × Nordic Red) was excluded from the study due to foot injury. There was no reason to suppose that the experimental treatments had caused this problem.

All calves were purchased from local dairy farms at age of ca. 3 weeks. They were transported to calf rearing farms and housed in an insulated barns. They received milk replacer (until the age of 75 d), GS and a commercial pelleted calf starter feed. The animals were transported to the experimental cattle barn of Luke when they reached on average 5 months of age, about 3 months before the start of the feeding experiment. During this pre-experimental period, the heifers were adapted to the housing conditions and the GS–based experimental diet supplemented with barley grain and vitamin-mineral mixture. During both the pre-experimental period and the feeding experiment, the animals were housed in an uninsulated barn in pens (10.0 m × 5.0 m) in groups of six heifers per pen, providing 8.3 m^2 per heifer. The rear half of the pen area was a peat and straw-bedded lying area, and the fore half was a feeding area with a solid concrete floor.

Experimental design and feeding

The study had a 2 × 3 factorial arrangement of treatments with two different dietary treatments and three carcass weights within both diets. The two experimental diets were (1) GS alone (**GSA**) and (2) GS supplemented with rolled barley grains (285 g/kg DM; **GSB**). In both diets, the proportion of mineral-vitamin mixture was 15 g/kg DM. The GS was a mixture of two different silages. Silage 1 was a mixture of timothy (*Phleum pratense*) and meadow fescue (*Festuca pratensis*), and silage 2 was a mixture of timothy and red clover (*Trifolium pratense*). In both diets, in the silage mixture, the proportions of the silage 1 and 2 were 800 and 200 g/kg DM, respectively. The targeted low, medium and high carcass weights were 300 (**LCW**), 325 (**MCW**) and 350 (**HCW**) kg, respectively.

In the feeding experiment, the heifers were fed total mixed rations *ad libitum* (proportionate daily refusals of 5%). A mixer wagon (Trioliet BW, Oldenzaal, the Netherlands) was used for preparing and delivering the total mixed rations. Both rations were produced every day, and feed was offered once a day. A Vytelle feed intake system (model 4000E; 111 Vytelle Ltd., Lenexa, KS, USA) was used to record individual daily feed intakes so that each pen contained two feeder nodes. The animals had free access to water throughout the feeding experiment. At the beginning of the pre-experimental period, the animals were allotted to 14 blocks by BW and within each block randomly to the two dietary treatments. In the pens of six heifers, the animals were randomly allotted to the three target carcass weights, two animals per each weight. There were seven pens for both dietary treatments. At the start of the feeding experiment, the animals were on average 226 (±21.6) days old and weighed on average 257 (±42.7) kg. The heifer which was excluded from the experiment was in feeding group GSA and slaughter group LCW.

Both silages used in the feeding experiment were produced at the experimental farm of Luke in Ruukki, Finland. They were prepared from first and second cut swards. Timothy variety was Nuutti (Boreal Plant Breeding Ltd., Jokioinen, Finland), meadow fescue variety was Valtteri (Boreal Plant Breeding Ltd., Jokioinen, Finland), and red clover variety was Selma (Boreal Plant Breeding Ltd., Jokioinen, Finland). The stands were cut by using a mower conditioner (Elho 280 Hydro Balance, Elho Production Ltd., Pännäinen, Finland), wilted for approximately 24 h after cutting, and harvested using a precision-chop forage harvester (New Holland FX 60, CNH Industrial N.V., Amsterdam, the Netherlands). Both silages were ensiled in bunker silos and treated with a formic acid-based additive (AIV ÄSSÄ Na; Eastman, Oulu, Finland) applied at a rate of 5 kg/t of fresh forage. The cereal grain included in the diet GSB was spring-sown barley (*Hordeum vulgare*, cv. Vertti; Boreal Plant Breeding Ltd., Jokioinen, Finland). It was harvested with a conventional combine harvester, dried to the targeted DM concentration of 870–880 g/kg and stored in a vertical silo. The grain was rolled within seven days prior to feeding. The composition of the mineral-vitamin mixture (Kasvuape E-Hiven; A-Rehu Ltd., Seinäjoki, Finland) was fully described by Huuskonen et al. (2017).

Feed sampling and analyses

During the experiment, silage subsamples were taken twice a week, pooled over four weeks and stored at −20 °C until analysed. Silage samples were analysed for DM, ash, CP, NDF, indigestible NDF, silage fermentation characteristics [pH, water-soluble carbohydrates, lactic and formic acids, volatile fatty acids, ammonia N content of total N] and digestible organic matter in DM (D-value). Barley sub-samples were collected weekly, pooled over periods of eight weeks and analysed for DM and CP. The samples were analysed using near IR spectroscopy (FOSS NIRSystems 6500 spectrometer, Hillerød, Denmark) at the laboratory of Valio Ltd. (Seinäjoki, Finland). The device was calibrated for measuring chemical composition of GS and barley grain. Silage fermentation characteristics were analysed by electrometric titration as described by Moisio and Heikonen (1989).

The metabolisable energy (**ME**) concentration of the GS was calculated as ME (MJ/kg DM) = 16.0 × digestible organic matter (kg/kg DM) (MAFF, 1984). The ME concentration of barley grain and mineral-vitamin mixture was calculated based on the tabulated digestibility coefficients, analysed chemical composition and tabulated values.

The protein value of the feeds is expressed as amino acids absorbed from the small intestine (metabolisable protein) and the protein balance value in the rumen according to Luke (2025c). The protein balance value in the rumen describes the balance between the dietary supply of rumen-degradable protein and the microbial requirements of it. The relative intake potential of silage DM was calculated as described by Huhtanen et al. (2007).

BW and carcass measurements

The heifers were weighed on two consecutive days at the beginning and at the end of the experiment. In addition, during the experiment, they were weighed approximately every four weeks. Animals were selected for slaughter based on BW and assumed dressing proportion of 530 g/kg. The BW gain was calculated as the difference between the means of the initial and final BW divided by the number of growing days. The estimated rate of carcass gain was calculated as the difference between the final carcass weight and the carcass weight in the beginning of the experiment divided by the number of growing days. The carcass weight at the start of the experiment was assumed to be 0.50 × initial BW based on earlier studies (unpublished data).

The heifers were slaughtered at the Atria Ltd. commercial slaughterhouse in Kauhajoki, Finland in five batches. After slaughter, the carcasses were weighed hot. The cold carcass weight was estimated as 0.98 of the hot carcass weight. Dressing proportions were calculated from the ratio of cold carcass weight to final BW. The carcasses were classified for conformation and fatness in accordance with the EU beef carcass classification scheme on a continuous15-point scale (Conroy et al., 2010). For conformation, the development of the carcass profiles, in particular the essential parts (round, back, shoulder), was taken into consideration according to the EUROP classification (E: excellent, U: very good, R: good, O: fair, P: poor). Each level of the conformation scale was subdivided into three sub-classes to produce a transformed scale ranging from 1 to 15, with 15 being the best conformation. For fat cover degree, the amount of fat on the outside of the carcass and in the thoracic cavity was taken into account using a classification range from 1 to 5 (1: low, 2: slight, 3: average, 4: high, 5: very high). Each fat score was subdivided into three sub-classes to produce a transformed scale ranging from 1 to 15, with 15 being most fatty.

Calculation of environmental impacts

Environmental impacts resulting from the use of different diets (GSA and GSB) and carcass weights (LCW, MCW and HCW) were estimated with life cycle assessment approach, following IPCC (2006, 2021) and National Inventory Report methods for Finland (Statistics Finland, 2015) as described in Hietala et al. (2021). The utilised approach used specific prediction models for enteric methane production (Ramin and Huhtanen, 2013) and for dinitrogen oxide emissions from perennial grass cultivation (Regina et al., 2013) and was updated to include the most recent characterisation factors for greenhouse gases according to IPCC (2021), which were for biogenic methane 27 and for nitrous oxides 273. Eutrophication and acidification impacts were assessed as in Hietala et al. (2021), characterised to phosphate equivalents (**PO_4 eq**) using factors 3.06 for P, 0.42 for N, 0.04 for NH_3 and 0.015 for NOx (Heijungs et al., 1992; Seppälä et al., 2004), and as acid equivalents (**AE**) with factors 0.463, 0.535 and 0.186 for SO_2, NH_3 and NOx, respectively (Seppälä et al., 2006). For the assessment focusing on the growing period, system boundary was set from cradle to gate for the growing period and functional unit (**FU**) was 'kg produced carcass weight'.

For the life cycle assessment, inventory data were collected from the conducted feeding trials and included the initial BW, carcass weight, total DM intake, composition of total mixed rations and nutritional quality of the feed ingredients. These were completed with data from Finnish Feed Tables (Luke, 2025c). Feed crop production was assessed within the available life cycle assessment model, using the inventory data for GS and barley from Finnish extensions services 'ProAgria' as in Hietala et al. (2021). The feed nutritional values were utilised for assessment of excreted nutrients and methane emissions from enteric fermentation. For manure storage, solid manure was assumed with straw (35%) and peat (65%) as bedding materials.

Statistical analyses

The individual animal was the experimental unit. The results were analysed using a linear mixed model for a response variable Y_{ijkl} (diet i, carcass weight j, pen k, animal l): $Y_{ijkl} = \mu + D_i + C_j + (D \times C)_{ij} + \beta W_{ijkl} + P_k + (C \times P)_{jk} + e_{ijkl}$, where μ is the intercept, D_i, C_j and $(D \times C)_{ij}$ are the fixed effects of diet (GSA, GSB), carcass weight (LCW, MCW, HCW) and their interaction, respectively, β is the fixed regression effect of initial BW W_{ijkl} (covariate), P_k and $(C \times P)_{jk}$ are the random effects of pen and carcass weight-pen interaction to account for correlated Y_{ijkl} measurements from the same pen, and e_{ijkl} is the random error. The random terms P_k, $(C \times P)_{jk}$ and e_{ijkl} are assumed to be independent and normally distributed.

Differences between the treatments were tested using orthogonal contrasts: (1) diet (GSA vs. GSB); (2) linear effect of carcass weight; (3) quadratic effect of carcass weight; (4) linear interaction between diet and carcass weight, and (5) quadratic interaction between diet and carcass weight. The results were considered statistically significant when $P < 0.05$, which is used when presenting the results in the tables. The presented model means were estimated by the fixed part of the model. The analyses were performed with the GLIMMIX procedure of the SAS software (version 9.4, SAS Institute Inc., Cary, NC, USA).

Results

Feeds

The chemical composition and nutritional values of the experimental feeds and total mixed rations used are presented in Table 1. Silage 1 had a lower ME value and D value than recommended for growing and finishing cattle (680–700 g/kg DM). The composition and feed values of silage 2 were typical for silages containing red clover, corresponding to the average values in the Finnish Feed Tables (Luke, 2025c). Preservation quality of both silages was good as indicated by the low pH value and the low concentrations of total acids and ammonia N (Table 1). The barley grain had typical chemical composition and feed value, corresponding to the average values in the Finnish Feed Tables (Luke, 2025c). Due to the different concentrate proportions, total mixed ration compositions differed between the dietary treatments (Table 1). Replacing GS with barley grain in the total mixed rations increased DM and ME contents by 21 and 8%, respectively, whereas diet protein contents differed only slightly among the treatments.

Feed intake, growth performance and feed efficiency

The duration of the experiment was 402 and 336 days for GSA and GSB, respectively, and 313, 380 and 415 days for carcass weights 300, 325 and 350 kg, respectively (Table 2). Accordingly, the average slaughter age of the heifers was 627 and 562 days for GSA and GSB, respectively, and 540, 606 and 639 days for carcass weights 300, 325 and 350 kg, respectively. Excluding barley grain from the diet increased growing days by 19%. Increased carcass weight prolonged the growing period, and when the lowest carcass weight was compared to the highest, the increase was 32%. Slaughter age of the GSA heifers was 12% higher compared to the GSB heifers ($P < 0.001$). When comparing the effect of carcass weight on slaughter age, both linear ($P < 0.001$) and quadratic ($P = 0.001$) effects were found. The quadratic effect was probably due to not equal differences between the actual carcass weights (297, 331 and 348 kg).

No feeding × carcass weight interactions for DM, ME and CP intake were observed. The dietary treatments had no effects on daily DM intake, but total DM intake was 13% higher for the GSA compared to the GSB ($P < 0.001$). Barley grain supplementation increased daily ME intake of the heifers by 14% ($P < 0.001$) but did not affect daily CP intake. Carcass weight had no effects on daily DM intake or ME and CP intake but had a linear effect on total DM intake ($P < 0.001$). No feeding × carcass weight interactions for the BW gain or carcass gain were observed. Excluding barley grain from the diet decreased BW gain and carcass gain by 16 and 20%, respectively, compared to GSB ($P < 0.001$). Carcass weight had no effect on the growth rate. No feeding × carcass weight interactions for the feed conversion were observed in terms of DM, ME or CP intake per kg carcass gain. When comparing dietary treatments, the DM, ME and CP conversion rates declined by 19, 10 and 19%, respectively, when barley grain was excluded from the diet ($P < 0.001$, $P = 0.003$, $P < 0.001$, respectively). Carcass weight had no effect on the feed conversion rate.

Carcass traits

Mean carcass weights were close to targeted. No feeding × carcass weight interactions for the dressing proportion or carcass conformation were observed (Table 2). Dressing proportion and carcass conformation of GSA heifers were 3% ($P < 0.001$) and 11% ($P = 0.018$) lower, respectively, compared to GSB heifers. For carcass fat score, feeding × carcass weight quadratic interaction was observed ($P = 0.016$). The GSB heifers were fatter compared to GSA heifers ($P = 0.004$) and increasing carcass weight increased carcass fat score linearly ($P < 0.001$). However, in GBS heifers, the effect of carcass weight on carcass fat score was stronger, whereas in GSA heifers, only the highest carcass weight clearly increased carcass fatness (Fig. 1).

Table 1
Chemical compositions and feed values (mean ± SD) of the experimental feeds and calculated chemical compositions and feed values of the total mixed rations used in the feeding experiment of the finishing beef on dairy crossbred heifers fed two different total mixed rations and slaughtered at three different carcass weights.

Item	Feeds			Total mixed rations	
	Silage 1[1]	Silage 2[2]	Rolled barley	GSA[3]	GSB[4]
Number of feed samples	15	9	9		
DM, g/kg	348 ± 80.4	383 ± 124.2	894 ± 12.8	353	426
Organic matter, g/kg DM	925 ± 6.6	917 ± 4.4	ND		
CP, g/kg DM	144 ± 14.6	174 ± 26.0	135 ± 13.3	148	141
NDF, g/kg DM	533 ± 18.4	479 ± 52.5	ND		
Indigestible NDF, g/kg DM	80 ± 16.0	99 ± 29.2	ND		
Metabolisable energy, MJ/kg DM	10.6 ± 0.46	10.3 ± 0.50	13.2 ± 0.03	10.6	11.4
Metabolisable protein, g/kg DM	80 ± 3.9	87 ± 5.9	100 ± 2.0	81	86
Protein balance in the rumen, g/kg DM	25 ± 11.5	48 ± 18.5	−14 ± 11.2	27	8
Digestible organic matter in DM, g/kg DM	641 ± 15.5	645 ± 31.6	ND		
Silage DM intake index	104 ± 7.8	110 ± 5.0			
Fermentation quality of silages					
pH	4.07 ± 0.179	4.20 ± 0.148			
Volatile fatty acids, g/kg DM	13 ± 8.7	18 ± 10.7			
Lactic + formic acid, g/kg DM	42 ± 9.8	46 ± 18.5			
Water soluble carbohydrates, g/kg DM	78 ± 30.7	57 ± 37.0			
NH_4N in total N, g/kg	31 ± 6.0	15 ± 9.2			

Abbreviations: GSA = grass silage alone; GSB = grass silage supplemented with barley grain; ND = Not determined.
[1] Mixture of timothy and meadow fescue.
[2] Mixture of timothy and red clover.
[3] Silage 1 (785 g/kg DM), silage 2 (200 g/kg DM), mineral-vitamin mixture (15 g/kg DM).
[4] Silage 1 (560 g/kg DM), silage 2 (140 g/kg DM), rolled barley (285 g/kg DM), mineral-vitamin mixture (15 g/kg DM).

Table 2
Intake, growth performance and carcass traits of the finishing beef on dairy crossbred heifers fed two different total mixed rations and slaughtered at three different carcass weights.

Feeding (F)[1]	No concentrate			Medium concentrate				Orthogonal contrasts[3]				
Weight (W)[2]	Low	Medium	High	Low	Medium	High	SEM	F	W_{Lin}	W_{Quad}	F × W_{Lin}	F × W_{Quad}
Number of observations	13	14	14	14	14	14						
Duration of the experiment, d	341	418	446	285	341	383						
Initial age, d	227	222	228	226	230	221						
Initial BW, kg	259	256	265	257	255	252						
Final BW, kg	575	637	683	574	630	669						
Carcass weight, kg	294	327	343	299	335	352						
Slaughter age, d	568	640	674	511	571	604	6.1	<0.001	<0.001	0.001	0.251	0.601
Intake												
Silage DM, kg	3 047	3 849	4 114	1 895	2 349	2 657						
Barley DM, kg	0	0	0	772	956	1 082						
Mineral mixture DM, kg	46	59	63	41	50	57						
Total DM intake, kg	3 093	3 908	4 177	2 708	3 355	3 796	156.5	<0.001	<0.001	0.153	0.986	0.522
DM, kg/d	9.1	9.3	9.4	9.5	9.8	9.9	0.42	0.143	0.388	0.701	0.884	0.994
DM, g/kg metabolic BW	98	96	92	104	102	100	3.9	0.050	0.199	0.765	0.798	0.940
Metabolisable energy, MJ/d	96	99	99	109	112	113	4.6	<0.001	0.519	0.770	0.915	0.967
CP, kg/d	1.32	1.34	1.33	1.39	1.40	1.40	0.060	0.167	0.818	0.878	0.975	0.944
BW gain, g/d	926	912	936	1 111	1 101	1 090	25.3	<0.001	0.850	0.664	0.533	0.648
Carcass gain, g/d	482	476	471	597	607	589	13.2	<0.001	0.462	0.547	0.869	0.492
Feed conversion												
Kg DM/kg BW gain	9.8	10.3	10.1	8.6	9.0	9.1	0.40	<0.001	0.300	0.472	0.736	0.765
MJ ME/kg BW gain	104	108	106	98	102	103	4.3	0.149	0.405	0.536	0.744	0.805
Kg CP/kg BW gain	1.43	1.47	1.43	1.25	1.28	1.29	0.057	<0.001	0.700	0.625	0.782	0.722
Kg DM/kg carcass gain	18.7	19.6	19.9	16.0	16.2	16.8	0.71	<0.001	0.167	0.920	0.762	0.659
MJ ME/kg carcass gain	199	207	210	184	185	191	7.8	0.003	0.253	0.983	0.758	0.682
Kg CP/kg carcass gain	2.72	2.81	2.84	2.35	2.31	2.38	0.102	<0.001	0.484	0.890	0.723	0.620
Carcass characteristics												
Dressing proportion, g/kg	512	513	501	520	531	525	5.1	<0.001	0.569	0.087	0.116	0.848
Conformation, EUROP	5.6	5.1	5.7	5.9	6.2	6.4	0.35	0.018	0.333	0.449	0.494	0.319
Fat score, EUROP	7.1	7.9	11.6	7.5	10.5	12.1	0.52	0.004	<0.001	0.366	0.883	0.016

Abbreviations: ME = Metabolisable energy.
[1] The no concentrate diet included grass silage (GS) 985 g/kg DM and mineral-vitamin mixture 15 g/kg DM. The medium concentrate diet included GS 700 g/kg DM, rolled barley grain 285 g/kg DM and mineral-vitamin mixture 15 g/kg DM.
[2] The targeted carcass weights were for low 300 kg, medium 325 kg and high 350 kg.
[3] Orthogonal contrasts: (F) no concentrate vs. medium concentrate, (W_{Lin}) linear effect of weight, (W_{Quad}) quadratic effect of weight, (F × W_{Lin}) linear interaction between feeding and weight, and (F × W_{Quad}) quadratic interaction between feeding and weight.

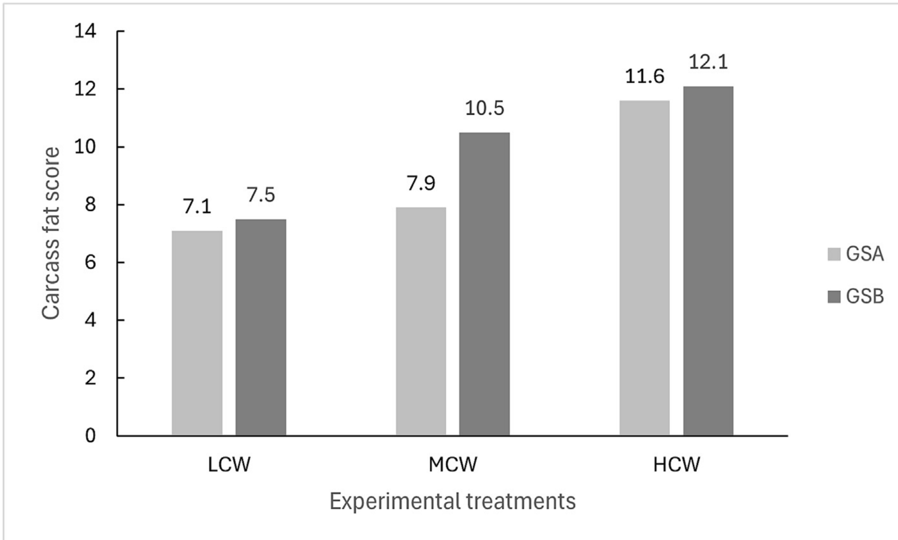

Fig. 1. Carcass fat score as EUROP classification (1 is lean, 15 is fat) in finishing beef on dairy crossbred heifers fed grass silage alone or grass silage supplemented with barley grain with carcass weights 300 kg, 325 kg or 350 kg. Interaction $P < 0.05$; diet × carcass weight; SEM = 0.52. Abbreviations: GSA = grass silage alone; GSB = grass silage supplemented with barley grain; LCW = low carcass weight; MCW = medium carcass weight; HCW = high carcass weight.

Environmental impacts

Life cycle assessment included three environmental impact categories (climate change impact, eutrophication potential and acidification potential), which were assessed for both dietary treatments, and for three different carcass weights. In both dietary treatments, increased carcass weight had a clear impact on all environmental impact categories. Increasing carcass weight increased the climate change impact per kg FU from 24.5 to 26.1 kg CO_2 eq for GSA and from 21.9 to 23.1 kg CO_2 eq for GSB (Fig. 2). When comparing HCW to LCW within GSA and GSB, the increase of climate change impact was 6% in both diets. The inclusion of concentrate feed in GSB resulted in a 10–11% lower climate change impact per FU compared to feeding with only silage (GSA) at equivalent carcass weights.

Regarding eutrophication potential, increased carcass weight increased it from 23.6 to 25.0 kg PO_4 eq for GSA and from 20.5 to 21.9 kg PO_4 eq for GSB. When comparing HCW to LCW within GSA and GSB, the increase of eutrophication potential was 6 and 7% in GSA and GSB, respectively. The concentrate supplementation

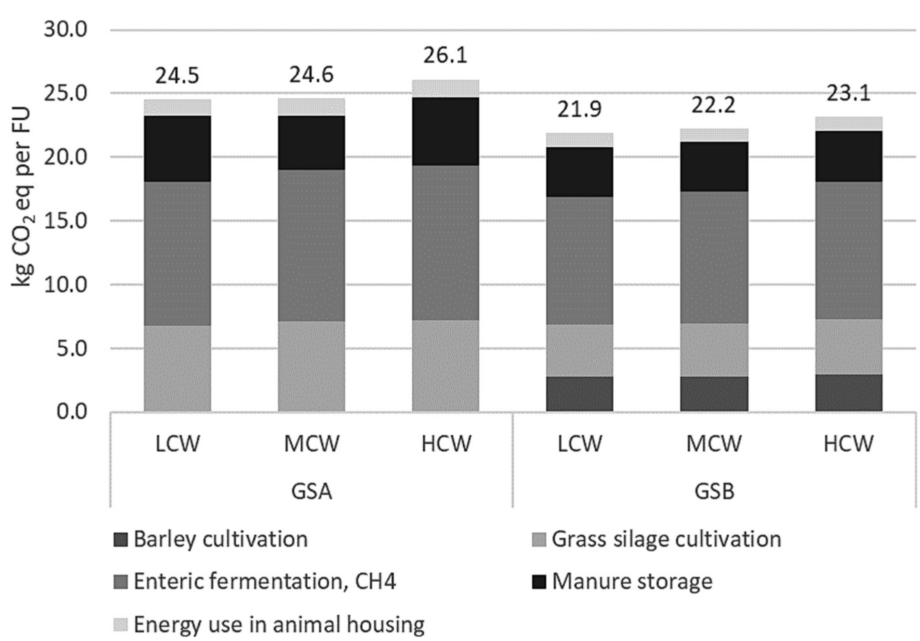

Fig. 2. Climate change impact as kg CO_2 eq per kg produced carcass weight (functional unit) with two different feeding treatments (grass silage alone and grass silage supplemented with barley grain) and three different carcass weights (300 kg, 325 kg and 350 kg) of the finishing beef on dairy crossbred heifers. Abbreviations: FU = functional unit; LCW = low carcass weight; MCW = medium carcass weight; HCW = high carcass weight; GSA = grass silage alone; GSB = grass silage supplemented with barley grain.

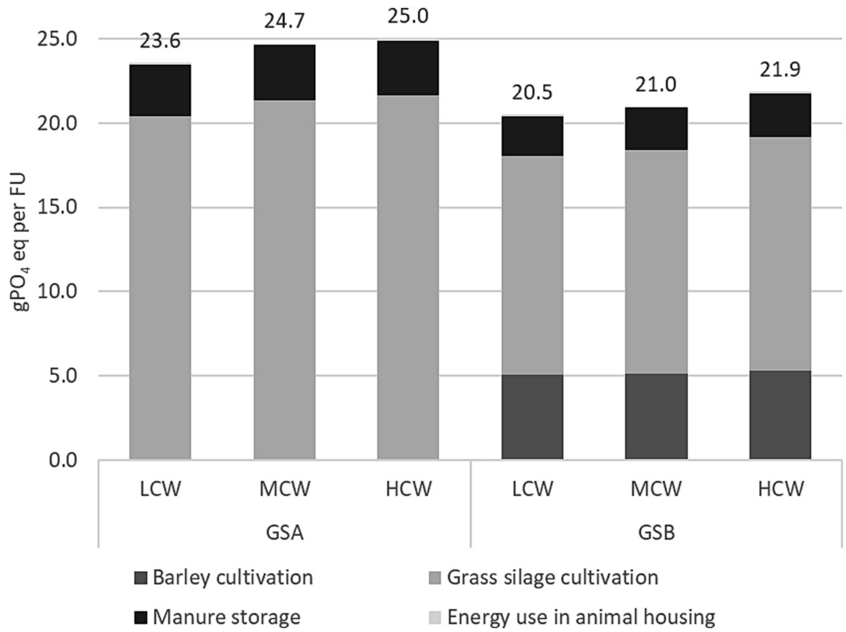

Fig. 3. Eutrophication potential as g PO_4 eq per kg produced carcass weight (functional unit) with two different feeding treatments (grass silage alone and grass silage supplemented with barley grain) and three different carcass weights (300 kg, 325 kg and 350 kg) of the finishing beef on dairy crossbred heifers. Abbreviations: FU = functional unit; LCW = low carcass weight; MCW = medium carcass weight; HCW = high carcass weight; GSA = grass silage alone; GSB = grass silage supplemented with barley grain.

reduced eutrophication potential per FU by 13–15% compared to no concentrate when comparing at equivalent carcass weights (Fig. 3). The acidification potential increased from 57.9 to 62.3 g AE eq at GSA and from 45.5 to 49.8 g AE eq at GSB with the increase in carcass weight. When comparing HCW to LCW within GSA and GSB, the increase of acidification potential was 8% and 9% in GSA and GSB, respectively. The impact was 20–23% lower with concentrate supplementation compared to producing equivalent carcass weights with GSA (Fig. 4). When GSA was compared to GSB at the same carcass weight, all environmental impact categories were higher at all three carcass weights.

Discussion

Effects of dietary treatments and carcass weight on animal performance

In the present study, dietary treatments had no effects on daily DM intake, in accordance with earlier studies in which supplementing GS-based rations with concentrate had no effect on daily DM intake of bulls (Huuskonen et al., 2007; Manni et al., 2016; Huuskonen et al., 2023). However, the result is contradictory with many previous results in which supplementing GS with concen-

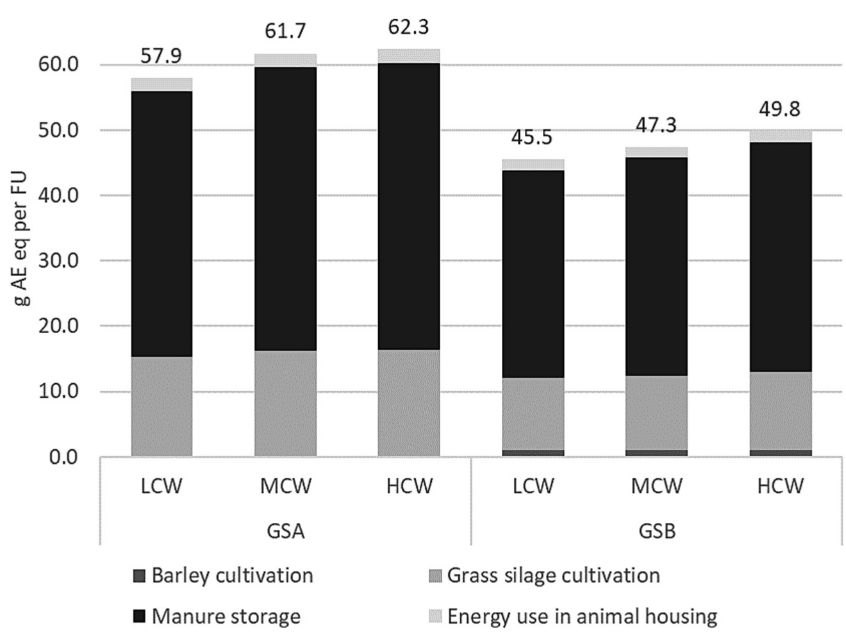

Fig. 4. Acidification potential as g acid equivalents per kg produced carcass weight (functional unit) with two different feeding treatments (grass silage alone and grass silage supplemented with barley grain) and three different carcass weights (300 kg, 325 kg and 350 kg) of the finishing beef on dairy crossbred heifers. Abbreviations: AE eq = acid equivalents; FU = functional unit; LCW = low carcass weight; MCW = medium carcass weight; HCW = high carcass weight; GSA = grass silage alone; GSB = grass silage supplemented with barley grain.

trate typically increases daily DM intake of growing cattle to some extent (Keane et al., 2006; Randby et al., 2010; Hessle et al., 2024). Also, in a previous meta-analysis by Huuskonen et al. (2013), increasing the level of concentrate supplementation in the diet increased daily DM intake of growing cattle. Forage intake potential is one substantial factor which affects DM intake so that greater response to concentrate feeding is expected when forage with low intake potential is used (Huuskonen et al., 2013). In the present study, both silages had good intake potential, as indicated by a relative intake potential of silage DM of over 100. Substitution rate is used to express the decrease in silage DM intake per kg increase of concentrate DM intake, and both silage intake potential and the level of concentrate are major factors affecting it (McNamee et al., 2001). In the present study, the substitution rate was 0.84. Relatively high substitution rate with moderate proportion of concentrate also indicated a good intake potential of the GS used, which may have affected the lack of differences observed between the dietary treatments. Carcass weight did not affect daily DM intake either, but increased carcass weight increased total DM intake because of a longer rearing time.

In the present study, the heifers achieved a moderate growth rate, on average 925 g/d, when GS was given as a sole feed, and it is in line with the result of Hessle et al. (2024). This supports the target to produce beef using feeds that are not directly suitable for human consumption. However, excluding barley grain from the diet impaired BW gain and carcass gain compared to GSB, as was hypothesised. The result is in line with several earlier studies (Keane et al., 2006; Randby et al., 2010; Hessle et al., 2024) in which increasing concentrate level has improved growth performance with silage-based diets. The most likely explanation for the impaired growth performance is the decrease in ME intake. Based on the meta-analysis, Huuskonen and Huhtanen (2015) established that ME intake was clearly the most important nutritional variable affecting BW gain of growing and finishing cattle. The results of the present study support this. In addition, the results of the meta-analysis by Huuskonen and Huhtanen (2015) showed only marginal effects of protein supply on growth. In the present study, CP intake did not differ between the treatments, highlighting the importance of ME intake for growth.

In the present study, the BW gain response to concentrate supplementation was 63 g BW gain/kg additional concentrate DM when comparing GSA and GSB treatments. This is approximately at the same level with previous GS-based feeding study by Huuskonen et al. (2023) with dairy bulls (60 g/d). As also hypothesised, feed conversion impaired when barley grain was excluded from the diet. Feed conversion generally declines as a result of decreased growth rate and increased DM intake.

Contrary to the hypothesis, carcass weight did not affect the growth performances nor feed efficiency. Typically, growth becomes slower, and feed efficiency impairs as animals grow older, as has been found in many previous studies when animals were fed evenly during the growing and finishing period (Huuskonen et al., 2007; Keane 2010; Manni 2018). One explanation for the result of the present study may be that despite even the highest carcass weight, dairy × Blonde d'Aquitaine crossbred heifers still had growth potential to some extent, although the increase in carcass fatness indicated a decline in their growth capacity.

When barley grain supplementation was used in the diet, more beef was produced during the same growing and finishing period compared to GSA. This was mostly due to higher BW gain of GSB heifers, but it was also affected by higher dressing proportion of GSB heifers. The effect of feeding on the dressing proportion is largely due to the fact that forages generally promote a greater gut fill compared to concentrates (Owens et al., 1995), which decreases dressing proportion.

According to our hypothesis, excluding barley grain from the diet decreased the carcass conformation. The result was similar to that of earlier studies in which increasing concentrate proportion increased carcass conformation (Keane et al., 2006; Nogalski et al., 2014; Huuskonen et al., 2023) but contrary to Cooke et al. (2004), Huuskonen et al. (2007), Randby et al. (2010) and Hessle et al. (2024) where carcass conformation was not affected by different dietary concentrate levels. The hypothesis that carcass conformation improves with increased carcass weight was not validated, similarly with the result of Cooke et al. (2004), Nogalski et al. (2014) and Hessle et al. (2024).

As hypothesised, carcasses of the GSB heifers were fatter compared to the GSA heifers. Additionally, carcass weights had a more pronounced effect on carcass fat score in GSB compared to GSA (diet × carcass weight interaction). In other words, carcass fat cover was more affected by carcass weight in GSB heifers compared to GSA. One obvious explanation for this is that typically both increasing concentrate and energy intake and increased carcass weight increases the carcass fat content, which has been reported in many previous studies (Nogalski et al., 2014; Huuskonen and Huhtanen 2015; Huuskonen et al., 2023).

Effects of feeding treatments and carcass weight on environmental impacts

Carcass weight and the diet had a clear effect on all environmental impact categories. For all three environmental impact categories, the lowest impacts per FU were achieved with GSB at LCW. On the other hand, the highest environmental impacts occurred with GSA at HCW. Results thus confirmed the hypotheses as environmental impacts were increased by excluding concentrate from the diet and by increasing carcass weight. It is noteworthy, that even the highest carcass weight of GSB had lower environmental impacts per FU for all three impact categories in comparison to GSA. This emphasises the fact that increasing carcass weight might not necessarily increase the environmental impact under all conditions. Feeding heifers a diet with a greater proportion of grain increased carcass gain and as a consequence, reduced the proportion of dietary ME required for maintenance. This dilution of maintenance resulted in less enteric methane produced per FU.

Environmental impacts of produced carcass weight in the present experiment with heifers were clearly higher than in previous experiments with bulls (Huuskonen et al., 2023; Huuskonen et al., 2025). Huuskonen et al. (2023) reported climate change impact of 19–21 kg CO_2 eq/FU, eutrophic emissions of 16–17 g PO_4 eq/FU and acidifying emissions of 38–39 g AE eq/FU when beef and dairy breed bulls were fed grass silage and barley grain-based rations with a 400 g/kg DM concentrate proportion. Huuskonen et al. (2025) fed beef breed bulls with three different total mixed rations, where grass silage and red clover silage were used as a sole forages and as a mixture and concentrate proportion in all diets was 400 g/kg DM. In the calculation of environmental impacts, four different datasets for red clover cultivation were used. Based on the results climate change impact varied between 15.1 and 18.2 kg CO_2 eq/FU, eutrophication impact between 8.2 and 18.7 g PO_4 eq/FU and acidification impact between 35 and 38 g AE eq/FU. One reason for the differences between bulls and heifers was lower growth rate and longer growing period of the heifers compared to bulls. In a similar study, Herron et al. (2021) compared environmental impacts of beef produced with different breeds, slaughter ages and diets with and without concentrate supplementation. Their life cycle assessment results were consistent with the current results as the shortest growing period resulted in the lowest climate change, eutrophication and acidification impacts. Also, the steers grown with concentrate supplementation performed better regarding all environmental impact catergories compared to steers grown without concentrate supplementation (Herron et al., 2021), which is in line with the results presented here. Similarly, Santos-Silva et al. (2023) compared climate change impact of BW gain of finishing bulls grown with concentrate-based and high forage diet. They concluded that a high forage diet doubled the enteric methane emission in comparison to concentrate-based diet, which is in line with the present results. Yet, they did not find similar difference in overall climate change impact of BW gain, as according to their results, the emission reductions from feed crop production nearly offset the emission increase from enteric fermentation. This was partly due to the larger differences in feed crop emission factors, as forage emission factor was approximately 20% of that of concentrate. In current calculations, the grass silage emissions were nearly 60% of the concentrate emission factor, mainly due to comparably lower concentrate emission factor but also the grass silage emission factor was slightly higher. For the Finnish production, the potential of improving environmental efficiency of feed crop production should thus be studied further as the environmental performance of crop production seemed low in comparison.

In the present experiment, methane from enteric fermentation accounted for 46–48% of the climate change impact per kilogram of produced carcass weight. Enteric methane was also responsible for the majority of the climate change impact increase when treatments were compared, contributing by 60–80% of the increase per FU. Increasing carcass weight particularly affected the length of the growing period, which in turn increased feed consumption and enteric methane emissions. While the feed conversion was not increased at the same rate, this led to higher emissions per FU with higher carcass weight.

Increasing carcass weight also led to higher eutrophication potential, especially from cultivation of feed crops and manure storage. The contribution of feed crops to eutrophication potential was 86–87% in GSA and 88% GSB. Emissions from manure storage accounted for 12–13% of total eutrophication potential. Increasing the carcass weight led particularly to an increase in emissions from feed crop cultivation, contributing to 78–83% of the increase in total eutrophication potential.

Regarding acidification potential, manure storage was the largest emission source, accounting for 70–71% of the emissions in both feeding treatments. The share of feed crop cultivation was 26% for GSA and 26–28% for GSB. Increasing the carcass weight from the lowest to the highest resulted especially in an increase in emissions from manure storage, which accounted for 80% of the total increase in acidifying emissions.

The assessments indicated that with concentrate supplementation, all environmental impact categories resulted in lower emissions relative to produced carcass weight. Increased carcass weight was seen to increase especially the emissions from feed digestion, feed crop production and manure handling per kg produced carcass weight. These emissions were subject to longer growing period and increased feed use, to achieve the target carcass weight. Several previous studies have concluded with similar results. Kokemohr et al. (2022) noted that concentrate supplementation is needed to sustain high growth rate, which can lead to increased emissions at farm level, yet when the rate of weight gain exceeds emission increase, the emission per functional unit decreases. Also, Doyle et al. (2023) studied environmental sustainability of beef production systems with and without concentrate. They concluded that lowest emissions per kg carcass weight were achieved with grain supplemented production due to earlier slaughter age (Doyle et al., 2023). Yet, they investigated also economic sustainability and several functional units and concluded that forage-based system had their advantages in profitability and in utilising only feeds not suitable for human consumption.

Current study limited the assessment of environmental sustainability to three different environmental impact categories, which have been identified as relevant for cattle production (de Vries et al., 2015; The European Dairy Association, 2025). Yet, the assessment omitted the greenhouse gas emissions from land use change and did not include other environmental impact categories such as biodiversity or water scarcity impact, which also might have variation in cattle production and narrow the differences between GSA and GSB.

Different sustainability dimensions of cattle production have been investigated in parallel in few recent Life Cycle Sustainability Assessments (Kokemohr et al., 2022; Zira et al., 2023). According to these studies, economic and environmental impacts seem to be aligned, yet there can be trade-offs to social impacts. Thus, in further studies, it would be important to include also the social risk assessment into cattle life cycle assessment to avoid trade-offs.

Conclusions

This study showed that feeding growing and finishing heifers with good quality grass silage, a reasonable growth rate can be achieved even with grass silage alone. However, concentrate supplementation improved performance of heifers and decreased environmental impacts beef produced by them. Even the highest carcass weight in GSB had lower environmental impacts than any of the carcass weights in GSA. Thus, when the target is to increase the production of environmentally more sustainable beef by increasing carcass weight, including concentrate in the diet is justified. Several factors contributed this. When barley grain was excluded from the diet, energy intake of the heifers decreased, leading to a decrease in growth rate and an increase in rearing time and total DM intake. In addition, feed conversion decreased as a result of decrease in growth rate and an increase in DM intake. Also, all carcass characteristics in terms of dressing proportion, conformation and fatness decreased. Although reasonable growth rate was achieved in GSA, significantly improved growth rate and decreased rearing time with a moderate level of concentrate improved environmental efficiency. Contrary to the feeding, effects of carcass weight on animal performances were rather small. The most significant effects were an increase in DM intake and carcass fatness with increasing carcass weight. Increased carcass weight and consequently prolonged growing period increased environmental impacts (climate change impact, eutrophication potential and acidification potential) per kg produced carcass weight. This was found especially as increased methane emission from enteric fermentation and also from the increased need for feed production. Since this study was conducted under specific conditions, there is a clear need for further research, especially on the effects of increased carcass weight on production results and environmental impacts.

Ethics approval

During the experiment, the animals were managed according to the Finnish legislation regarding the use of animals in scientific experimentation. This study design was reviewed and approved by Animal Welfare body (Government decree 564/2013 22§) of Natural Resources Institute Finland. Project authorisation was not needed as the experiments did not cause the animals a level of pain, suffering, distress or lasting harm equivalent to, or higher than, that caused by the introduction of a needle (2010/63/EU).

Data and model availability statement

None of the data were deposited in an official repository. The dataset presented in this study is available on request from the corresponding authors.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Basiel, B.L., Felix, T.L., 2022. Board invited review: crossbreeding beef × dairy cattle for the modern beef production system. Translational Animal Science 6, 1–21. https://doi.org/10.1093/tas/txac025. PMID: 35399737; PMCID: PMC8989152.

Capper, J.L., Bauman, D.E., 2013. The role of productivity in improving environmental sustainability of ruminant production systems. Annual Review of Animal Biosciences 1, 469–489. https://doi.org/10.1146/annurev-animal-031412-103727.

Conroy, S.B., Drennan, M.J., Kenny, D.A., McGee, M., 2010. The relationship of various muscular and skeletal scores and ultrasound measurements in the live animal, and carcass classification scores with carcass composition and value of bulls. Livestock Science 127, 11–21. https://doi.org/10.1016/j.livsci.2009.06.007.

Cooke, D.W.I., Monahan, F.J., Brophy, P.O., Boland, M.P., 2004. Comparison of concentrates or concentrates plus forages in a total mixed ration or discrete ingredient format: effects on beef production parameters and on beef composition, colour, texture and fatty acid profile. Irish Journal of Agricultural and Food Research 43, 201–216.

de Vries, M., van Middelaar, C.E., de Boer, I.J.M., 2015. Comparing environmental impacts of beef production systems: a review of life cycle assessments. Livestock Science 178, 279–288. https://doi.org/10.1016/j.livsci.2015.06.020.

Doyle, P., O'Riordan, E.G., McGee, M., Crosson, P., Kelly, A.K., Moloney, A., 2023. Temperate pasture-or concentrate-beef production systems: steer performance, meat nutritional value, land-use, food–feed competition, economic and environmental sustainability. The Journal of Agricultural Science 161, 704–719. https://doi.org/10.1017/S0021859623000540.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food Security: the challenge of feeding 9 billion people. Science 327, 812–818. https://doi.org/10.1126/science.1185383.

Greenwood, P.L., 2021. Review: an overview of beef production from pasture and feedlot globally, as demand for beef and the need for sustainable practices increase. Animal 15, 100295. https://doi.org/10.1016/j.animal.2021.100295.

Heijungs, R., Guinee, J.B., Huppens, G., Lnakreijer, R.M., Udo de Haes, H.A., Sleeswijk, A.W., 1992. Environmental life cycle assessment of products. MultiCopy, Leiden, the Netherlands. https://hdl.handle.net/1887/8062.

Herron, J., Curran, T.P., Moloney, A.P., McGee, M., O'Riordan, E.G., O'Brien, D., 2021. Life cycle assessment of pasture-based suckler steer weanling-to-beef production systems: effect of breed and slaughter age. Animal 15, 100247. https://doi.org/10.1016/j.animal.2021.100247.

Hessle, A., Dahlström, F., Lans, J., Karlsson, A.H., Carlsson, A., 2024. Beef production systems with dairy × beef heifers based on forage and semi-natural grassland. Acta Agriculturae Scandinavica, Section A – Animal Science 73, 105–116. https://doi.org/10.1080/09064702.2024.2305366.

Hietala, S., Heusala, H., Katajajuuri, J.M., Järvenranta, K., Virkajärvi, P., Huuskonen, A., Nousiainen, J., 2021. Environmental life cycle assessment of Finnish beef – cradle-to-farm gate analysis of dairy and beef breed beef production. Agricultural Systems 194, 103250. https://doi.org/10.1016/j.agsy.2021.103250.

Huhtanen, P., Huuskonen, A., 2020. Modelling effects of carcass weight, dietary concentrate and protein levels on the CH_4 emission, N and P excretion of dairy bulls. Livestock Science 232, 103896. https://doi.org/10.1016/j.livsci.2019.103896.

Huhtanen, P., Rinne, M., Nousiainen, J., 2007. Evaluation of the factors affecting silage intake of dairy cows; a revision of the relative silage dry matter intake index. Animal 1, 758–770. https://doi.org/10.1017/S175173110773673X.

Huuskonen, A., Huhtanen, P., 2015. The development of a model to predict BW gain of growing cattle fed grass silage-based diets. Animal 9, 1329–1340. https://doi.org/10.1017/S1751731115000610.

Huuskonen, A., Khalili, H., Joki-Tokola, E., 2007. Effects of three different concentrate proportions and rapeseed meal supplement to grass silage on animal performance of dairy-breed bulls with TMR feeding. Livestock Science 110, 154–165. https://doi.org/10.1016/j.livsci.2006.10.015.

Huuskonen, A., Huhtanen, P., Joki-Tokola, E., 2013. The development of a model to predict feed intake by growing cattle. Livestock Science 158, 74–83. https://doi.org/10.1016/j.livsci.2013.10.005.

Huuskonen, A., Pesonen, M., Kämäräinen, H., Kauppinen, R., 2014. Production and carcass traits of purebred Nordic Red and Nordic Red × beef breed crossbred bulls. Journal of Agricultural Science 152, 504–517. https://doi.org/10.1017/S0021859613000749.

Huuskonen, A., Pesonen, M., Honkavaara, M., 2017. Effects of replacing timothy silage by alsike clover silage on performance, carcass traits and meat quality of finishing Aberdeen Angus and Nordic Red bulls. Grass and Forage Science 72, 220–233. https://doi.org/10.1111/gfs.12247.

Huuskonen, A., Hietala, S., Hyvönen, J., Leinonen, I., Manni, K., 2023. Environmental impacts and animal performance of finishing bulls fed different silage-based total mixed rations. Livestock Science 268, 105166. https://doi.org/10.1016/j.livsci.2023.105166.

Huuskonen, A., Hietala, S., Pesonen, M., Manni, K., 2025. Effects of replacing timothy silage by red clover silage on environmental impacts, growth performance and carcass traits of finishing beef bulls. Livestock Science 299, 105755. https://doi.org/10.1016/j.livsci.2025.105755.

Intergovernmental Panel on Climate Change (IPCC), 2006. IPCC Guidelines for National Greenhouse Gas Inventories, prepared by the National Greenhouse Gas Inventories Programme. In: Volume 4: Agriculture, forestry and other land use (ed. Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K.). IGES, Kanagawa, Japan, Ap3.8. http://www.ipccnggip.iges.or.jp/public/2006gl/index.htm.

Intergovernmental Panel on Climate Change (IPCC), 2021. Climate Change 2021: The Physical Science Basis. In: Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (ed. V. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B.). Cambridge University Press, Cambridge, UK, pp. 1–2391. https://doi.org/10.1017/9781009157896.

Keane, M.G., 2010. A comparison of finishing strategies to fixed slaughter weights for Holstein Friesian and Belgian Blue × Holstein Friesian steers. Irish Journal of Agricultural and Food Research 49, 41–54.

Keane, M.G., Drennan, M.J., Moloney, A.P., 2006. Comparison of supplementary concentrate levels with grass silage, separate or total mixed ration feeding, and duration of finishing in beef steers. Livestock Science 103, 169–180. https://doi.org/10.1016/j.livsci.2006.02.008.

Kokemohr, L., Escobar, N., Mertens, A., Mosnier, C., Pirlo, G., Veysset, P., Kuhn, T., 2022. Life cycle sustainability assessment of European beef production systems

based on a farm-level optimization model. Journal of Cleaner Production 379, 134552. https://doi.org/10.1016/j.jclepro.2022.134552.
Lawrence, T.L.J., Fowler, V.R., 2002. Growth of farm animals. CABI Publishing, New York, NY, USA.
Lehikoinen, E., Parviainen, T., Helenius, J., Jalava, M., Salonen, A.O., Kummu, M., 2019. Cattle production for exports in water-abundant areas: the case of Finland. Sustainability 11, 1075. https://doi.org/10.3390/su11041075.
Leinonen, I., 2019. Achieving environmentally sustainable livestock production. Sustainability 11, 246. https://doi.org/10.3390/su11010246.
Luke, 2025a. Natural Resources Institute Finland (Luke). Official Statistics of Finland (OSF): Meat production 2023. Helsinki: Natural Resources Institute Finland. Retrieved on 30 January 2025 from: https://www.luke.fi/en/statistics/meat-production/meat-production-2023.
Luke, 2025b. Natural Resources Institute Finland (Luke). Official Statistics of Finland (OSF): balance sheet for food commodities. Retrieved on 30 January 2025 from: https://www.luke.fi/en/statistics/balance-sheet-for-food-commodities/balance-sheet-for-food-commodities-2023-preliminary-and-2022-final-figures.
Luke, 2025c. Natural Resources Institute Finland (Luke). Feed tables and nutrient requirements. Retrieved 13 February 2025 from: http://www.luke.fi/feedtables.
MAFF, 1984. Energy allowances and feeding systems for ruminants. ADAS Reference Book 433. HMSO, London, UK.
Manni, K., Rinne, M., Huuskonen, A., 2016. Effects of barley intake and allocation regime on performance of growing dairy bulls offered highly digestible grass silage. Livestock Science 191, 72–79. https://doi.org/10.1016/j.livsci.2016.07.004.
Manni, K., 2018. Restricted energy intake strategies for growing and finishing dairy bulls offered grass silage-based diets: doctoral dissertation. *Natural Resources and Bioeconomy Studies* 41, 61. Retrieved on 24 February 2025 from: http://urn.fi/URN:ISBN:978-952-326-616-2.
McGregor, E.M., Campbell, C.P., Miller, S.P., Purslow, P.P., Mandell, I.B., 2012. Effect of nutritional regimen including limit feeding and breed on growth performance, carcass characteristics and meat quality in beef cattle. Canadian Journal of Animal Science 92, 327–341. https://doi.org/10.4141/cjas2011-126.
McNamee, B.F., Kilpatrick, D.J., Steen, R.W.J., Gordon, F.J., 2001. The prediction of grass silage intake by beef cattle receiving barley-based supplements. Livestock Science 68, 25–30. https://doi.org/10.1016/S0301-6226(00)00213-X.
Moisio, T., Heikonen, M., 1989. A titration method for silage assessment. Animal Feed Science and Technology 22, 341–353. https://doi.org/10.1016/0377-8401(89)90078-3.
Nguyen, T., Hermansen, J., Mogensen, L., 2010. Environmental consequences of different beef production systems in the EU. Journal of Cleaner Production 18, 756–766. https://doi.org/10.1016/j.jclepro.2009.12.023.
Nogalski, Z., Wielgosz-Groth, Z., Purwin, C., Nogalska, A., Sobczuk-Szul, M., Winarski, R., Pogorzelska, P., 2014. The effect of slaughter weight and fattening intensity on changes in carcass fatness in young Holstein-Friesian bulls. Italian Journal of Animal Science 13, 66–72. https://doi.org/10.4081/ijas.2014.2824.
Organisation for Economic Co-operation and Development (OECD) and the Food and Agriculture Organization (FAO) of the United Nations, 2024. OECD-FAO Agricultural Outlook 2024-2033. OECD/FAO, Paris, France, Rome, Italy. https://doi.org/10.1787/4c5d2cfb-en.
Owens, F.N., Gill, D.R., Secrist, D.S., Coleman, S.W., 1995. Review of some aspects of growth and development of feedlot cattle. Journal of Animal Science 73, 3152–3172. https://doi.org/10.2527/1995.73103152x.
Ramin, M., Huhtanen, P., 2013. Development of equations for predicting methane emissions from ruminants. Journal of Dairy Science 96, 2476–2493. https://doi.org/10.3168/jds.2012-6095.
Randby, Å.T., Nørgaard, P., Weisbjerg, M.R., 2010. Effect of increasing plant maturity in timothy-dominated grass silage on the performance of growing/finishing Norwegian Red bulls. Grass and Forage Science 65, 273–286. https://doi.org/10.1111/j.1365-2494.2010.00745.x.
Regina, K., Kaseva, J., Esala, M., 2013. Emissions of nitrous oxide from boreal agricultural mineral soils—statistical models based on measurements. Agriculture, Ecosystems & Environment 164, 131–136.
Santos-Silva, J., Alves, S.P., Francisco, A., Portugal, A.P., Dentinho, M.T., Almeida, J., da Silva, J.L.R., Fialho, L., Cachucho, L., Jeronimó, E., Barradas, A., Rodrigues, A., Rodrigues, N., Teixeira, R.F.M., Domingos, T., Bessa, R.J., 2023. Forage based diet as an alternative to a high concentrate diet for finishing young bulls - Effects on growth performance, greenhouse gas emissions and meat quality. Meat Science 198, 109098. https://doi.org/10.1016/j.meatsci.2023.
Seppälä, J., Knuuttila, S., Silvo, K., 2004. Eutrophication of aquatic ecosystems. A new method for calculation the potential contributions of nitrogen and phosphorus. The International Journal of Life Cycle Assessment 9, 90–100. https://doi.org/10.1007/BF02978568.
Seppälä, J., Posch, M., Johansson, M., Hettelingh, J.P., 2006. Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator. The International Journal of Life Cycle Assessment 11, 403–416. https://doi.org/10.1065/lca2005.06.215.
Statistics Finland, 2015. Greenhouse gas emissions in Finland 1990-2013. National Inventory Report under the UNFCCC and the Kyoto Protocol. National Inventory Report (NIR) 2015 submission. Retrieved on 30 October 2015 from Statistics Finland, Helsinki 2015. Access method: https://unfccc.int/files/national_reports/annex_i_ghg_inventories/national_inventories_submissions/application/zip/fin-2015-nir-30oct15.zip.
The European Dairy Association, 2025. Product environmental footprint category rules for dairy products. Blonk, a Mérieux NutriSciences Company, Gouda, the Netherlands. https://eda.euromilk.org/wp-content/uploads/2025/02/PEFCR-DairyProducts_update_final.pdf.
Vestergaard, M., Jørgensen, K.F., Çakmakçı, C., Kargo, M., Therkildsen, M., Munk, A., Kristensen, T., 2019. Performance and carcass quality of crossbred beef x Holstein bull and heifer calves in comparison with purebred Holstein bull calves slaughtered at 17 months of age in an organic production system. Livestock Science 223, 184–192. https://doi.org/10.1016/j.livsci.2019.03.018.
Wilkinson, J.M., Lee, M.R.F., 2018. Review: use of human-edible animal feeds by ruminant livestock. Animal 12, 1735–1743. https://doi.org/10.1017/S175173111700218X.
Zira, S., Röös, E., Rydhmer, L., Hoffmann, R., 2023. Sustainability assessment of economic, environmental and social impacts, feed-food competition and economic robustness of dairy and beef farming systems in South Western Europe. Sustainable Production and Consumption 36, 439–448. https://doi.org/10.1016/j.spc.2023.01.022.