RUMINANT NUTRITION

Optimum roughage proportion in barley-based feedlot cattle diets: growth performance, feeding behavior, and carcass traits

Karen M. Koenig,^{†,1} Gwinyai E. Chibisa,^{†,‡} Gregory B. Penner,^{||} and Karen A. Beauchemin[†]

[†]Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, Lethbridge, AB, Canada, [‡]Department of Animal and Veterinary Science, University of Idaho, Moscow, ID 83844-2330, ^{||}Department of Animal and Poultry Science, University of Saskatchewan, Saskatoon, SK, Canada

¹Corresponding author: karen.koenig@canada.ca

ORCID numbers: 0000-0002-9207-583X (G. E. Chibisa); 0000-0002-6396-2130 (G. B. Penner).

Abstract

High grain diets are fed to finishing beef cattle to maximize animal performance in a cost-effective manner. However, a small amount of roughage is incorporated in finishing diets to help prevent ruminal acidosis, although few studies have examined optimum roughage inclusion level in barley-based diets. The objective of the study was to evaluate the effects of roughage proportion in barley-based finishing diets on growth performance, feeding behavior, and carcass traits of feedlot cattle. Crossbred beef steers ($n = 160$; mean body weight $\pm$ SD, 349.7 ± 21.4 kg) were allocated to 20 pens that were assigned randomly to four dietary treatments (five pens of eight steers per treatment). The treatment diets contained barley silage at 0%, 4%, 8%, and 12% of dietary dry matter (DM). The remainder of the diets (DM basis) consisted of 80%, 76%, 72%, and 68% barley grain, respectively, 15% corn dried distiller's grains, 5% mineral and vitamin supplement, and 32 mg monensin/kg diet DM. The diets were fed as total mixed rations for ad libitum intake (minimum of 5% refusal) once per day. Cattle were weighed on 2 consecutive days at the start and end of the experiment and on 1 d every 3 wk throughout the experiment (124 d). Two pens for each treatment group were equipped with an electronic feeding system (GrowSafe Systems Ltd., Calgary, Alberta) to monitor feed intake and feeding behavior of individual cattle. The data for dry matter intake (DMI), average daily gain (ADG), gain:feed (G:F) ratio, and carcass traits were analyzed as a completely randomized design with fixed effect of barley silage proportion and pen replicate as experimental unit. Feeding behavior data were analyzed similarly, but with animal as experimental unit. Averaged over the study, DMI increased linearly (11.1, 11.3, 11.7, 11.8 kg/d; $P = 0.001$) as barley silage proportion increased from 0%, 4%, 8%, and 12% of DM, but ADG was not affected (carcass-adjusted, 1.90, 1.85, 1.87, 1.89 kg/d; $P \geq 0.30$). Consequently, G:F ratio decreased linearly (carcass-adjusted, 168.9, 163.8, 158.5, 160.6 g/kg DMI; $P = 0.023$). When averaged over the study, proportion of barley silage in the diet had no linear or quadratic effects ($P > 0.10$) on meal frequency, duration of meals, intermeal duration, or meal size, but eating rate decreased linearly with increasing silage proportion ($P = 0.008$). There was no diet effect on liver abscesses ($P \geq 0.92$), and effects on carcass characteristics were minor or nonexistent. We conclude that increasing the proportion of barley silage in a feedlot finishing diet at the expense of barley grain to minimize the incidence of ruminal acidosis may decrease feed conversion efficiency.

Key words: barley, eating behavior, feedlot cattle, forage, growth performance, ruminal acidosis

Abbreviations

ADF	acid detergent fiber
ADG	average daily gain
BW	body weight
CP	crude protein
DM	dry matter
DMI	dry matter intake
G:F	gain:feed
HCW	hot carcass weight
NDF	neutral detergent fiber
OM	organic matter
pef	physical effectiveness factor
TMR	total mixed ration.

Introduction

Finishing beef cattle in North America are typically fed high grain diets with only a small proportion of roughage to maximize productivity in a cost-effective manner (Turgeon et al., 2010; Gentry et al., 2016). Finishing diets are typically supplemented with 6 to 12% roughage (dry matter [DM] basis; Koenig and Beauchemin, 2011; Samuelson et al., 2016) to provide physically effective neutral detergent fiber (peNDF), which helps prevent digestive disorders (Chibisa et al., 2020). The grains are highly processed (dry-rolled, steam flaked, high moisture) to increase ruminal and total-tract digestibility of starch. Low-roughage, highly fermentable diets improve feed efficiency and reduce feed costs (Owens et al., 1997), but prevalence of acidosis, bloat, and liver abscesses is increased. These digestive disorders account for about one-quarter to one-third of the deaths in feedlot cattle (Galyean and Rivera, 2003).

Inconsistent intakes, reduced fiber digestibility and altered epithelium permeability caused by sub-acute acidosis may decrease the energy supply to the animal and may increase energy expenditure for proinflammatory responses (Kvidera et al., 2017), which may lead to poor growth rate and poor feed conversion efficiency. Individual animal feeding behavior can be modified in response to metabolic disease (Schwartzkopf-Genswein et al., 2003); however, direct evidence that ruminal acidosis decreases animal performance is scarce. Castillo-Lopez et al. (2014) examined variation among group-housed feedlot cattle fed the same backgrounding and finishing diets and reported that average daily gain (ADG) and gain:feed (G:F) ratio were positively correlated to mean ruminal pH and negatively correlated to duration and prevalence of ruminal acidosis. Despite positive associations between feedlot cattle performance and decreased ruminal acidosis for cattle fed a common diet, it is not clear whether increasing the proportion of roughage in the diet to provide peNDF and prevent ruminal acidosis improves animal performance. In a meta-analysis of the literature, Galyean and Dafoor (2003) reported a positive association between dry matter intake (DMI) of feedlot cattle and neutral detergent fiber (NDF) content of diets suggesting a decrease in G:F ratio with increased roughage proportion.

Few studies have examined optimum levels of roughage in barley-based feedlot diets. Most feedlots in the United States use corn grain, while Canadian feedlots use mainly barley grain. Grain source affects the risk of acidosis, with lower ruminal pH in cattle fed barley compared to corn due to greater extent of starch digestion in the rumen for barley (Plascencia et al., 2018). Thus, greater roughage inclusion may be needed in barley-based diets to slow eating rate, promote rumination, reduce the rate of

fermentation of carbohydrates, and ultimately promote healthy rumen function. Koenig and Beauchemin (2011) reported that barley silage proportion had no effect on ADG of feedlot cattle, but DMI increased linearly when the proportion of barley silage was increased from 3% to 15% of DM, and concomitantly G:F ratio decreased linearly. Optimum barley silage inclusion to maximize feed conversion efficiency was 3% to 6% of DM. Chibisa et al. (2020) reported that adding up to 12% barley silage (DM basis) to a barley-based feedlot diet had no effect on DMI of cattle, but total-tract diet digestibility decreased, rumination time increased, and mean and minimum ruminal pH increased. The animals in that study were individually fed, and because the study was a Latin square with 28-d periods, animal performance was not measured. However, extrapolation of the results to commercial feedlot cattle suggests that growth rate would decline due to decreased metabolizable energy intake as proportion of forage increased and barley grain decreased, despite the cattle exhibiting less ruminal acidosis.

Therefore, the objective of our study was to evaluate the effects of increasing the proportion of roughage (barley silage) in a barley grain-based finishing diet (containing monensin) at the expense of barley grain on growth performance, feeding behavior, and carcass traits. We hypothesized that although increasing the proportion of barley silage may increase rumination time and decrease ruminal acidosis, G:F ratio, and potentially ADG, would decrease.

Materials and Methods

The experiment was conducted at the Beef Cattle Research Feedlot of Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre (Lethbridge, AB) in accordance with guidelines of the Canadian Council on Animal Care (2009) and was preapproved (protocol #ACC1304) by the Institutional Animal Care and Use Committee.

Experimental design, animals, and housing

A uniform group of 160 Herford-Angus crossbred beef steers (12 to 14 mo old) originating from a single calf crop (Onefour, AB; substation of the Lethbridge Research and Development Centre) were used in an experiment conducted as a completely randomized design with four dietary treatments (dietary proportions of barley silage), five replicate pens (eight animals/pen) per diet, and six 21-d periods (19 d in period 6). Before starting the study, the steers were fed a backgrounding diet at the Research Centre for at least 80 d. The backgrounding diet consisted of 61% barley silage, 33% barley grain, and 6% pelleted mineral and vitamin supplement (DM basis). Following the backgrounding phase, the cattle were weighed on 2 d (nonfasted; Cattlelac Hydraulic Squeeze with 4 load cells (WB31); Red Deer, AB; and Cardinal Detecto 758 Indicator; Cardinal Scale Manufacturing Co., Webb City, MO), stratified by body weight (BW) from light to heavy, allocated to four groups of five replicate pens (20 pens in total; eight steers per pen) of equal BW, and randomly assigned to the four dietary treatments. The steers were then adapted over 28 d to a common finishing diet containing 12% barley silage DM in five steps, each with an incremental increase in the concentrate:silage ratio. Steers were vaccinated to control respiratory diseases (Bovi-Shield Gold 5, Pfizer Animal Health, Kirkland, QC) and implanted with a growth promotant containing trenbolone acetate (120 mg), estradiol (24 mg), and tylosan tartrate (29 mg; Component TE-S with Tylan, Elanco Animal Health, Guelph, ON) in accordance with label instructions.

The cattle were housed in open pens that measured 19.5 × 14 m with earthen floors and windbreak fencing. Three pens per treatment were fitted with standard fence-line concrete feed bunks (15 m) with an adjacent 1.65-m wide concrete apron. The remaining two pens for each treatment were equipped with electronic feed bunks (two bunks/pen; GrowSafe Systems Ltd., Calgary, Alberta; Gibb et al., 1998) to monitor feed intake and feeding behavior of individual cattle. Steers in the feeding behavior pens were ear-tagged with a radio frequency identification transponder button (Allflex Canada, St-Hyacinthe, QC). A common automatic water fountain was shared between two adjacent pens. All pens were bedded away from the feed bunk at the same time during the experiment (on 7 d from February to June) with an equal amount of barley straw (1 large square bale/pen; approximately 400 kg) as required based on precipitation and air temperature. The temperature, precipitation, and wind speed during the study were recorded at a meteorological station located at the Research Centre and are shown in [Supplementary Figure 1](#).

Dietary treatments

The treatment diets contained whole crop barley silage (hulled variety) at 0%, 4%, 8%, and 12% of diet DM. The barley silage was harvested at a mid-dough stage of maturity ($41.7 \pm 1.91\%$ DM), chopped at a theoretical cut length of 5 mm, and stored in a bunker silo for 7 mo prior to use. It contained $16.0 \pm 2.18\%$ starch and $53.6 \pm 1.41\%$ NDF (DM basis; [Table 1](#)). The remainder of the diet consisted of (DM basis) 80%, 76%, 72%, and 68% hulled barley grain for the four diets, respectively, 15% corn dried distiller's grains with solubles from a single lot, and 5% pelleted (diameter 6.35 mm) mineral and vitamin supplement ([Table 2](#)). During the first 8 d of the study, steers assigned to the 8%, 4%, and 0% barley silage diets were transitioned in 1 to 3 steps, each with a 4 percentage unit decrease in silage DM and corresponding increase in concentrate, to their respective diets. Barley grain was purchased commercially every 10 to 12 d (minimum specified test weight, 57.5 kg/hL) and was dry rolled to a processing index of 80% to 82%. The processing index was determined as the volume weight of grain after processing divided by the volume weight of whole barley grain before processing × 100% (0.5 L cup; Seedburo, Chicago, IL). Monensin was included in the supplement to provide 32 mg/kg of dietary DM (Rumensin premix, Elanco Animal Health), but tylosin for liver abscess control was not used. The diets were formulated to supply energy and protein to steers gaining 1.5 kg/d and minerals and vitamins to meet or exceed requirements ([NASEM, 2016](#)). A feeder wagon equipped with a mixing auger and a weigh scale was used to prepare the diets as total mixed rations (TMR), which were offered once daily between 0830 and 1000 h for ad libitum intake (minimum of 5% refusal). Steers had free access to fresh water throughout the experiment. Steers were fed to a pen average target end-point of 605 kg of BW (unadjusted full weight basis) and slaughtered on days 124 and 125 of the study.

Feed intake

Feed offered to each pen was recorded daily and feed refusals were measured at the end of each week and removed from the feed bunk. Dry matter intake of each pen was determined as the difference between the amount of feed offered each day and refused at the end of each week, corrected for DM content of TMR and orts. Samples of feed ingredients, TMR offered, and orts were collected weekly and analyzed for DM in a forced-air oven at 55 °C for 48 h. Weekly silage DM content was used to adjust

Table 1. Chemical and particle size analysis of main dietary ingredients (mean ± SD)

Item	Dry-rolled barley grain ¹	Barley silage	Corn DDGS	Supplement
Chemical analysis, ² % DM				
No. of samples	6	6	1	1
DM, %	92.4 ± 1.41	41.7 ± 1.91	91.6	92.2
OM	97.6 ± 0.06	90.7 ± 0.41	95.3	64.7
CP	12.1 ± 0.47	11.1 ± 0.35	31.5	9.1
NDF	21.6 ± 0.94	53.6 ± 1.41	36.4	9.3
ADF	5.0 ± 0.40	33.3 ± 1.43	18.7	3.6
Starch	56.5 ± 2.66	16.0 ± 2.18	1.4	37.3
Crude fat	1.6	1.7	9.3	1.1
Retained on PSPS ³ , % as-is				
No. of samples	1	6	1	1
19 mm	0	17.6 ± 5.89	0	0
8 mm	0	39.9 ± 2.45	0.1	64.9
1.18 mm	96.2	40.4 ± 4.79	54.1	31.0
pan	3.8	2.1 ± 1.05	45.8	4.1
pef ₈	0	0.574	0	0.649
peNDF ₈ , % of DM	0	30.8	0	6.0
pef _{1.18}	0.962	0.979	0.542	0.959
peNDF _{1.18} , % of DM	0	52.5	19.7	8.9
Retained on sieve ⁴ , % DM				
No. of samples	33	3	1	1
4.75 mm	0	22.6 ± 2.22	0.9	79.6
4.00 mm	2.3 ± 2.83	11.1 ± 0.67	0.7	1.3
3.35 mm	34.3 ± 9.47	23.3 ± 1.48	1.7	1.6
2.36 mm	51.0 ± 7.62	20.8 ± 1.15	6.4	3.8
1.18 mm	10.9 ± 3.98	14.3 ± 1.24	29.7	7.0
850 µm	0.5 ± 0.21	3.9 ± 0.17	19.0	1.6
Pan	1.0 ± 0.46	4.0	41.6	5.1

¹Processing index was $81.7\% \pm 0.39$ ($n = 6$), defined as the weight of 500 mL of grain after processing/weight of 500 mL of grain before processing × 100%.

²Samples pooled by period for silage and grain, and for the experiment for DDGS and supplement. Crude fat was performed on samples pooled for the experiment.

³Particle size distribution measured using the Penn State Particle Separator: pef₈ and pef_{1.18} = physical effectiveness factor determined as the total proportion of particles retained on two sieves (19 and 8 mm) and three sieves (19, 8, and 1.18 mm), respectively; peNDF_{8.0} and peNDF_{1.18} = physically effective NDF determined as NDF content of TMR (% DM) multiplied by pef₈ and pef_{1.18}, respectively.

⁴Determined by dry sieving through a series of sieves arranged in descending mesh size.

the ingredient proportions of the diets if DM deviated by >3% from the average. The weekly samples collected were pooled by 3-wk periods and stored at -20 °C.

Animal performance

Once the cattle were allocated to their respective treatment groups, they were reweighed individually (non-fasted) on 2 consecutive days at the start (days 0 and 1) and end (days 123 and 124) of the experiment and on 1 d at 3-wk intervals (periods) throughout the experiment between 0800 and 1000 h and before the delivery of fresh feed. Body weight was multiplied by a factor of 0.96 to account for gut fill and was reported as shrunk BW. Carcass-adjusted final shrunk BW was calculated

Table 2. Ingredients and chemical composition of the experimental diets (mean ± SD)

Item	Barley silage (% of dietary DM)			
	0	4	8	12
Ingredient, % DM				
Barley silage	0	4	8	12
Barley grain, dry rolled	80	76	72	68
Corn DDGS	15	15	15	15
Supplement ¹				
Barley grain, ground	3.36	3.36	3.36	3.36
Calcium carbonate	1.31	1.31	1.31	1.31
Salt	0.15	0.15	0.15	0.15
Mineral and vitamin premix ²	0.05	0.05	0.05	0.05
Vitamin E (500,000 IU/kg)	0.006	0.006	0.006	0.006
Rumensin premix ³	0.016	0.016	0.016	0.016
Molasses	0.10	0.10	0.10	0.10
Flavoring	0.003	0.003	0.003	0.003
Chemical composition ⁴ , % DM				
No. of samples	6	6	6	6
DM, % as-fed	92.0 ± 0.91	87.0 ± 1.01	83.8 ± 0.83	79.5 ± 0.92
OM	95.3 ± 0.53	95.3 ± 0.23	95.4 ± 0.54	94.4 ± 0.24
NDF	21.9 ± 1.27	23.5 ± 1.36	25.1 ± 1.15	26.6 ± 1.25
ADF	7.5 ± 0.68	9.2 ± 1.09	9.5 ± 0.85	11.1 ± 0.79
Starch	47.3 ± 1.94	45.6 ± 1.87	44.0 ± 1.79	42.4 ± 1.72
CP	14.3 ± 0.55	14.5 ± 0.48	14.6 ± 0.51	14.6 ± 0.38
Crude fat	3.5	3.0	3.0	2.3
Retained on PSPS ⁵ , % as-is				
No. of samples	32	29	27	27
19 mm	0	0.2 ± 0.07	0.3 ± 0.09	0.6 ± 0.20
8 mm	3.9 ± 1.96	5.2 ± 0.74	6.5 ± 0.88	8.6 ± 1.05
1.18 mm	88.2 ± 3.70	86.6 ± 2.80	85.2 ± 1.05	82.5 ± 1.58
pan	7.9 ± 2.3	8.0 ± 2.48	8.0 ± 1.16	8.3 ± 1.06
pef ₈	0.039	0.054	0.068	0.092
peNDF ₈ , % of DM	0.85	1.27	1.71	2.44
pef _{1.18}	0.921	0.921	0.919	0.916
peNDF _{1.18} , % of DM	20.2	21.6	23.1	24.4
Retained on sieve ⁶ , % DM				
No. of samples	4	4	4	4
4.75 mm	5.3 ± 1.57	5.3 ± 2.96	5.4 ± 0.72	4.5 ± 1.21
4.00 mm	0.4 ± 0.14	0.7 ± 0.13	1.1 ± 0.22	1.6 ± 0.36
3.35 mm	11.6 ± 3.84	14.0 ± 4.37	15.8 ± 4.38	17.1 ± 3.57
2.36 mm	44.9 ± 3.51	47.7 ± 2.92	45.7 ± 2.94	42.9 ± 1.94
1.18 mm	25.7 ± 3.91	23.7 ± 1.97	23.0 ± 2.90	22.2 ± 2.56
850 µm	4.1 ± 0.63	3.5 ± 0.81	3.6 ± 0.76	4.2 ± 1.02
Pan	8.0 ± 2.36	5.1 ± 1.77	5.4 ± 1.50	7.5 ± 2.08

¹Ingredients of supplement were pelleted (diameter 6.35 mm).

²Provided per kg diet DM: 53 mg/kg of Zn, 14 mg/kg of Cu, 25 mg/kg of Mn, 0.6 mg/kg of I, 0.26 mg/kg of Se, 0.18 mg/kg of Co, 8940 IU/kg of vitamin A, 450 IU/kg of vitamin D and 12 IU/kg of vitamin E.

³Monensin concentration of the diets was 32 mg/kg DM. The premix contained 200 g monensin/kg (Elanco Animal Health, Guelph, ON).

⁴Period samples, except for crude fat where the samples from each period were combined for the experiment.

⁵PSPS, Penn State Particle Separator; pef₈ and pef_{1.18}, physical effectiveness factor determined as the total proportion of particles retained on 2 sieves (19 and 8 mm) and 3 sieves (19, 8, and 1.18 mm), respectively; peNDF₈ and peNDF_{1.18}, physically effective NDF determined as NDF content of TMR (% DM) multiplied by pef₈ and pef_{1.18}, respectively.

⁶Determined by dry sieving through a series of sieves arranged in descending mesh size.

as the hot carcass weight (HCW) divided by the average dressing percentage of 60%. Average daily gain was calculated as the difference between the initial and final shrunk BW divided by the number of days of each period or overall (live weight and carcass-adjusted basis), and G:F ratio was calculated as ADG divided by DMI for each period and overall (live weight and carcass-adjusted basis). Net energy contents of the diets were calculated from growth performance and DMI as described by Zinn et al. (2002) based on estimates of energy gain (EG, Mcal/d = 0.0493 × shrunk BW^{0.75} × ADG^{1.097} for large-frame steer

calves; NASEM, 2016) and maintenance energy expenditure (EM, Mcal/d = 0.77 × shrunk BW^{0.75}). Net energy of maintenance (NEM, Mcal/kg) of the diets was calculated from the quadratic formula, $x = (-b \pm \sqrt{(b^2 - 4ac)})/2a$, where $a = -0.877$ DMI, $b = 0.877$ EM + 0.41 DMI + EG, and $c = -0.41$ EM (Zinn and Shen, 1998) and net energy of gain (NEG, Mcal/kg) was calculated as 0.877 NEM - 0.41.

At the end of the experiment, steers were weighed, and subsequently shipped in two groups on 2 consecutive days to a federally inspected commercial abattoir (Cargill Proteins, High River, AB, Canada) for standard carcass evaluation. Following

slaughter, carcasses were inspected and chilled for 24 h, before evaluation by an accredited grader (Canadian Beef Grading Agency, Calgary, AB, Canada) according to [Canadian Food Inspection Agency \(2016\)](#) guidelines. Carcass trait information obtained included hot carcass weight, dressing percentage, longissimus thoracic area, average back fat thickness, grade fat thickness at the 12th rib, marbling score, lean meat yield, and quality grade. Dressing percentage was determined by dividing the HCW by final BW (shrunk) before shipping $\times 100\%$.

Livers were scored for severity of abscesses using a 4-point numeric scale where 0 (none) indicates no visible abscess, 1 (mild) indicates 1 or 2 small abscesses or inactive scars, 2 (moderate) indicates 1 or more large or several small abscesses, and 3 (severe) indicates > 4 small abscesses or 1 or more abscesses greater than 2.5 cm in diameter ([Brown et al., 1975](#)).

Feeding behavior

Feed intake and feeding behavior of individual steers (16 animals/treatment) were monitored by the GrowSafe feeding system (GrowSafe Systems, Airdrie, AB, Canada) throughout the study. The identification number of each steer was transmitted when the radio frequency identification transponder was within 0.5 m of the antenna and the feed bunk load cells were read at 1-min intervals. Eating behavior of individual steers was described as meal frequency (events/day), meal duration (min/meal), intermeal duration (min), meal size (kg DM/meal), and eating rate (g DM/min). A meal was defined for each individual steer as a visit to the bunk followed by an absence from the bunk of 300 s or more ([Schwartzkopf-Genswein et al., 2002](#)). Meal size was the amount of feed DM consumed per meal, whereas eating rate was calculated by dividing the meal size by the meal duration.

Chemical and particle size analysis

Period subsamples of diets and main ingredients were oven dried (55 °C for 48 h) and sequentially ground using a cutter mill through a 4-mm and then a 1-mm diameter screen (model 4 Wiley mill, Thomas Scientific, Swedesboro, NJ) and stored at ambient temperature until chemically analyzed. Analytical DM was determined by drying ground samples in a forced-air oven at 135 °C for 2 h ([AOAC, 2016](#); method 930.15) followed by hot weighing and used to correct chemical results to DM basis. Ash content was determined by combustion at 550 °C for 5 h ([AOAC, 2016](#); method 942.05). Organic matter (OM) content was calculated as the difference between 100 and the percentage of ash. The NDF ([AOAC, 2016](#); method 2002.04; reflux method) and acid detergent fiber (ADF; [AOAC, 2016](#); method 973.18) concentrations were determined by extraction using a refluxing apparatus. Thermostable amylase (Termamyl 120 L, Type L; Novozymes A/S, Bagsvaerd, Denmark) and sodium sulfite were used in the NDF method. Samples ground through a 1-mm screen were further ground using a ball mill (Mixer Mill MM2000; Retsch, Haan, Germany) to a fine powder for the determination of starch and total nitrogen (N). Starch content was determined by enzymatic hydrolysis and colorimetric detection of glucose according to the method described by [Koenig et al. \(2013\)](#) while total N content was quantified by flash combustion, gas chromatographic separation, and thermal conductivity detection ([AOAC, 2016](#), method 990.03; Carlo Erba Instruments, Milan, Italy). The crude protein (CP) content was calculated as $N \times 6.25$. Crude fat content was determined by ether extraction for 6 h ([AOAC, 2016](#), method no 920.39; E-816 Hot Extraction Unit, Büchi Labortechnik AG, Flawil, Switzerland).

Particle size distribution of TMR and main ingredients was determined using the Penn State Particle Separator with three sieves (19, 8, and 1.18 mm; [Lammers et al., 1996](#); determined on an as-is basis), and by sieving through a series of sieves (apertures of 4.75, 4.00, 3.35, 2.36, 1.18, and 0.85 mm; W. S. Tyler, Inc., Mentor, OH) arranged in descending mesh size (Ro-Tap Sieve Shaker, Laval Lab, Laval, QC). The physical effectiveness factor (pef) was determined as the total proportion of particles retained on two sieves (19 and 8 mm, pef_8) and 3 sieves (19, 8, and 1.18 mm, $\text{pef}_{1.18}$), respectively, and physically effective NDF (peNDF_8 and $\text{peNDF}_{1.18}$) was determined as NDF content of sample (% DM) multiplied by the respective pef. The material on each of the Ro-Tap sieves was dried and the weight of particles retained on each screen was then expressed as a proportion of the original sample dry weight.

Statistical analysis

Data for initial and final BW, and carcass traits by pen were analyzed as a mixed linear model (SAS Inst. Inc., Cary, NC) with diet as a fixed effect and pen within diet as the experimental unit. Data for DMI, ADG, and G:F for each pen for each 3-wk period were analyzed as a mixed linear model with diet, period (as a repeated measure), and the diet $\times$ period as fixed effects and pen as the experimental unit. The restricted maximum likelihood method was used for estimating variance components and the Kenward-Roger option was used to adjust the degrees of freedom. The variance and covariance error structures that were investigated included compound symmetry, heterogeneous compound symmetry, and auto-regressive. The error structure with the lowest Akaike information criteria fit statistic was selected for the model. Data are reported as least square means and differences among treatments were determined using orthogonal contrasts for linear and quadratic relationships. For the repeated measures model, the SLICE option was used when the diet $\times$ period interaction was significant to partition and test the simple main effects. Data for feeding behavior were analyzed similarly using repeated measures (period), but with individual animal as the experimental unit. Chi-square analysis was used for liver abscess score and quality grade. Differences were considered significant at $P \leq 0.05$ and trends were discussed at $0.05 < P < 0.10$.

Results

Two steers were removed from the study within the first 5 wk (1 each fed the 4% and 12% barley silage diets for urolithiasis and chronic bloat, respectively) and their corresponding data were removed prior to statistical analysis. Ten steers (2 fed 0%, 3 fed 4%, 4 fed 8%, and 1 fed 12% barley silage diet) were treated for foot rot (8), upper respiratory infection (1), and shoulder lameness (1), but remained in the study.

The barley grain had a processing index of (mean $\pm$ SD) $81.7 \pm 0.39\%$ and the barley silage contained $53.6 \pm 1.41\%$ NDF with a pef_8 value of 0.574 ([Table 1](#)). Increasing the proportion of barley silage from 0% to 12% DM increased the dietary NDF content by 4.7 percentage units and decreased starch by 4.9 percentage units ([Table 2](#)). Although there was a 2.4-fold increase in pef_8 content of the diets due to the increase in barley silage proportion, dietary peNDF_8 content only increased by < 2 percentage units. The $\text{pef}_{1.18}$ was not sensitive to changes in barley silage proportion, and therefore $\text{peNDF}_{1.18}$ content of the diets reflected changes in NDF content, but not particle size.

Dry matter intake averaged across pens by week and diet, with corresponding SD, is shown in [Supplementary Figure 2](#). Averaged over the study, DMI increased linearly ($P = 0.001$) as barley silage proportion increased, but ADG (live weight and carcass-adjusted basis) was not affected ($P \geq 0.30$), and thus G:F ratio (live weight and carcass-adjusted basis) decreased linearly ($P = 0.017$ and $P = 0.023$, respectively; [Table 3](#)). The increase in overall DMI offset the linear decrease ($P = 0.002$) in NEm and NEg of the diet resulting in similar energy intake across the dietary treatments. There were period effects for DMI, ADG, and G:F ($P < 0.001$) as shown in [Figure 1](#), but no diet $\times$ period interactions ($P \geq 0.23$). The DMI increased gradually during the study reaching maximum in periods 3 and 4, with a decline in period 5, and recovering in period 6. The ADG and G:F ratio were maximum in periods 2 and 3, and period 2, respectively.

When averaged over the study, proportion of barley silage in the diet had no linear or quadratic effects ($P \geq 0.13$) on meal frequency, duration of meals, intermeal duration, or meal size, but eating rate decreased linearly with increasing silage level ($P = 0.008$; [Table 4](#)). Eating rate increased each period until period 5 where it remained constant until the end of the study (period effect; $P < 0.001$; [Figure 2](#)). There were diet $\times$ period interactions ($P < 0.001$) for meal frequency and duration as shown in [Figure 3](#). Meal frequency gradually declined each period ($P < 0.001$), and within some periods there were small differences among diets. Meal duration varied slightly among periods ($P < 0.001$), with small differences among diets within periods 2 to 5. There were also period ($P < 0.001$) and diet $\times$ period interactions ($P < 0.001$) for intermeal duration and meal size ([Figure 4](#)). Intermeal duration gradually increased from 130 min in period 1 to 205 min by period 5, where it remained until the end, but within period ranking of the dietary treatments was inconsistent. Meal size increased from 0.84 kg DM in period 1 to a high of 1.57 kg DM in period 5, with inconsistent dietary differences within periods.

There was no dietary treatment effect on liver abscesses ($P \geq 0.92$; [Table 5](#)). Abscesses (scores 2, 3, and 4) were observed on 42.7% of the livers, with 4% of the livers from cattle fed 4% and 8% barley silage diets having severe abscesses. Hot carcass weight was not affected by treatment ($P \geq 0.26$), but there was a linear tendency ($P = 0.07$) for a very small decrease in dressing percentage with increasing barley silage proportion. There was also a linear tendency ($P = 0.07$) for increasing lean yield with increasing barley silage proportion. Longissimus muscle area, average and grade fat, and marbling score were not affected by silage proportion ($P \geq 0.12$).

Discussion

The economics of finishing beef cattle support the use of high grain diets with low roughage inclusion for a variety of reasons. Roughage is usually more expensive than grain when compared on a metabolizable energy basis; higher forage diets require large inventories of forages; high fiber diets result in greater quantities and handling of manure; and the lower digestibility of high fiber diets decreases G:F ratio ([Stock et al., 1990](#); [Turgeon et al., 2010](#); [Gentry et al., 2016](#)). Unless DMI increases to offset the decrease in digestibility, ADG decreases with increased roughage feeding, which increases the number of days to market. However, it is generally recognized that some roughage is needed in the diet to optimize rumen function, with the optimum level depending upon numerous acidosis risk factors, such as extent of grain processing, inclusion of ionophores and antibiotics, bunk management, tolerance for risk, and so forth ([Schwartzkopf-Genswein et al., 2003](#); [Drouillard, 2018](#)). Consequently, most feedlot finishing diets contain 6% to 12% roughage DM, ionophores, and antibiotics to help prevent ruminal acidosis and liver abscesses ([Samuelson et al., 2016](#)). For cattle fed barley-based diets without supplemental antibiotics for liver abscess control (but with monensin), [Chibisa et al. \(2020\)](#) reported that

Table 3. Growth performance of beef feedlot steers fed finishing diets with increasing proportions of barley silage ($n = 5$ pens/treatment)

Item ¹	Barley silage (% of dietary DM)				P-value			
	0	4	8	12	SEM ²	Diet	Linear	Quadratic
Shrunk BW, ³ kg								
Start of step-up (d -28)	336	336	336	335	1.0	0.77	0.35	0.63
Initial (d 1)	385	386	382	382	1.5	0.20	0.084	0.70
Final (d 124)	612	614	611	615	4.2	0.86	0.77	0.74
Carcass-adjusted final (d 124) ⁴	619	614	613	615	4.0	0.74	0.45	0.43
DMI, ⁵ kg/d	11.1	11.3	11.7	11.8	0.14	0.010	0.001	0.70
ADG, ^{5,6} kg/d	1.84	1.84	1.84	1.88	0.029	0.69	0.33	0.59
Carcass-adjusted ADG, kg/d	1.90	1.85	1.87	1.89	0.029	0.69	0.94	0.30
G:F ratio, ^{5,6} g/kg DM	165.5	163.0	158.4	160.5	1.66	0.039	0.017	0.18
Carcass-adjusted G:F ratio, g/kg DM	168.9	163.8	158.5	160.6	2.70	0.07	0.023	0.20
NEm, ⁷ Mcal/kg DM	2.10	2.07	2.02	2.03	0.016	0.008	0.002	0.29
NEg, ⁷ Mcal/kg DM	1.43	1.41	1.36	1.37	0.014	0.008	0.002	0.28

¹Data are reported as least squares means with pen as the experimental unit.

²Pooled standard error of the mean. The statistical model for DMI, ADG, and G:F ratio included the main effect of diet, period, and diet $\times$ period.

³Shrunk BW ($BW \times 0.96$; [NASEM, 2016](#)).

⁴Carcass-adjusted final shrunk BW was calculated as the HCW divided by an average dressing percentage of 60%.

⁵Period effect, $P < 0.001$; diet $\times$ period, $P \geq 0.23$.

⁶Average daily gain and gain:feed ratio based on shrunk BW.

⁷Net energy content of the diets was calculated from estimates of energy gain (EG, Mcal/d = $0.0493 \times \text{shrunk BW}^{0.75} \times \text{ADG}^{1.097}$ for large-frame steer calves; [NASEM, 2016](#)) and maintenance energy expenditure (EM, Mcal/d = $0.77 \times \text{shrunk BW}^{0.75}$) as described by [Zinn et al. \(2002\)](#). Net energy of maintenance (NEm, Mcal/kg) were calculated from the quadratic formula [$x = (-b \pm \sqrt{b^2 - 4ac})/2a$], where $a = -0.877$ DMI, $b = 0.877$ EM + 0.41 DMI + EG, and $c = -0.41$ EM ([Zinn and Shen, 1998](#)) and net energy of gain (NEg, Mcal/kg) were calculated as 0.877 NEm - 0.41 .

Figure 1. Dry matter intake (DMI; top), shrunken average daily gain (ADG, middle), and shrunken gain:feed (G:F; bottom) by period averaged over dietary treatments. Period, $P < 0.001$; diet $\times$ period, $P \geq 0.23$. *Within panel, period means with different letters differ ($P < 0.05$). Pooled period SEM = 0.11 (top), 3.588 (middle), and 0.045 (bottom).

increasing the barley silage proportion from 0% to 12% of DM increased minimum (+0.34 units) and mean (+0.34) ruminal pH, and decreased the duration and area of pH below the acidosis thresholds of pH 5.5 and 5.2. That study demonstrated that increased inclusion of peNDF in the form of barley silage in a barley-based diet helped prevent ruminal acidosis, but dietary effects on feedlot cattle performance were not examined.

In the present study, increasing the barley silage proportion in finishing diets from 0% to 12% of DM linearly increased DMI and slowed eating rate but ADG was not affected, and G:F ratio decreased linearly. The 1.5%, 4.3%, and 3.0% decrease in G:F ratio for 4%, 8%, and 12% silage diets compared with 0% silage would be expected to increase feed costs. Feed conversion efficiency is the primary factor influencing the cost of gain and thus contributes significantly to the economics of the feedlot (Retallick et al., 2013). The observed 1.8%, 5.4%, and 6.2% increase in DMI with 4%, 8%, and 12% silage compared with 0% silage is consistent with the expectation that the cattle would eat more feed to compensate for the decrease in diet digestibility, thereby maintaining digestible energy intake and consistent ADG (Galyean and Dafoor, 2003). Using similar diets, Chibisa et al. (2020) reported that diet DM digestibility decreased from 86% (0% silage), to 82.1%, 81.1%, and 79.5% for 4%, 8%, and 12% barley silage, respectively, because the silage was less digestible than the barley grain it replaced in the diet. In the present study, the increase in DMI with increased silage proportion increased NDF intake from 0.50% of BW for 0% silage to 0.63% of BW for 12% silage, which is considerably less than the estimated maximum possible (approximately 1.1% to 1.3% of BW; Mertens 1987), indicating that intake was not limited by gut fill even with the greatest roughage inclusion level.

The DMI gradually increased with increasing BW during the study reaching a maximum by period 3, with a notable decline in period 5, before recovering in period 6. The decline in DMI in period 5 (days 86 to 106 of the study) was not expected based on other literature (Owens and Hicks, 2019) and could possibly be due to the increase in precipitation during that same period. Precipitation may have increased mud depth in the pens and possibly discouraged animal movement to the feed bunks although the pens were bedded with straw as needed. Another possibility is that, despite best efforts, DMI was underestimated in period 5 due to incorrect estimates of DM content of TMR and orts because of the precipitation, as the feed bunks were not sheltered from the rain. Alternatively, it is possible that the severity of ruminal acidosis increased during the study as DMI increased (Castillo-Lopez et al., 2014), which may have resulted in cattle going off-feed later in the finishing stage. However, DMI decreased in period 5 for all 4 treatments; thus, it is probable that the decline in intake was not related to ruminal acidosis.

Increased particle size of the TMR due to increased roughage proportion was reflected by changes in pef_8 concentration of the TMR, which increased from 0.039 for 0% silage to 0.092 for 12% silage. Similar changes occurred for particles ≥ 3.35 mm when assessed using sieves. The barley silage had a pef_8 of 0.574 (i.e., 57.4% of the weight of particles was retained on the 8- and 19-mm sieves of the PSPS), and 57% of the particle weight was retained on ≥ 3.35 -mm sieves. The particle size of the barley silage was typical of cereal silage chopped using a theoretical cut length of 5 mm (Yang and Beauchemin, 2006). As expected, the increase in roughage incrementally increased the dietary concentration of peNDF_8 (from 0.08% to 2.44% DM for 0% to 12% barley silage DM). Chibisa et al. (2020) showed that a similar increase in peNDF_8 concentration of feedlot finishing diets increased rumination time, minimum pH, and maximum ruminal pH. It should be noted that the peNDF_8 values for the diets in the present study and those reported by Chibisa et al. (2020) are relatively low compared with the minimum peNDF of 7% to 10% recommended by Fox and Tedeschi (2002), based on book values rather than measured values. The low peNDF_8 values occurred because only silage and supplement provided peNDF_8 , and these were both in relatively low proportions

Table 4. Feeding behavior of beef feedlot steers fed finishing diets with increasing proportions of forage and allocated to pens with GrowSafe feed bunks

Item ¹	Barley silage (% of dietary DM)				SEM ²	P-value		
	0	4	8	12		Diet	Linear	Quadratic
DMI, ³ kg/d	10.4	10.6	10.4	10.1	0.28	0.64	0.43	0.31
Meal frequency, ³ events/d	8.84	8.01	9.28	9.15	0.34	0.049	0.15	0.31
Duration, ³ min/meal	10.5	12.1	10.9	11.1	0.56	0.23	0.78	0.22
Intermeal duration, ² min	168.8	191.9	161.4	171.7	8.50	0.081	0.57	0.45
Meal size, ³ kg DM/meal	1.27	1.45	1.22	1.21	0.065	0.041	0.17	0.13
Eating rate, ⁴ g DM/min	124.8	123.8	114.9	110.0	4.37	0.055	0.008	0.66

¹Data are reported as least squares means, with animal (8 animals/pen, 2 pens/treatment) as the experimental unit ($n = 16$).

²Pooled standard error of the mean. The statistical model included the main effect of diet, period, and diet $\times$ period.

³Period, $P < 0.001$; diet $\times$ period, $P < 0.001$.

⁴Period, $P < 0.001$; diet $\times$ period, $P = 0.27$.

Figure 2. Eating rate by period averaged over dietary treatments. Diet_{linear}, $P = 0.008$; period, $P < 0.001$; diet $\times$ period, $P = 0.27$. Period means are shown above the histograms. ^{a-c}Period means with different letters differ ($P < 0.05$). Pooled diet $\times$ period SEM = 6.16.

in the diets. Chibisa et al. (2020) concluded that measured peNDF₈ values may not be very useful for formulating feedlot cattle diets to prevent sub-acute ruminal acidosis because concentrations are low and fermentability of carbohydrates is not accounted for.

The major effect of increasing roughage proportion in the diet on feeding behavior was a linear decrease in eating rate (g DM/min) with increasing silage level. Smaller particle size of concentrates enhances the ease of swallowing, and thus concentrates are consumed faster than forages (Beauchemin, 2018). Therefore, the decrease in eating rate reflected the increase in particle size of the TMR due to added roughage. It is important to indicate that the subset of cattle used to measure feeding behavior had similar DMI across roughage levels in contrast to the increase in DMI with greater roughage proportion observed overall in the study. The lack of effect of roughage proportion on DMI of the subset of cattle used for feeding behavior was unexpected, but may have been due to the use of GrowSafe feed bunks rather than the long feed troughs used in the main pens. The GrowSafe feed bunks restrict feeding to one animal

at a time (similar to individually penned animals) compared with the group feeding environment that was provided by the main pens. Bunk space in the main pens (187 cm/animal) was considerably greater than the 22 to 30 cm/animal (Meyer and Bryant, 2017) provided by most commercial feedlots, thus competition at the feed bunk after feed allocation would have been minimal. Thus, there was greater competition at the GrowSafe feed bunks at the time of feeding compared with the main pens, although there were numerous times throughout the day when competition was low yet cattle did not access the GrowSafe feed bunks. Therefore, it is unlikely that access time to feed limited DMI. Feeding diets similar to those used in the present study to individually penned cattle, Chibisa et al. (2020) reported no effect on DMI, confirming the results observed for the subset of cattle in the pens with GrowSafe feed bunks.

A lower eating rate for cattle consuming higher roughage diets would mean that to increase DMI, the cattle would need to increase eating time by increasing meal duration, meal frequency, eating rate, or a combination. If competition is created at the feed bunk due to limited bunk space or

Figure 3. Meal frequency (top) and meal duration (bottom) as affected by barley silage proportion and period. Within panel, period, $P < 0.001$; diet $\times$ period, $P < 0.001$; and diet means with different letters within period differ ($P \leq 0.05$). ns, not significant ($P > 0.05$). Pooled diet $\times$ period SEM = 0.48 (top) and 0.74 (bottom).

infrequent feeding, the cattle may not be able to adjust meal frequency or duration, and therefore eating rate may increase and promote binge-eating, leading to increased prevalence of digestive disorders (Schwartzkopf-Genswein et al., 2003; Meyer and Bryant, 2017). Thus, feeding higher roughage diets may require greater bunk space per animal.

Eating rate of all diets increased as the cattle increased in BW over the study, as indicated by the significant period effect. The other feeding behavior characteristics, including meal frequency, duration of meals, intermeal duration, and meal size also varied with period; however, significant diet $\times$ period interactions indicated that the responses over time were not consistent among the diets, although the dietary differences within period were relatively minor.

Antibiotics are often used by commercial feedlots to prevent digestive disorders and liver abscesses (Reinhardt and Hubbert, 2015; Drouillard, 2018). As routine use of antibiotics in animal feeds is increasing discouraged by regulatory authorities, the study investigated whether increasing dietary forage proportion decreased liver abscesses in cattle fed diets that did not contain tylosin. The incidence of total liver abscesses (scores 2, 3, and 4; 42.7% of livers) in the study was similar to expectations for high grain diets without the use of in-feed tylosin (56.2%; Brown et al.,

1975). Prevalence of total liver abscesses from feedlot cattle in the United States is usually between 10% and 20%, but ranges from 0% to 70% depending on numerous factors (Reinhardt and Hubbert, 2015). Liver abscesses are caused by pathogens (e.g., *Fusobacterium necrophorum* and *Trueperella pyogenes*) that are thought to cross the ruminal or intestinal epithelial barrier when damaged by ruminal acidosis and ruminitis (Nagaraja and Lechtenberg, 2007; Reinhardt and Hubbert, 2015) and consequent changes in pH and osmolality throughout the gastrointestinal tract (Pederzoli et al., 2018). Although ruminal pH was not measured in the present study, Chibisa et al. (2020) reported an increase in minimum (+0.34 units) and mean (+0.34 units) ruminal pH, and concomitant decreases in duration and area of pH below thresholds used to classify ruminal acidosis, with increased barley silage added to diets (i.e., 0% versus 12% of DM). Ruminal pH < 5.5, a threshold used for sub-acute acidosis, occurred for almost 50% of each day in cattle fed 0% silage, and was reduced to 17% of each day for cattle fed diets with 4%, 8%, and 12% silage in the study reported by Chibisa et al. (2020). For ruminal pH < 5.2, a threshold used for acute acidosis, the 3 h/d observed for cattle fed 0% silage was reduced to ≤ 1 h/d for cattle fed 4%, 8%, and 12% silage. Given that increasing the proportion of forage in the diet decreased sub-acute acidosis in

Figure 4. Intermeal interval (top) and meal size (bottom) as affected by barley silage proportion and period. Within panel, period, $P < 0.001$; diet $\times$ period, $P < 0.001$; and diet means with different letters within period differ ($P \leq 0.05$). ns, not significant ($P > 0.05$). Pooled diet $\times$ period SEM = 17.43 (top) and 0.102 (bottom).

the study by Chibisa et al. (2020), liver abscesses were expected to decrease in the present study, but that was not the case. It is possible that the reduction in acidosis in the present study was not as great as in the study by Chibisa et al. (2020) because DMI increased with increasing proportion of silage in the present study. Increased DMI would have increased the amount of OM matter fermented in the rumen resulting in short-chain fatty acid production, which negatively affects ruminal pH (Castillo-Lopez et al., 2014). There is also some evidence to suggest that ruminal pH is higher in pen-fed cattle compared with individually penned cattle (Castillo-Lopez et al., 2014).

The small linear decrease in dressing percentage with increasing barley silage proportion was likely due to a small increase in rumen size and greater weight of the digestive tract with higher forage diets (Price et al., 1978; Owens and Gardner, 2000). The linear tendency for increased lean yield with increased silage proportion was attributed to the small increase in lean yield for 12% silage, and was due to a nonsignificant increase in longissimus muscle area and concomitant nonsignificant decrease in fat cover. The slight decrease in fat cover is consistent with the observation that higher concentrate diets promote greater backfat thickness due to the increase in propionate,

the major glucose precursor (Smith and Crouse, 1984). Chibisa et al. (2020) reported an increase in acetate:propionate ratio with increased roughage inclusion, supporting that less propionate production likely occurred on the 12% silage diet. Koenig and Beauchemin (2011) increased the barley silage proportion in barley-based feedlot diets from 3% to 15% of DM, in increments of 3% of DM, and observed that the highest silage proportion decreased grade fat and increased lean yield. Therefore, the tendencies for very minor changes in carcass traits with relatively small increases in roughage proportion observed in the present study are consistent with expectations, and likely not a major impediment to feeding higher roughage finishing diets (up to 12% of dietary DM).

Conclusions

Increasing barley silage proportion in a barley-based feedlot finishing diet from 0% to 4%, 8%, and 12% of DM to decrease the occurrence of ruminal acidosis decreased feed conversion efficiency, without affecting rate of gain of cattle. Increased roughage proportion slowed eating rate, had no effect on prevalence of liver abscesses, and had only minor effects on

Table 5. Liver abscesses and carcass traits of beef feedlot steers fed finishing diets with increasing proportions of barley silage (n = 5 pens/treatment)

	Barley silage, % of dietary DM					P-value ²		
Item ¹	0	4	8	12	SEM	Diet	Linear	Quadratic
Liver abscesses, ^{2,3} % of cattle (number of cattle)								
None and mild (0 and 1)	58.3 (14)	53.6 (12)	62.5 (15)	55.0 (12)	–	0.92	–	–
Moderate (2 and 3)	41.7 (10)	42.3 (10)	33.3 (8)	45.0 (9)	–	0.96	–	–
Severe (3+)	0 (0)	4.2 (1)	4.2 (1)	0 (0)	–	1.00	–	–
Total (2, 3, and 3+)	41.7 (10)	46.4 (11)	37.5 (9)	45.0 (9)	–	0.96	–	–
Carcass traits								
Hot carcass weight, kg	371	369	368	368	2.4	0.55	0.26	0.41
Dressing percentage, %	60.7	60.1	60.2	60.0	0.22	0.15	0.07	0.47
Longissimus thoracis area, cm ²	83.5	82.0	84.7	86.8	1.79	0.36	0.16	0.35
Average fat, mm	18.6	18.4	19.1	17.0	0.63	0.17	0.19	0.14
Grade fat, mm	17.1	17.0	17.8	15.4	0.68	0.16	0.20	0.12
Marbling score ⁴	24.3	28.1	33.5	25.3	4.28	0.40	0.64	0.16
Lean meat yield, ⁵ %	51.8	51.6	51.7	53.6	0.60	0.13	0.07	0.13
Quality grade, ³ %								
AAA	95.0	92.3	85.0	97.4	–	0.96	–	–
AA	5	7.7	12.5	2.6	–	0.36	–	–
Prime	0	0	2.5	0	–	–	–	–

¹Data are reported as least squares means with pen as the experimental unit.

²Liver abscess scores were obtained for three pens of cattle on each dietary treatment.

³Chi-square analysis was used for liver abscess score and quality grade.

⁴Marbling score of 60.0 to 89.9 = modest, 50.0 to 59.9 = small, 40.0 to 49.9 = slight, and 30.0 to 39.9 = traces.

⁵Lean meat yield, % = 57.96 – (0.027 × hot carcass weight, kg) + (0.202 × longissimus thoracis area, cm²) – (0.703 × average fat cover, mm).

carcass characteristics. The results indicate a trade-off between improving feed conversion efficiency to decrease feeding costs and decreasing the prevalence of ruminal acidosis to improve animal health and welfare, when considering roughage inclusion rate. Alternatives to increasing roughage proportion throughout the finishing period to attenuate ruminal acidosis need further examination, including effects of management (e.g., fluctuating roughage proportion during the finishing period, feeding frequency, particle size, undigestible fiber content) and use of feed additives (e.g., direct-fed microbials), and environmental factors such as bunk space and pen conditions. Increased costs of greater roughage inclusion or other approaches to preventing ruminal acidosis need to be accessed relative to decreased costs associated with morbidity and mortality of cattle due to digestive disorders.

Supplementary Data

Supplementary data are available at *Journal of Animal Science* online.

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Conflict of interest statement

The authors declare no real or perceived conflicts of interest.

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