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Effects of replacing timothy silage by red clover silage on environmental impacts, growth performance and carcass traits of finishing beef bulls

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HIGHLIGHTS

- Red clover and timothy silage-based diets in finishing bulls were studied.
- Replacing timothy silage by red clover silage led to lower climate change impacts.
- Replacing timothy silage by red clover silage reduced eutrophication emissions.
- Carcass fatness of the bulls decreased with increasing diet red clover proportion.

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ABSTRACT

The objective of the study was to evaluate the effects of replacing timothy grass silage (GS) by red clover silage (RS) on environmental impacts, growth performance and carcass traits of finishing beef bulls. Total mixed rations (TMR) based on GS, RS and mixture of GS and RS (1:1 on dry matter (DM) basis; GRS) were fed *ad libitum* to sixty bulls. The proportion (g/kg DM) of the silages in the TMRs were as follows: (1) GS (600); (2) RS (600); (3) GS (300) and RS (300). Concentrate proportion was 400 g/kg DM with all treatments. Environmental impacts of the treatments were estimated using life cycle assessment approach with the following key impact categories: climate change, eutrophication, and acidification potential. As the red clover-grass modelling was acknowledged to have most uncertainty, it was completed with different scenarios of clover cultivation. Replacing GS by RS did not affect DM intake, gain, carcass weight or carcass conformation of the bulls. Carcass fat score of the bulls decreased with increasing RS proportion. As an average of the calculated scenarios the climate change impact was 17.8, 15.9, and 15.8 kg CO_2 equivalents/kg of produced carcass, eutrophic emissions 18.6, 15.0, and 9.9 g phosphate equivalents/kg of produced carcass and acidifying emissions 38, 35, and 35 g acid equivalents/kg of produced carcass for GS, GRS, and RS, respectively. It can be concluded that replacing GS partially or completely with RS reduced environmental impacts (climate change impact, eutrophic emissions, acidifying emissions) per kg of produced carcass.

1. Introduction

Forage based beef production is an important component of sustainable agriculture because of the ability of cattle to transform feeds not suitable for direct human consumption into high-quality food (Godfray et al., 2010; Kuhmonen et al., 2024). In parts of Northern Europe, the limitations of climate restrict the area suitable for cereal cropping, and grassland is particularly important in meeting the feed requirements of cattle. Although different grasses such as timothy (*Phleum pratense*), meadow fescue (*Festuca pratensis*) and tall fescue (*Festuca arundinacea*) are predominantly used in grassland farming in the Nordic countries, forage legumes, particularly clovers, may play an increasingly significant role in the future. In the Nordic countries, red clover (*Trifolium pratense*) is the most used forage legume for cattle feeding because it is winter-hardy and offers opportunities to utilize the nitrogen-fixing ability even in the harsh environmental conditions of high latitudes

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(Carlsson and Huss-Danell, 2003; Rinne et al., 2023). By utilizing the biological nitrogen fixation of legumes, it is possible to reduce the use of chemically produced nitrogen fertilizers and improve the nitrogen self-sufficiency of farms.

When red clover is included in grass silage-based rations and fed to lactating dairy cows it typically has positive effects, such as increasing feed intake and milk production (Dewhurst et al., 2003; Huhtanen et al., 2007; Vanhatalo and Jaakkola, 2016). It is also observed that higher silage dry matter (DM) intake (DMI) was found for dairy cows consuming mixed grass silage plus legume diets compared to cows that received only one forage (Bertilsson and Murphy, 2003; Dewhurst et al., 2003; Kuoppala et al. 2009). Compared to research related to milk production, there exist only a few reports in growing and finishing cattle comparing red clover silages or mixed grass/red clover silages to pure grass silages in the diet. However, in old British experiments (Day et al., 1978; Thomas et al., 1981; Steen and McIlmoyle, 1982) pure red clover silage or mixtures of grass and red clover silages resulted in higher intakes and gain of growing cattle compared with pure grass silage. More recently, Pesonen et al. (2014) reported no effects in feed intake or growth of growing bulls fed either pure grass silage or a mixture of grass and red clover silage. Conversely, Berthiaume et al. (2015) observed that a mixture of grass and red clover silages resulted in higher gain and superior feed efficiency of steers compared with pure grass silage.

Currently, consumers and businesses are increasingly aware of the environmental impacts caused by cattle production. In consequence, the demand for food which is produced with low environmental footprint is increasing. The environmental impacts of a product are commonly assessed with Life Cycle Assessment (LCA) approach, which provides detailed environmental information throughout the production chain of the specific product. These results can be communicated as environmental footprints of a product. As the demand for more environmentally sustainable products is increasing, this increases also the pressure for meat production across the food chain, to identify their environmental impact hot spots and improve their sustainability. In beef production feed crop production is one of the major contributors to environmental footprint of beef (Mogensen et al., 2014; Hietala et al., 2021; Huuskonen et al., 2023) which should be considered when comparing different nutritional mitigation strategies. In Finland beef production system differs from many other countries regarding several important aspects, e.g. slaughter age, slaughter weight and feed composition. One key difference to most of the beef production countries is that soybean meal is not used at all, and the use of maize silage is very rare in Finnish cattle production, whereas grass silage and cereal based feeding has a key role in cattle feeding (Hietala et al. 2021). Hietala et al. (2021) defined typical Finnish beef production systems and estimated the average environmental footprints of Finnish beef including greenhouse gas (GHG) emissions as well as eutrophication and acidification potential. However, when evaluating the environmental footprints of different feed production and feeding strategies, in addition to statistical average data, more detailed information is needed, for example feed intake, growth and feed conversion.

The current geopolitical situation has led to an increase in N fertilizer prices. Because N fertilization usually results in significant yield responses in grass silage production (Termonen et al., 2020) the current situation is likely to further increase interest in the use of forage legumes on beef cattle farms. Phelan et al. (2015) concluded that when comparing ruminant systems based on N-fertilized grass or cereals, forage legume-based systems tend to have less negative environmental impacts on biodiversity, N losses to water and GHG emissions. Therefore, it could be assumed that the environmental footprint of beef produced with red clover silage would be lower compared to beef produced with grass silage unless there are significant differences in the feed conversion rate between the diets. The objective of the present study was to evaluate the effects of replacing timothy silage by red clover silage on environmental impacts, growth performance and carcass traits of finishing beef bulls. Based on earlier studies, it was hypothesized that replacing timothy silage by red clover silage in the diet could increase feed intake of the bulls but does not have major effects on growth performance or carcass traits. It was also hypothesized that the partial or complete replacement of timothy silage by red clover silage would result in lower GHG emissions and eutrophication, and acidification potential compared to pure timothy silage when impacts of feed production is considered.

2. Material and methods

2.1. Animals and housing

A feeding experiment was carried out in the experimental cattle unit of Natural Resources Institute Finland (Luke) in Ruukki starting in January 2022 and ending in August 2022. The experiment was conducted using 30 purebred Hereford (HF) and 30 purebred Simmental (SI) bulls. All animals were purchased from commercial herds where they spent their first summer at pasture with their dams. The bulls were moved to the experimental cattle unit of Luke at an average age of seven months, two months before the start of the feeding experiment. During this pre-experimental period the bulls were adapted to housing conditions and silage plus barley grain based feeding. The bulls remained healthy throughout the pre-experimental period.

At the start of the feeding experiment HF and SI bulls were on average 266 (±20.4) and 264 (±19.2) days old and weighed 369 (±35.7) and 438 (±50.5) kg, respectively. 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 authorization 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).

The bulls were housed in an uninsulated barn in pens (10.0 m × 5.0 m; 5 bulls in each pen), providing 10.0 m^2 per bull. The rear half of the pen area was a peat-bedded lying area and the fore half was a feeding area with a solid concrete floor. A Vytelle feed intake system (model 4000E; Vytelle Ltd., Kansas, KS, USA) was used to record individual daily feed intakes so that each pen contained two Vytelle feeder nodes. The bulls had free access to water during the whole feeding experiment.

2.2. Feeding, feeds and experimental design

At the beginning of the experiment, both HF and SI bulls were randomly allotted to pens which were randomly allotted to three feeding treatments so that each treatment included two HF pens and two SI pens (20 bulls per treatment). The three experimental diets included red clover silage (RS) or grass silage (GS) as sole forage or a mixture of RS and GS (1:1 on DM basis; GRS) (Table 1). The silage proportion (600 g/kg DM) and the proportions of rolled barley (385 g/kg DM) and mineral-vitamin mixture (15 g/kg DM) were the same in each diet (Table 1). The bulls were fed total mixed rations ad libitum (proportionate refusals of 5 %). Rations were mixed in a mixer wagon (Trioliet, BW Oldenzaal, The Netherlands) once a day. Three SI bulls (two RS and one GS) were excluded from the study due to hoof problems. There was no reason to suppose that the experimental diets had caused these problems. The other 57 bulls remained healthy throughout the study.

Table 1
The proportion (g/kg dry matter) of the feeds in the experimental diets.

Treatment	GS	GRS	RS
Grass silage	600	300	
Red clover silage		300	600
Rolled barley grain	385	385	385
Mineral-vitamin mixture	15	15	15

Experimental silages were produced at the farm of Luke in Ruukki (64°44′N, 25°15′E) and harvested from either pure red clover (RS) or pure timothy (GS) stands. Red clover variety was Selma (Boreal Plant Breeding Ltd., Jokioinen, Finland) and the stand was one year old. For timothy, the variety was Nuutti (Boreal Plant Breeding Ltd., Jokioinen) and the stand was two years old. In 2021, red clover was harvested at flowering stage (in June 24 and September 8, primary growth and regrowth, respectively) and timothy at heading stage (in June 23 and August 18, primary growth and regrowth, respectively). The fertilizer for the first cut was YaraMila Y4 (N 20 %, P 2 %, K 12 %), and the application rates were 200 and 350 kg/ha for RS and GS, respectively. Regrowth of both crop stands were fertilized with YaraMila NK2 (N 22 %, K 12 %) with application rates 100 and 300 kg/ha for RS and GS, respectively. In 2022, the first cut harvesting date of RS and GS was June 22. The fertilizer was YaraMila Y4, and the application rates were 200 and 400 kg/ha for RS and GS, respectively. Both silages were cut by using a mower conditioner (Elho 280 Hydro Balance, Oy Elho Production Ab, 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 5.8 kg/t of fresh forage.

Spring-sown barley (cv. Brage) was used as a cereal grain in present experiment. 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 7 days prior to feeding. The composition of the mineral-vitamin mixture used (Kasvuape E-Hiven; A-Rehu Ltd., Seinäjoki, Finland) is fully described by Huuskonen et al. (2017).

2.3. Feed sampling and analysis

During the feeding experiment silage sub-samples were taken twice a week, pooled over periods of four weeks and stored at –20 °C prior to analyses. Thawed samples were analyzed for DM, ash, crude protein (CP), neutral detergent fibre (NDF) assayed with a heat stable amylase and expressed exclusive of residual ash, silage fermentation quality (pH, water-soluble carbohydrates, lactic and formic acids, ethanol, volatile fatty acids and ammonia N content of total N), and digestible organic matter (DOM) in DM (DOMD, d-value). Barley sub-samples were collected weekly, pooled over periods of eight weeks and analyzed for DM, ash, CP and NDF. The DM, ash, CP, NDF and DOMD were determined by standard methods as described by Huuskonen et al. (2020a,b). Fresh silage samples were analyzed for fermentation characteristics by electrometric titration as described by Moisio and Heikonen (1989).

The metabolizable energy (ME) concentration of silages was calculated as ME (MJ/kg DM) = 16.0 × DOMD (kg/kg DM) (MAFF, 1984). The ME concentration of barley grain and mineral-vitamin mixture was calculated based on the tabulated digestibility coefficients and analyzed chemical composition, except that for crude fibre and crude fat concentrations tabulated values were used (Luke, 2025). The protein value of the feeds is expressed as amino absorbed from the small intestine (metabolizable protein) and the protein balance value in the rumen (PBV) according to Luke (2025). The relative intake potential of silage DM (SDMI index) was calculated as described by Huhtanen et al. (2007).

2.4. Live weight and carcass measurements

The bulls were weighed on two consecutive days at the beginning of the experiment and thereafter approximately every 28 days. Before slaughter they were weighed on two consecutive days. The target for the average carcass weight was 380 kg and 430 kg for HF and SI bulls, respectively, which are near the average carcass weights for slaughtered HF and SI bulls in Finland (Pesonen and Huuskonen, 2015). The bulls were selected for slaughter based on live weight (LW) and assumed dressing proportions (530 and 550 g/kg for HF and SI bulls, respectively) which were assessed based on earlier studies in Finland with beef breed bulls (Pesonen, 2020). The LW gain (LWG) was calculated as the difference between the means of the initial and final LW 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 at the beginning of the experiment divided by the number of growing days. The carcass weight at the start of the present experiment was assumed to be 0.50 and 0.52 × initial LW for HF and SI bulls, respectively, because previous experiments have found a similar difference in dressing proportions between these breeds (Huuskonen and Pesonen 2017; Huuskonen et al. 2018).

Ultrasound measurements were made one day before slaughter. Ultrasound subcutaneous fat (mm) at the first lumbar vertebrae, ultrasound depth (cm) and area (cm^2) of *longissimus dorsi* muscle at the first lumbar vertebrae and ultrasound intramuscular fat (IMF) (%) were performed as described by Huuskonen and Pesonen (2017) with a Pie 200 SLC scanner (FPS 8; DFR 2–4 inches) equipped with the QUIP (Quality Ultrasound Indexing Program) software (Version 2.6) and a ASP-18 transducer (3.5 MHz) without a stand-off pad.

The bulls were slaughtered in the Atria Ltd. commercial slaughterhouse in Kauhajoki, Finland in two batches. All three feeding treatments were represented in both 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 LW. The carcasses were graded for conformation and fat score in accordance with the EU beef carcass classification scheme on a continuous 15-point scale (Conroy et al., 2010).

2.5. Calculations of environmental impacts

Life cycle modelling approach. Environmental impacts of each feeding treatments (GS, GRS, RS) were estimated with LCA approach, following IPCC (2006, 2021) and National Inventory Report methods for Finland (Statistics Finland, 2015). The utilized approach was complemented with specific prediction models for methane from enteric fermentation (Ramin and Huhtanen, 2013) and for dinitrogen oxide from perennial grass cultivation (Regina et al., 2013). The LCA method has been described in detail in Hietala et al. (2021). The available assessment model was updated to include IPCC (2021) characterization factors for GHG, which were for biogenic methane 27 and for nitrous oxides 273. Eutrophication and acidification impacts were assessed as in Hietala et al. (2021), and eutrophication results are given as phosphate (PO_4) equivalents and acidifying impacts are reported as acid equivalents (AE). Eutrophic emissions were characterized to PO_4 eq using factors 3.06 for P, 0.42 for N, 0.04 for NH_3 and 0.015 for NO_x (Heijungs et al., 1992; Seppälä et al., 2004). Acidifying emissions were characterized to AE using characterization factors 0.463, 0.535 and 0.186 for SO_2, NH_3 and NO_x, respectively (Seppälä et al., 2006). The LCA model was complemented with inclusion of clover grass cultivation assessment as a new crop. The inventory data used is given in Table 2 and described here in section regarding inventory data collection. Assessment was conducted as partial LCA of beef production, including the finishing period of the experiment. System boundary was set for the fattening period, from farm gate to gate and functional unit was ‘kg produced carcass’.

Inventory data collection. Inventory data was collected from feeding experiment and included the initial LW, carcass weight, total DMI, composition of total mixed rations and nutritional quality of the feed ingredients. These were completed with data from Finnish Feed Tables (Luke, 2025), which were adjusted to fit the measured feed quality for each feed component.

Feed crop production used the inventory data from Hietala et al. (2021) for grass silage and barley. For red clover cultivation inventory data was collected from multiple sources. Pure red clover cultivation data for Finnish conditions was not available, thus cultivation data for clover-grass mix was used instead. Data was collected from Finnish

Table 2
Characteristics of feed crop cultivation used in Life Cycle Assessment.

Crop	Grass silage	Clover grass, 'ESDavg'	Clover grass, 'LITavg'	Clover grass, 'LITMax'	Clover grass, 'ESDmin'	Barley	Barley, nurse crop
Crop yield, kg DM/ha	5550	5723	6835	7117	5632	3500	2800
N input, kg N/ha	155	35	50	50	50	60–85[1]	48–68[1]
P input, kg P/ha	16	6	30	30	30	14	14
K input, kg K/ha	30	32	30	30	30	30	30
Renewal sequence, every n year	4	3	3	3	3	annual	annual
Cuts, n/year	2	2	2	2	2	2	2
Reference	a	a	b	c	a	a	d

[1]Different N fertilisation level depending on soil type, organic soil 60/48 kg N/ha, clay 85/68 kg N/ha, other mineral 80/64 kg N/ha for barley/barley nurse crop, respectively.
a ProAgria, extension service organisation database.
b Nykänen et al. (2000), Riesinger (2010) and Kajava et al. (2019).
c Riesinger et al. 2010.
d ProAgria, extension service organisation database (20 % lower yield and N input assumed compred to average barley).

extensions services 'ProAgria' covering 1 580 ha of clover-grass cultivation with typical two cuts. As the clover-grass modelling was acknowledged to have uncertainty, it was completed with different scenarios of clover cultivation.

- literature-based average yield without organic soils for clover (LITavg),
- extension services data average with average soil types for all crops (ESDavg),
- extension services data minimum yield without organic soils for all crops (ESDmin),
- literature-based maximum yield with average soil types for all crops (LITmax)

The characteristics for the literature-based scenarios were gained from Nykänen et al. (2000), Riesinger (2010) and Kajava et al. (2019) and harvested yield was estimated as weighted average for LITavg and as average yield from Riesinger (2010) for LITmax. For the literature-based scenarios fertilizer input was set as maximum 50 kg N/ha and both P and K as 30 kg/ha for clover cultivation. For the ESD scenarios, yield and inputs were gained from the dataset collected from ProAgria. For the average clover cultivation, crop yield was 5 723 kg DM/ha, with 35 kg N/ha of which 15 kg N/ha was manure N, and 6 kg P/ha and 32 kg K/ha. The minimum yield dataset, ESDmin, was narrowed to include the extension services data for clover grass cultivation without the organic soils. In this dataset (ESDmin), the average yield for clover silage was 5 632 kg DM/ha with 34 kg N/ha, of which 15 kg N/ha was manure N, and 6 kg P/ha and 30 kg K/ha.

The feed values were utilized for assessment of excreted nutrients and methane emissions from enteric fermentation. For manure storage, for all treatments solid manure was assumed with straw and peat as bedding material.

For grass silage, the crop cultivation modelling was conducted as described in Hietala et al. (2021). Modelling was based on data derived as ten-year averages from agricultural extension service, ProAgria, from years 2002–2011. Finnish extension services data are collected annually from Finnish farms, being the most comprehensive primary data source on field cultivation. The collected grass silage data included over 24 000 ha of annually cultivated area on cattle farms. Grass silage yield was on average 5 550 kg DM/ha with 155 kg N/ha fertilization and barley yield was 3 500 kg/ha with 60–85 kg N/ha fertilization, and for nurse crop barley, 20 % lower crop yield and N fertilization was assumed. Utilized inventory data is described in Table 2.

2.6. Statistical methods

The results are shown as least squares means. The data were subjected to analysis of variance using the SAS GLM procedure (version 9.4, SAS Institute Inc., Cary, NC, USA). The statistical model used was

$$y_{ijklm} = \mu + \delta_k + \alpha_i + \gamma_j + \theta_{ijm} + \beta x_{ijkl} + e_{ijklm}$$

where μ is the intercept and e_{ijklm} is the residual error term associated with l^{th} animal. α_i, is the effect of i^{th} diet (GS, GRS, RS), while γ_j and δ_k are the effects of the breed (HF, SI) and slaughtering batch (1,2), respectively, and θ_{ijm} is the effect of pen. The effect of pen was used as an error term when differences between feeding treatments were compared because treatments were allocated to animals penned together. Initial LW was used as a covariate (βx_{ijkl}) in the model. Differences between the treatments were tested using orthogonal contrasts: (1) linear effect of red clover silage inclusion, (2) quadratic effect of red clover silage inclusion.

3. Results

3.1. Feeds

Chemical composition and feeding values of the experimental feeds are presented in Table 3. Due to the rainy weather conditions during harvesting, the DM concentrations of both RS and GS were relatively low. According to feed analyses, there was no difference in CP concentration between RS and GS, but GS had 16 % higher NDF and 10 % higher ME concentration compared to RS. Nevertheless, RS had 4 % higher SDMI index compared to GS. The fermentation characteristics of both RS and GS were good as indicated by the low pH value and the low concentrations of ammonia N in total N and total fermentation acids (Table 3). The barley grain had typical chemical compositions and feeding values, corresponding to the average values in the Finnish Feed Tables (Luke, 2025). Due to differences in composition of the experimental silages, GRS and RS rations included less NDF and ME compared to GS (Table 3). In all rations the PBV value fulfilled the Finnish recommendation for growing cattle (PBV of the diet above -10 g/kg DM for animals above 200 kg LW) (Luke, 2025).

3.2. Feed intake and animal performance

The feeding experiment lasted 224 days. The slaughter age of the bulls was 490 days, and final LW 755 kg, on average (Table 4). No significant diet × breed interactions were observed for any parameter. There were no differences among the feeding treatments in the slaughter age or final LW. Replacing GS by RS did not affect total DMI or CP intake of the bulls, but the ME intake tended to decrease linearly with increasing RS proportion ($P < 0.10$) (Table 4).

There were no differences among feeding treatments in LWG or carcass gain (Table 4). A significant quadratic effect of RS inclusion on CP conversion rate (kg CP/kg carcass gain) was observed so that the CP conversion was most effective with GRS feeding. In addition, there was a

Table 3
Chemical compositions and feeding values (mean ± standard deviation) of the experimental feeds and calculated chemical compositions and feeding values of the total mixed rations used in the feeding experiment.

	Feeds				Total mixed rations		
	Grass silage	Red clover silage	Rolled barley	Mineral-vitamin mixture	GS[a]	GRS[b]	RS[c]
Number of feed samples	8	8	8	2			
Dry matter (DM), g/kg	235 ± 13.0	243 ± 24.9	885 ± 2.1	986 ± 0.9	341	346	351
Organic matter (OM), g/kg DM	977 ± 5.5	918 ± 9.7	978 ± 0.3	65 ± 0.5	953	947	942
Crude protein, g/kg DM	138 ± 10.2	135 ± 23.5	117 ± 5.4	9 ± 0.2	130	129	128
Neutral detergent fibre, g/kg DM	584 ± 17.0	505 ± 23.1	213 ± 28.4	24 ± 0.4	436	412	388
Metabolizable energy, MJ/kg DM	10.3 ± 0.26	9.4 ± 0.21	13.1 ± 0.19	5.0 ± 0.1	11.4	11.2	10.9
Metabolizable protein, g/kg DM	77 ± 2.4	76 ± 3.9	96 ± 1.0	5 ± 0.2	85	84	84
Protein balance in the rumen, g/kg DM	23 ± 7.8	23 ± 19.6	−28 ± 5.5	1 ± 0.1	3	3	3
Digestible OM in DM, g/kg DM	641 ± 15.5	585 ± 12.2	ND[d]	ND			
Silage DM intake index	93 ± 3.7	97 ± 4.7					
Fermentation quality of silages							
pH	3.77 ± 0.123	3.99 ± 0.199					
Volatile fatty acids, g/kg DM	21 ± 4.8	20 ± 4.2					
Lactic + formic acid, g/kg DM	61 ± 9.0	72 ± 20.3					
Water soluble carbohydrates, g/kg DM	25 ± 5.7	28 ± 26.4					
NH_4N in total N, g/kg	50 ± 7.5	38 ± 17.4					

[a] Grass silage (600 g/kg DM), rolled barley (383 g/kg DM), mineral-vitamin mixture (15 g/kg DM).
[b] Red clover silage (300 g/kg DM), grass silage (300 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM).
[c] Red clover silage (600 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM).
[d] Not determined.

Table 4
Intake, growth performance and carcass traits of the bulls fed different total mixed rations.

Feeding	GS[a]	GRS[b]	RS[c]	SEM[d]	*P*-values[e] 1	2
Number of observations	19	20	18			
Duration of the experiment, d	227	223	223	4.0	0.437	0.668
Final live weight, kg	759	758	749	8.0	0.376	0.707
Slaughter age, d	495	488	488	5.8	0.414	0.614
Intake						
Dry matter (DM) intake, kg/d	11.2	11.2	11.3	0.19	0.778	0.597
DM intake, g/kg metabolic live weight	95	94	96	1.5	0.589	0.436
Metabolizable energy (ME), MJ/d	128	125	123	2.1	0.087	0.890
Crude protein (CP), kg/d	1.46	1.42	1.42	0.023	0.223	0.467
Live weight gain, g/d	1584	1615	1571	41.0	0.824	0.432
Carcass gain, g/d	900	941	899	23.6	0.997	0.143
Feed conversion						
Kg DM/kg carcass gain	12.7	12.0	12.8	0.31	0.808	0.063
MJ ME/kg carcass gain	144	135	139	3.5	0.263	0.112
Kg CP/kg carcass gain	1.65	1.53	1.60	0.039	0.447	0.046
Carcass characteristics						
Carcass weight, kg	403	408	400	5.0	0.630	0.286
Dressing proportion, g/kg	531	537	533	3.7	0.655	0.206
Conformation, EUROP	8.4	8.6	8.9	0.22	0.129	0.744
Fat score, EUROP	6.5	6.6	5.2	0.28	0.001	0.024
Ultrasound measurements						
Subcutaneous rump fat, mm	7.2	6.4	5.4	0.42	0.003	0.842
Intramuscular fat, %	3.5	3.4	2.9	0.13	<0.001	0.332
Depth of longissimus dorsi muscle, cm	7.4	7.2	7.2	0.09	0.112	0.494
Area of longissimus dorsi muscle, cm^2	98.5	98.6	97.8	1.61	0.768	0.799

[a] Grass silage (600 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM).
[b] Red clover silage (300 g/kg DM), grass silage (300 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM).
[c] Red clover silage (600 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM).
[d] Standard error of the mean.
[e] Orthogonal contrasts: (1) linear effect of red clover silage inclusion, (2) quadratic effect of red clover silage inclusion.

tendency ($P < 0.10$) that also feed conversion rate (kg DM/kg carcass gain) was the most effective in GRS diet.

The carcass weight of the bulls was 404 kg, dressing proportion 534 g/kg, and carcass EUROP conformation 8.6, on average (Table 4). There were no differences among feeding treatments in carcass weight, dressing proportion or carcass conformation score. Carcass fat score decreased with increasing RS proportion, with both linear and quadratic effects being significant (Table 4). In addition, both ultrasound measured subcutaneous rump fat and intramuscular fat decreased with increasing RS proportion. There were no differences in ultrasound measured depth or area of *longissimus dorsi muscle* among the feeding treatments (Table 4).

3.3. Environmental impacts

The environmental impacts of replacing grass silage partly or fully with red clover silage was evaluated using four different scenarios for red clover cultivation. In all used scenarios, the GS diet had a higher climate change impact compared to diets where red clover was included (Fig. 1). Between GRS and RS diets used scenarios affected the results

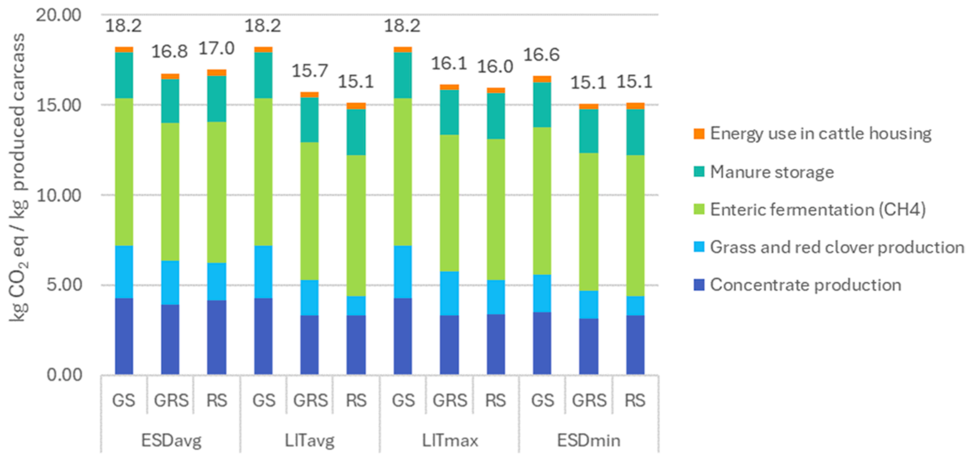

Fig. 1. Climate change impact (kg CO_2 eq/kg produced carcass) of the bulls fed with three different total mixed rations and four scenarios for clover and crop cultivation. GS diet included grass silage (600 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM). GRS diet included red clover silage (300 g/kg DM), grass silage (300 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM). RS died included red clover silage (600 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM). Different datasets used to describe clover grass, included ESDavg (average yield and soil types based on extension services data), LITavg (average yield from literature, no organic soils for clover), LITmax (maximum yield from literature, average soil types), EDSmin (minimum yield based on extension services data, no organic soils for any crop).

slightly. Depending on the used scenario, GRS resulted in slightly lower (ESDavg), slightly higher (LITavg, LITmax) or similar (ESDmin) climate change impacts compared to RS (Fig. 1). In scenarios where organic soil use was involved in crop cultivation, the differences between diets were more distinct. For LITavg, it was assumed red clover was not cultivated on organic soils and other crops were cultivated on average soil types of cattle farms. Here, GRS resulted in 14 % lower and RS 17 % lower climate change impact compared to GS. Main source for these differences was silage cultivation, and the highest climate change impact was in GS, and was 31 % less in GRS, and 63 % less in RS. With ESDmin dataset, it was assumed all crops were cultivated on mineral soils, without organic soils. In this scenario RS and GRS resulted in same climate change impact and it was 9 % lower compared to GS. Overall, depending on the used dataset, inclusion of red clover in diet reduced the climate change impact of the produced carcass by 7 to 17 %.

Besides climate change impact, also eutrophication potential and acidification were investigated. A similar trend to that in climate change potential was found in both eutrophying and acidifying impacts The GS had the highest impacts per produced carcass kg compared with diets including red clover. For eutrophication impact, the lowest impact was in RS, while for acidifying impact there was no difference between GRS and RS (Table 5, Figs. 2, 3).

Table 5
Required field area and environmental impacts of three different feeding strategies. Field area and emissions according to LITavg dataset (average yield from literature, no organic soils for clover).

Feeding	GS[a]	GRS[b]	RS[c]
Duration of the experiment, d	227	223	223
Produced carcass during the experiment, kg	204	210	200
Intake, kg dry matter/total experimental period			
Grass silage	1530	746	0
Red clover silage	0	746	1513
Rolled barley grain	981	957	971
Required field area, ha			
Grass silage	0.27	0.14	0
Red clover silage	0	0.11	0.22
Rolled barley grain	0.30	0.29	0.30
Total	0.57	0.54	0.52
Emissions during the feeding experiment/kg produced carcass			
Climate change impact, kg CO_2 eq	18.2	16.8	17.0
Eutrophic emissions, g PO_4 eq	18.6	15.9	11.3
Acidifying emissions, g AE eq	38	35	35

[a] Grass silage (600 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM).
[b] Red clover silage (300 g/kg DM), grass silage (300 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM).
[c] Red clover silage (600 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM).

4. Discussion

Red clover silage used in the present experiment had a lower analysed d-value and CP content compared to the average values in the Finnish Feed Tables (Luke, 2025). Although RS had 4 % higher SDMI index compared to GS, replacing GS by RS did not affect DMI of the bulls. In a previous meta-analysis Huuskonen et al. (2013) observed that DMI of growing and finishing cattle can be predicted from LW and diet composition with a reasonable accuracy. Based on the equations reported by Huuskonen et al. (2013) and the dietary compositions of the present rations there is no difference in predicted total DMI between the feeding treatments (the difference <1 %) which corresponds to the observed results of the present experiment.

Contrary to the results observed in the present experiment, Day et al. (1978) and Thomas et al. (1981) reported that pure RS or mixtures of RS and GS resulted in higher DMI and gain of growing cattle compared with pure GS. Differences between the present study and those previous findings may be due to differences in concentrate feeding strategies used. In the experiments by Day et al. (1978) and Thomas et al. (1981) silages were fed as sole feeds or with lower concentrate allowances compared to the present experiment. The importance of silage is emphasized if it is used as a sole feed compared to a situation where moderate concentrate feeding is used as in the present study. More recently, Pesonen et al. (2014) observed no effects in DMI or LWG of growing bulls fed either pure GS or a mixture of GS and RS when diet concentrate proportion was either 330 or 660 g/kg DM. On the other hand, Berthiaume et al. (2015) reported no effects on DMI but improved average daily gain and feed efficiency when pure GS was replaced with a mixture of GS and RS.

In the present experiment, the effects of the experimental treatments on growth performance and carcass traits were minor. Consistent with the present experiment, Pesonen et al. (2014) found no difference in carcass weight, dressing proportion and carcass conformation of finishing bulls fed either pure GS or GS and RS mixture. In the present experiment carcass fat score and IMF decreased when replacing GS by

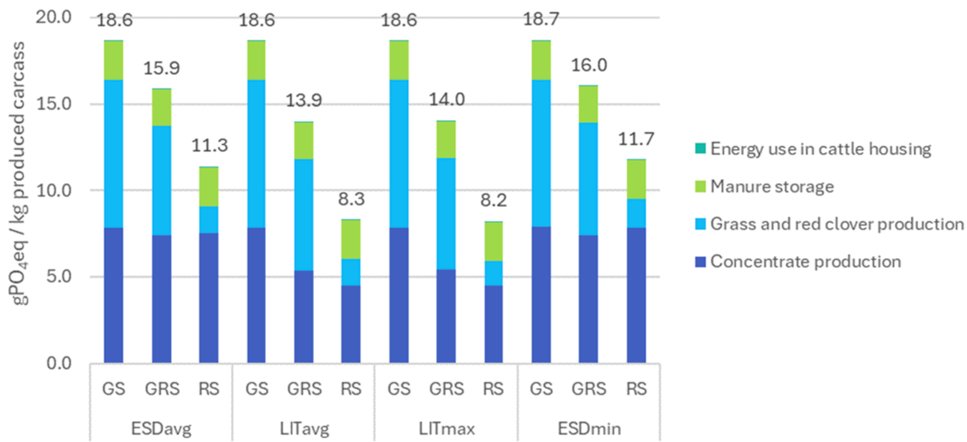

Fig. 2. Eutrophication impact (g PO_4 eq/kg produced carcass) of the bulls fed with three different total mixed rations and four scenarios for clover and crop cultivation. GS diet included grass silage (600 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM). GRS diet included red clover silage (300 g/kg DM), grass silage (300 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM). RS died included red clover silage (600 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM). Different datasets used to describe clover grass, included ESDavg (average yield and soil types based on extension services data), LITavg (average yield from literature, no organic soils for clover), LITmax (maximum yield from literature, average soil types), EDSmin (minimum yield based on extension services data, no organic soils for any crop).

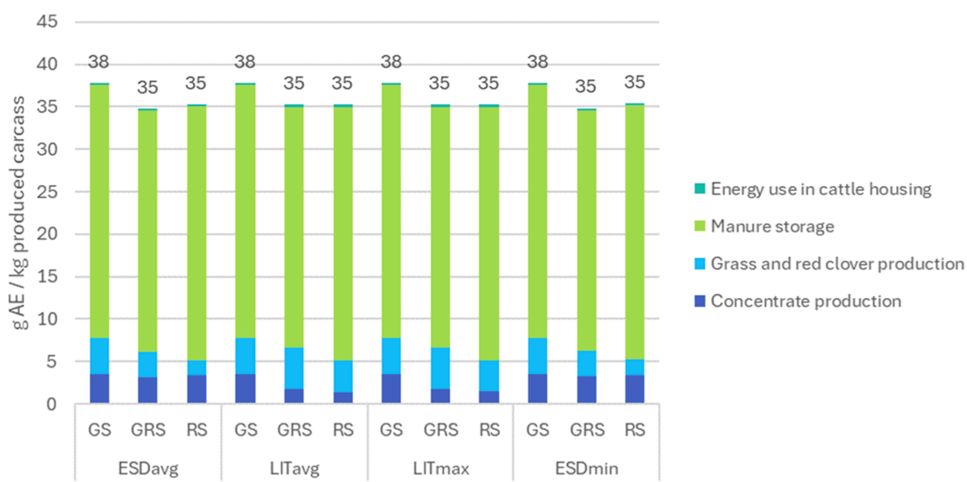

Fig. 3. Acidification impact (g AE/kg produced carcass) of the bulls fed with three different total mixed rations and four scenarios for clover and crop cultivation. GS diet included grass silage (600 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM). GRS diet included red clover silage (300 g/kg DM), grass silage (300 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM). RS died included red clover silage (600 g/kg DM), rolled barley (385 g/kg DM), mineral-vitamin mixture (15 g/kg DM). Different datasets used to describe clover grass, included ESDavg (average yield and soil types based on extension services data), LITavg (average yield from literature, no organic soils for clover), LITmax (maximum yield from literature, average soil types), EDSmin (minimum yield based on extension services data, no organic soils for any crop).

RS. This is consistent with Pesonen et al. (2014) who observed that carcass fat score was 13 % higher in bulls fed a GS based diet compared to a mixed GS and RS based diet. Also, Berthiaume et al. (2015) reported that a mixture of GS and RS tended to result in lower fat cover of steers compared with pure GS. This effect could be related to the enzyme polyphenol oxidase (PPO) since red clover PPO has been reported to link proteins into more complex cross-linked polymers which make them resistant to microbial degradation (Lee et al., 2009). The less degradation in the rumen will lead to more protein availability and absorption in the small intestine. There is some indication from previous studies that higher protein availability will produce less, and low protein availability will produce more subcutaneous and intramuscular fat (Gibb et al., 2008; Bharanidharan et al., 2021; Jeon et al., 2021).

Previously, Huuskonen et al. (2023) reported climate change impact of 19–21 kg CO_2 eq/kg of produced carcass, eutrophic emissions of 16–17 g PO_4 eq/kg of produced carcass and acidifying emissions of 38–39 g AE eq/kg of produced carcass when beef and dairy breed bulls were fed grass silage and barley grain based rations with a 400 g/kg DM concentrate proportion under similar conditions as in the present study. The characterisation factors for climate change impact were updated for this study, while Huuskonen et al. (2023) used characterisation factor 34 for biogenic methane and 298 for dinitrogen oxide, resulting slightly higher impacts also due to different method. Considering this, environmental impacts reported by Huuskonen et al. (2023) were on the same level as the results calculated with GS feeding in the present experiment. The effects of including white clover to grass-based finishing systems have been studied by Jebari et al. (2025). They concluded that inclusion of white clover to feeding reduced climate change impact of produced live weight by 12 %. Similarly, O'Brien et al. (2023) investigated the shifting from ryegrass-based production to grass and white clover system and its effects to several environmental impact categories. They concluded that climate change impact, land occupation and acidification potential were reduced with introduction of white clover, while eutrophying emissions were increased (O'Brien et al., 2023).

In the present study, the comparison of the environmental impacts was conducted for GRS and RS diets with four different datasets for clover grass cultivation. However, the selected dataset had only minor effects on the calculated environmental impacts, partly due to better efficiency of the clover grass in all datasets and partly due to assumptions regarding the use of organic soils. For all cases, red clover had lower nitrogen input and higher nutrient efficiency, which reduced the environmental impacts in comparison to grass silage, together with the similar or higher yields. Also, the selected soil type affected the results largely and scenarios which included organic soils had higher climate change impacts for feed cultivation. In comparison of climate change impact, eutrophication and acidification potential, GS resulted in highest impact in all cases. For GRS and RS diets the clover data affected the results slightly. Yet with nearly all different datasets, RS performed with lowest climate change impact and GRS resulted in climate change impacts nearly similar or same as RS. Only for ESDavg GRS resulted in slightly lower climate change impact compared to RS. The results are in line with the recent previous studies (O'Brien et al., 2023; Jebari et al. 2025).

The observed slightly lower climate change impact in GRS in comparison to RS with ESDavg was due to slightly higher carcass yield in GRS and slightly higher DMI in RS, resulting in higher emission from concentrate cultivation, enteric fermentation and manure storage for RS compared to GRS. In this dataset for clover, it was assumed that all crop cultivation was on soil types of average Finnish cattle farm, including 14 % of organic soils. For red clover this would not be typical, as it is not typically cultivated on peat soils, and thus this comparison can be seen as worst-case scenario.

With datasets considering the use of organic soils in clover and feed crop cultivation, the differences between diets were more distinct. For LITavg, it was assumed clover was not cultivated on organic soils and other feed crops were cultivated on average soil types of cattle farms. Main source for differences between diets was silage cultivation, which had the largest climate change impact in GS, and was 31 % less in GRS, and 63 % less in RS. With ESDmin dataset, it was assumed all crops were cultivated on mineral soils, without organic soils. Thus, all crops were equally benefiting from not having cultivation on organic soils, and with this dataset RS and GRS resulted in same climate change impact 15.1 kg CO_2 eq/kg produced carcass. Differences were seen namely in silage cultivation, which emissions were higher with GRS, and due to slightly higher DMI and lower carcass gain, all remaining life cycle stages resulted slightly higher with RS. In overall, from the comparisons, depending on the used dataset, inclusion of red clover in feeding reduced the climate change impact of the kg produced carcass by 7 to 17 %.

For eutrophying potential, the reduction of impacts between GS and GRS was between 14 and 25 % and GS and RS 37 to 56 % and for acidification potential on average 8 %. Eutrophying impacts were largely affected by the fertilisation, thus less fertilisation input and higher yields resulted in smaller impacts. For acidification, manure storage was the main contributor, which was affected only slightly due to diet. The main differences between diets originated in field crop cultivation and fertiliser use and diets with less fertiliser inputs performed better.

5. Conclusions

It can be concluded that, according to our hypothesis, replacing grass silage partially or completely with red clover silage reduced climate change impact, eutrophic emissions, and acidifying emissions per kg of produced carcass. In addition, carcass fat score decreased when replacing grass silage by red clover. However, lean and low-fat carcasses are not a problem in the Finnish meat market, where consumers generally favour low fat products. No significant differences were observed in the intake, gain and carcass characteristics results of the bulls between red clover silage and timothy silage based diets. Therefore, the greatest benefits of using red clover in beef production are likely to be realized through feed production chain. Including red clover in the diet of beef cattle reduces the climate change impact and eutrophication emissions of beef production.

Data availability

The data supporting the findings of this study will be made available upon reasonable request to the corresponding author.

CRediT authorship contribution statement

Arto Huuskonen: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sanna Hietala:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Maiju Pesonen:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Katariina Manni:** Writing – review & editing, Methodology, Investigation, Conceptualization.

Declaration of competing 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

Berthiaume, R., Lafrenière, C., Girard, C., Campell, C.P., Pivotto, L.M., Mandell, I.B., 2015. Effects of forage silage species on yearling growth performance, carcass and meat quality, and nutrient composition in a forage based beef production system. Can. J. Anim. Sci. 95, 173–187. https://doi.org/10.4141/cjas-2014-107.
Bertilsson, J., Murphy, M., 2003. Effects of feeding clover silages on feed intake, milk production and digestion in dairy cows. Grass Forage Sci. 58, 309–322. https://doi.org/10.1046/j.1365-2494.2003.00383.x.
Bharanidharan, R., Thirugnanasambantham, K., Idibhi, R., Bang, G., Jank, S.S., Baek, Y. C., Kim, K.H., Moon, H.Y., 2021. Effects of dietary protein concentration on lipid metabolism gene expression and fatty acid composition in 18-23 month old Hanwoo steers. Animals 11, 3378. https://doi.org/10.3390/ani11123378.
Carlsson, G., Huss-Danell, K., 2003. Nitrogen fixation in perennial forage legumes in the field. Plant Soil 253, 353–372. https://doi.org/10.1023/A:1024847017371.
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. Livest. Sci. 127, 11–21. https://doi.org/10.1016/j.livsci.2009.06.007.
Day, N., Harkess, R.D., Harrison, D.M., 1978. A note on red clover silage for cattle finishing. Anim. Prod. 26, 97–100. https://doi.org/10.1017/S000335610001206X.
Dewhurst, R.J., Fisher, W.J., Tweed, J.K.S., Wilkins, R.J., 2003. Comparison of grass and legume silages for milk production. 1. Production responses with different levels of concentrate. J. Dairy Sci. 86, 2598–2611. https://doi.org/10.3168/jds.S0022-0302(03)73855-7.
Gibb, D.J., Hao, X., Mc Allister, T.A., 2008. Effect of dried distillers' grains from wheat on diet digestibility and performance of feedlot cattle. Can. J. Anim. Sci. 88, 659–665. https://doi.org/10.4141/CJAS08040.
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.

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 136 p. https://hdl.handle.net/1887/8062.

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. Agric. Syst. 194, 103250. https://doi.org/10.1016/j.agsy.2021.103250.

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., Hietala, S., Hyvönen, J., Leinonen, I., Manni, K., 2023. Environmental impacts and animal performance of finishing bulls fed different silage-based total mixed rations. Livest. Sci. 232, 103896. https://doi.org/10.1016/j.livsci.2019.103896.

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

Huuskonen, A., Jaakkola, S., Manni, K., 2020a. Intake, gain and carcass traits of Hereford and Charolais bulls offered diets based on triticale, barley and grass silages. Agric. Food Sci. 29, 318–330. https://doi.org/10.23986/afsci.89813.

Huuskonen, A., Pesonen, M., 2017. A comparison of first-, second- and third-cut timothy silages in the diets of finishing beef bulls. Agric. Food Sci. 26, 16–24. https://doi.org/10.23986/afsci.60413.

Huuskonen, A., Pesonen, M., Honkavaara, M., 2017a. 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 Forage Sci. 72, 220–233. https://doi.org/10.1111/gfs.12247.

Huuskonen, A., Rämö, S., Pesonen, M., 2018. Effects of primary growth compared to regrowth grass silage on feed intake, growth performance and carcass traits of growing bulls. Agric. Food Sci. 27, 232–242. https://doi.org/10.23986/afsci.74582.

Huuskonen, A., Rinne, M., Manni, K., 2020b. Effects of different barley grain preservation techniques on intake, growth and carcase traits of finishing dairy bulls fed grass silage-based rations. J. Agric. Sci. 158, 748–755. https://doi.org/10.1017/S0021859621000022.

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

Intergovernmental Panel on Climate Change (IPCC), 2021. Climate Change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel On Climate Change, in 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. (Eds.), Cambridge University Press. https://doi.org/10.1017/9781009157896.

Jebari, A., Takahashi, T., Lee, M.R., Collins, A.L., Coleman, K., Carswell, A., Segura, C., Cardenas, L., McAuliffe, G.A., 2025. Carbon footprints of greenhouse gas mitigation measures for a grass-based beef cattle finishing system in the UK. Int. J. LCA 30, 654–667. https://doi.org/10.1007/s11367-025-02428-9.

Jeon, S., Lee, M., Seo, J., Kim, J.-H., Kam, D.-K., Seo, S., 2021. High-level dietary crude protein decreased backfat thickness and increased carcass yield score in finishing Hanwoo beef cattle (*Bos taurus coreanae*). J. Anim. Sci. Technol. 63, 1064–1075. https://doi.org/10.5187/jast.2021.e96.

Kajava, S., Sairanen, A., Jääskeläinen, M., 2018. Säilörehuntuotannon tehokkuus. In: Kajava, S. (Ed.), EuroMaito-verkosto – tukea maidontuotannon resurssitehokkuuden ja kestävyyden kehittämiseen. Luonnonvarakeskus, Helsinki, pp. 6–15.

Kuhmonen, T., Kuhmonen, I., Huuskonen, A., 2024. Sustainability-driven regime shifts in complex adaptive systems: the case of animal production and food system. Sustain. Prod. Consump. 52, 469–486. https://doi.org/10.1016/j.spc.2024.11.022.

Kuoppala, K., Ahvenjärvi, S., Rinne, M., Vanhatalo, A., 2009. Effects of feeding grass or red clover silage cut at two maturity stages in dairy cows. 2. Dry matter intake and cell wall digestion kinetics. J. Dairy Sci. 92, 5634–5644. https://doi.org/10.3168/jds.2009-2250.

Lee, M.F.L., Tweed, J.K.S., Minchin, F.R., Winters, A.L., 2009. Red clover polyphenol oxidase: activation activity and efficacy under grazing. Anim. Feed Sci. Technol. 149, 250–264. https://doi.org/10.1016/j.anifeedsci.2008.06.013.

Luke, 2025. Feed tables and nutrient requirements. Natural Resources Institute Finland (Luke), Helsinki, Finland. http://www.luke.fi/feedtables (cited 21 January 2025).

MAFF, 1984. Energy allowances and feeding systems for ruminants. In: ADAS Reference book, 433. Ministry of Agriculture, Fisheries and Food. Her Majesty`s Stationery Office, London, p. 85.

Mogensen, L., Kristensen, T., Nguyen, T.L.T., Knudsen, M.T., Hermansen, J.E., 2014. Method for calculating carbon footprint of cattle feeds – including contribution from soil carbon changes and use of cattle manure. J. Clean. Prod. 73, 40–51. https://doi.org/10.1016/j.jclepro.2014.02.023.

Moisio, T., Heikonen, M., 1989. A titration method for silage assessment. Anim. Feed Sci. Technol. 22, 341–353. https://doi.org/10.1016/0377-8401(89)90078-3.

Nykänen, A., Granstedt, A., Laine, A., Kunttu, S., 2000. Yields and clover contents of leys of different ages in organic farming in Finland. Biol. Agric. Hortic. 18, 55–66. https://doi.org/10.1080/01448765.2000.9754864.

O'Brien, D., Markiewicz-Keszycka, M., Herron, J., 2023. Environmental impact of grass-based cattle farms: a life cycle assessment of nature-based diversification scenarios. Resour. Environ. Sustain. 14, 100126. https://doi.org/10.1016/j.resenv.2023.100126.

Pesonen, M., 2020. Growth performance, carcass characteristics and meat quality of different beef breeds in typical Finnish production systems: doctoral Dissertation. Nat. Resour. Bioecon. Stud. 43, 89 p. Available: https://jukuri.luke.fi/handle/10024/546141.

Pesonen, M., Huuskonen, A., 2015. Production, carcass characteristics and valuable cuts of beef breed bulls and heifers in Finnish beef cattle population. Agric. Food Sci. 24, 164–172. https://doi.org/10.23986/afsci.50930.

Pesonen, M., Joki-Tokola, E., Huuskonen, A., 2014. The effect of silage plant species, concentrate proportion and sugar beet pulp supplementation on the performance of growing and finishing crossbred bulls. Anim. Prod. Sci. 54, 1703–1708. https://doi.org/10.1071/AN14141.

Phelan, P., Moloney, A.P., McGeough, E.J., Humphreys, J., Bertilsson, J., O'Riordan, E. G., O'Kiely, P., 2015. Forage legumes for grazing and conserving in ruminant production systems. Crit. Rev. Plant Sci. 34, 281–326. https://doi.org/10.1080/07352689.2014.898455.

Ramin, M., Huhtanen, P., 2013. Development of equations for predicting methane emissions from ruminants. J. Dairy Sci. 96, 2476–2493. https://doi.org/10.3168/jds.2012-6095.

Regina, K., Kaseva, J., Esala, M., 2013. Emissions of nitrous oxide from boreal agricultural mineral soils—statistical models based on measurements. Agric. Ecosyst. Environ. 164, 131–136. https://doi.org/10.1016/j.agee.2012.09.013.

Riesinger, P., 2010. Agronomic Challenges For Organic Crop Husbandry. Doctoral thesis. University of Helsinki, Detartment of Agriculturas Sciences, p. 90.

Rinne, M., Franco, M., Manni, K., Huuskonen, A., 2023. Evaluating the effects of wilting, mixing with timothy and silage additive application on red clover silage quality. Agric. Food Sci. 32, 207–218. https://doi.org/10.23986/afsci.137136.

Seppälä, J., Knuuttila, S., Silvo, K., 2004. Eutrophication of aquatic ecosystems. A new method for calculation the potential contributions of nitrogen and phosphorus. Int. J. LCA 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. Int. J. LCA 11, 403–416. https://doi.org/10.1065/lca2005.06.215.

Statistics Finland, 2015. Greenhouse gas emissions in Finland 1990-2013. National Inventory Report (NIR) 2015 submission. 30 October 2015. https://unfccc.int/files/national_reports/annex_i_ghg_inventories/national_inventories_submissions/application/zip/fin-2016-nir-15jun16.zip.

Steen, R.W.J., McIlmoyle, W.A., 1982. An evaluation of red clover silage for beef production. Anim. Prod. 34, 95–101. https://doi.org/10.1017/S0003356100000520.

Termonen, M., Korhonen, P., Kykkänen, S., Kärkönen, A., Toivakka, M., Kauppila, R., Virkajärvi, P., 2020. Effects of nitrogen application rate on productivity, nutritive value and winter tolerance of timothy and meadow fescue cultivars. Grass Forage Sci. 75, 111–126. https://doi.org/10.1111/gfs.12461.

Thomas, C., Gibbs, B.G., Tayler, J.C., 1981. Beef production from silage. 2. The performance of beef cattle given silages either perennial ryegrass or red clover. Anim. Prod. 32, 149–153. https://doi.org/10.1017/S0003356100024934.

Vanhatalo, A., Jaakkola, S., 2016. Intake and performance with temperate forage legume-based ruminant production systems. Legume Perspect. 12, 17–18.