



Impacts of including sprouted barley in the ration on feedlot performance and carcass traits of Angus steers

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ABSTRACT

Controlled-environment systems that sprout cereal grains may help address challenges like drought and land loss, yet their application in finishing beef diets remains unstudied. This study utilized Angus steers stratified by weight ($385 \text{ kg} \pm 10.3$) into two groups ($n = 30/\text{group}$). The control (CON) diet was a traditional finishing ration for the Intermountain West, while the other had 20 % dry matter (DM) sprouted barley (SB). Animals were fed for 128 d in pens with Vytelle units to measure intake and feeding behavior. Collection of performance metrics were assessed on d 0, 30, 60, 90, and 128, while all carcass traits were collected on d 128 at harvest. Using the observed production data and historical prices, economic metrics were calculated. Steers fed SB had decreased ($P < 0.0001$) dry matter intake (DMI) over the study. There was a diet $\times$ day ($P = 0.004$) observed for G:F. Total ruminal volatile fatty acid (mM; VFA) was impacted by diet $\times$ day ($P = 0.007$), and steers fed SB had an increased ($P = 0.03$) USDAYG. Steers receiving CON had decreased ($P < 0.0001$), total feed costs (TFC), cost of gain (COG) ($P = 0.002$), feed conversion to hot carcass weight (FC/kg HCW; $P < 0.0001$), and feed conversion to marbling score (FC/MS; $P = 0.002$), while CON also had increased net return (NR; $P = 0.002$) compared to SB. When sprouted barley is included in the diets of finishing beef cattle, it maintains growth performance and carcass quality, although its economic viability remains uncertain.

1. Introduction

The demand for agricultural resources is poised to escalate significantly by 2050, propelled by the expanding global population (Alexandratos and Bruinsma, 2012). Beef producers face hurdles in delivering consistent feedstuffs with reliable nutrient content due

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Table 1

Diet composition and nutrient analysis of diets fed to growing steers.

	CON ^a , %	20 % SB ^a , %
Step 1:		
Diet Composition, % DM		
Alfalfa	24.80	33.00
Rolled Barley	43.40	45.10
Sprouted Barley	0	20.80
Corn Silage	30.70	0
Mineral	1.10	1.10
Nutrient Composition^b, % DM		
DM ^c	59.60	37.03
CP ^d	13.25	16.80
NE _m ^e , Mcal/kg	0.35	0.35
NE _g ^f , Mcal/kg	0.23	0.22
NDF ^g	30.15	28.03
ADF ^h	20.55	20.20
Ash	7.25	7.83
Step 2:		
Alfalfa	18.80	25.4
Rolled Barley	54.30	52.5
Sprouted Barley	0	20.9
Corn Silage	25.80	0
Mineral	1.10	1.1
Nutrient Composition^b, % DM		
DM	61.55	36.93
CP	12.80	15.33
NE _m , Mcal/kg	0.38	0.39
NE _g , Mcal/kg	0.24	0.25
NDF	28.00	24.17
ADF	18.85	17.37
Ash	6.91	6.78
Step 3:		
Alfalfa	12.4	14.5
Rolled Barley	66.5	62.3
Sprouted Barley	0	20.9
Corn Silage	18.8	0
Mineral	2.3	2.3
Nutrient Composition^b, % DM		
DM	68.15	36.47
CP	12.85	15.23
NE _m , Mcal/kg	0.38	0.39
NE _g , Mcal/kg	0.25	0.25
NDF	25.95	21.90
ADF	16.15	14.53
Ash	6.50	6.13
Step 4:		
Alfalfa	8.5	8.5
Rolled Barley	80.5	67.9
Sprouted Barley	0	21.3
Corn Silage	8.7	0
Mineral	2.3	2.3
Nutrient Composition^b, % DM		
DM	78.3	34.97
CP	13.33	15.77
NE _m , Mcal/kg	0.40	0.40
NE _g , Mcal/kg	0.27	0.27
NDF	23.40	21.90
ADF	14.53	14.07
Ash	5.45	5.91

^a CON diet consisted of a typical ration for the Intermountain West with 80 % rolled barley concentrate; SB diet was similar to CON, but corn silage and some rolled barley was replaced with sprouted barley at 20 % dry matter

^b Nutritional composition of diets from analytical laboratory

^c DM: dry matter

^d CP: crude protein

^e NE_m, Mcal: net energy maintenance per kilogram of feed

^f NE_g, Mcal: net energy gain per kilogram of feed

^g NDF:neutral detergent fiber

^h ADF: acid detergent fiber.

to erratic weather patterns, notably droughts. The western United States endured drought conditions 40 % of the time between 2000 and 2019, with a historically severe drought occurring within that period (Leeper et al., 2022). Additionally, the rapid urbanization of agricultural lands compounds the challenge of maintaining high-quality feed production, as evidenced by the loss of 1.3 million acres of farmland from 2020 to 2021 (USDA, 2023). These challenges highlight the need for innovative and sustainable agricultural approaches.

Among emerging technologies, vertical farming systems (VFS) stand out as a potential option, though their influence on carcass quality, feedlot performance, and economic efficiency has not been clearly established. By controlling certain factors in VFS such as water, temperature, and light, sprouts can reach 12–16 centimeters in height within six days, offering a potential consistent feed source for livestock. With sprouted barley containing approximately 12.6 % dry matter (DM), 17.8 % crude protein, and 0.43 Mcal NE_m/kg on a DM basis, VFS hold the potential to provide animals with fresh feed regardless of weather conditions (Crump et al., 2024). Moreover, they enable year-round production of high-quality feed, mitigating the impact of seasonal fluctuations, drought, and urbanization. These systems can potentially impact larger feed sustainability goals by providing a climate resilient feed source and decreasing land usage. This approach offers an alternative option to traditional farming and diminishes excessive needs for land and water if barley seeds can be procured. This novel feed may alter ruminal function and overall feed efficiency, which makes its evaluation in finishing cattle diets necessary. Limited research on feeding sprouted barley exists and is limited to dairy cattle, sheep, ruminal fermentation dynamics, and alternative sprouting methods (Reed et al., 2005; Zang et al., 2024; Crump et al., 2025; Salas-Solis et al., 2026). These studies have reported that sprouted barley can replace some conventional feed without mixed impacts on animal performance, while potentially improving ruminal nutrient degradability and fermentation characteristics. The extent to which these outcomes translate to feedlot steers, specifically performance, carcass development, and economic efficiency, have not been established.

Given increasing emphasis on sustainability and efficiency in beef production, it is important to explore alternative feed options, such as sprouted barley. While VFS can show potential in improving feed production, their impact on carcass quality, feedlot production parameters, and economic efficiency is still unclear. The objective of this study was to investigate whether incorporating sprouted barley into the diets of finishing Angus steers impacts feedlot performance, carcass characteristic, or economic metrics. It was hypothesized that the inclusion of sprouted barley in finishing Angus steer diets would not affect growth performance, but would alter patterns of carcass fat deposition.

2. Methods

2.1. Animal care & diets

The study was conducted at Utah State University South Farm located in Logan, Utah from January–May in 2023. Care and use of all animals utilized in this study were approved by IACUC #13709. All steers were given electronic (EID) tags and kept in covered four pens outfitted with Vytelle feeding bunks (Vytelle, Kansas City, MO, USA). Sixty finishing steers, approximately one year old, were stratified by BW ($384 \text{ kg} \pm 4.7$) into two different diet groups ($n = 30/\text{group}$) with 15 per pen. The first diet (CON) consisted of a typical finishing ration for the Intermountain West consisting of 80 % concentrate, with a series of three step-up rations being administered each for seven d of the study at 43 %, 54 %, and 66 % concentrate (Table 1). The second ration (SB) contained 20 % sprouted barley (DM basis) which replaced all corn silage, and some barley grain compared to CON, which also included similar step-up rations (Table 1). All diets were formulated to meet nutrient requirements. Sprouted barley was included at 20 % (DM); this inclusion level was chosen based on unpublished, preliminary research, and recommendations from industry professionals to align with current industry practices. Silage and a portion of the grain were replaced instead of alfalfa because of their compositional similarity to sprouted barley, with the additional objective of reducing concentrate in the ration. Since a single inclusion rate was evaluated, the present study does not determine potential dose–response effects. Both rations were combined in a vertical mixer (Shuler model 5020, Griswold, IA, USA) for approximately 15 min and then fed *ad libitum* using Vytelle units. Samples of the feed were gathered daily while the first three steps (seven d each) were being fed. Feed samples were then collected once per week and combined every 30 d for the final ration and sent for commercial analysis by Cumberland Valley Analytical (Waynesboro, PA, USA) using wet chemistry techniques. In brief, wet chemistry analysis uses chemical extraction, digestion, and reaction-based lab techniques to measure nutrients in feed-stuffs and rations (Van Soest et al., 1991). Diets were fed for a total of 128 d. On d 0, 30, 60, 90, and 128 BW, ruminal fluid, jugular blood, ribeye area (REA), and 12th rib fat thickness (REFT) ultrasound were taken. When animals reached an industry standard of 12 mm of REFT with a BW of $595.88 \text{ kg} \pm 17.36$ cattle were harvested.

2.2. Growing barley sprouts

Barley sprouts were cultivated on-site using a VFS under controlled conditions (Renaissance Ag, Vineyard, UT, USA). The VFS measured 5.8 m in length, 3.1 m in width, and 2.8 m in height, and was equipped with dual climate control systems to ensure optimal growth conditions. Within the unit, there were seven rows, each containing three plastic trays. The trays, measuring 79.4 cm in length, 88.9 cm in width, and 6.35 cm in height, were divided into three sections, providing a total growable area of 2093.5 square cm per tray for sprouting. Golden eye variety barley was utilized for this study which is a spring six row barley seed. Seeds for this study were sourced from Western Seeds (Tremonton, Utah, USA) through the Intermountain Farmers Association (Salt Lake City, Utah, USA). Dry seeds were measured daily with 4.6 kg of seeds per tray (1.5 kg per section) and spread evenly across the surface of the tray. The internal temperature of the system was regulated at 21°C, and watering occurred every hour for 15 sec through 18 sprinklers per row. To stimulate chlorophyll activation, fluorescent lights were positioned at the front end of the unit during the final three d of sprouting.

After six d, the sprouts were harvested and incorporated into a total mixed ration (TMR) in a vertical feed mixer. Trays were thoroughly cleaned and reseeded following each harvest cycle.

2.3. Rumen fluid collection and analysis

Rumen fluid samples were collected by veterinary personnel using an esophageal tube. To ensure the absence of saliva, approximately 20 ml of the first rumen fluid pulled was discarded. The pH was promptly measured using a portable pH meter (Oakton pHTestr, Vernon Hills, IL, USA). Rumen fluid was then filtered through a fine stainless-steel mesh strainer (approximately 1–2 mm mesh) to remove large particulate material. To stabilize, 1000 μ L was added to 1.5 ml microcentrifuge tube containing 200 μ L of 25 % metaphosphoric acid before storage at -80°C . When analysis was ready to be performed, samples were thawed overnight at 4°C . After samples were thawed, they were centrifuged $13.8 \times g$ at 20°C for two min. Subsequently, 1.2 ml of supernatant was transferred to another microcentrifuge tube, where 200 μ L of 0.85 % crotonic acid was added and vortexed. After a 30 min incubation at room temperature, tubes were centrifuged $13.8 \times g$ at 20°C for 10 min, and the resulting supernatant was aliquoted into autosampler vials (Part number:5182–0716, Agilent, Santa Clara, CA, USA). Calibration was executed at eight points using a mix of seven acids (acetic, propionic, and butyric acids at 10–0.08 mM, and isobutyric, valeric, isovaleric, and caproic acids at 5–0.04 mM) before loading into a gas chromatograph (Agilent 6890) equipped with a ZB-FFAP column (30 M $\times$ 0.52 mm ID $\times$ 1.0 μ m film thickness; Phenomenex, Torrance, CA, USA) and a flame ionization detector. A 50:1 split rate was used, with a 200°C injector temperature. Peak identification was based on retention time, and regression equations were applied to convert peak area ratios into volatile acid concentrations. All VFA concentrations are reported in millimolar concentrations.

2.4. Ultrasound of ribeye area and 12th rib fat thickness

An ultrasound machine (ExaGo, Universal Imaging, Bedford Hills, NY, USA) was used to measure REA and REFT. Canola oil was used as an acoustic couplant for the ultrasound probe that was placed between the 12th and 13th rib. ImageJ software (National Institutes of Health and the Laboratory for Optical and Computational Instrumentation, University of Wisconsin) was utilized to measure REA (cm^2) and REFT (mm).

2.5. Blood collection and serum metabolite profiling

Blood was drawn via jugular puncture and subsequently centrifuged at 1200 rpm for 15 min to separate plasma. Plasma was aliquoted into 1.5 ml tubes and frozen at -20°C until subsequent analysis of plasma urea nitrogen (PUN). A colorimetric assay kit was used to determine PUN concentration (Invitrogen, Urea Nitrogen Colorimetric Detection Kit; ThermoFischer Scientific) following the manufacturer's protocol and as previously described (Hadfield et al., 2021; Reichhardt et al., 2021a).

2.6. Feed intake & behavior

Feed intake and feeding behavior was measured with Vytelle technology and analyzed as previously described (McGee et al., 2014; Reichhardt et al., 2021b). In brief, feeding behavior data was analyzed by two main categorical traits: bunk visits (BV) and feed bouts (FB). Bunk visits are recorded when a single EID is read when an animal enters the bunk, regardless if any feed was consumed or not. Feed bouts are recorded when a single EID is read when an animal enters the bunk and a minimum of 10 g of feed is consumed. Based on the number of BV the average duration of each BV was analyzed (BVDUR). In relation to the FB data, the duration of each FB was also calculated (FBDUR). Dry matter intake (DMI) was calculated for each of the series of step up rations (d 10, 17, 24, 30) then for every 30 d after. The gain to feed ratio (G:F) was calculated by dividing total weight gained by kilograms of dry matter eaten. This measure was calculated every 30 d with d 30 being from d 1–30, d 60 being d 31–60 etc. Nutrient intake was calculated by multiplying the DMI for the animal by the percentage of each nutrient found in the diet nutrient analysis with same intervals being calculated as G:F.

2.7. Carcass characteristics

At the end of the study animals were commercially harvested (JBS, Hyrum, Utah, USA) where hot carcass weight (HCW), yield grade (YG), marbling score (MS), and REA data were obtained. Livers were scored using a modified Elanco Liver Check System (Elanco, Greenfield, IN, USA). Livers with no trauma were given a score of 0; livers with two or less abscesses that were smaller than two cm in diameter were given a 1; livers with greater than two but less than five abscesses larger than two cm but smaller than four cm in diameter were given a 2; livers with five or more abscesses greater than two cm in diameter or at least one abscess greater than four cm in diameter were given a 3; livers with two or more large adhesions greater than four cm in diameter, or if abscesses were adhered to other organs or the diaphragm were given a 4; livers with ruptured abscesses that were condemned were given a 5. Each liver was assessed and given a score by two individual clinical veterinarians at the time of harvest on the offal table, after which each of these scores were then averaged. Carcasses were then hung for 24 h to allow meat to chill. After the 24-h period carcasses were cut between the 12th and 13th rib and allowed 15 min for REA to bloom. The REA was then measured and given a MS according to USDA camera grading standards. All traits such as HCW, MS, REA, DP, and USDAYG were all measured according to industry standards. Carcass adjusted final live weight was calculated by assuming an industry standard 63.5 % dress percentage (Foraker et al., 2022). The HCW

was then divided by 0.635 resulting in a carcass adjusted final weight. Carcass adjusted final weights mitigate variations in rumen fill, hide, internal organ, and water weight and focus strictly on usable product. Adjusted ADG and G:F were then calculated using the carcass adjusted final weight.

2.8. Economic analysis

Post-harvest, the total feed costs (TFC), feedlot cost of gain (COG), feed cost to hot carcass weight (FC:HCW), feed cost to marbling score (FC:MS), and net return (NR) over feed costs were calculated for economic comparison across treatments. For each steer, the TFC was determined as the summation of the product of total feed (kg. as-fed) for each ration and the weighted cost (\$/kg) of each feed component, with the weights corresponding to the as-fed percentage of each component in the total ration. National historical average prices over five years (2019–2023) (USDA-NASS, 2024b) were used for all feed components except for minerals and SB. Due to limited historical data, the cost of mineral was based on actual expenses during the feeding trial. The cost of SB was estimated per kg as-fed, factoring in costs for barley seed input, water, electricity, labor, and depreciation as detailed in Table 2. Straight-line depreciation was applied with an assumed 20-year useful life and a 10 % salvage value. The VFS was assumed to operate at full average capacity. Deviations from full capacity may occur due to specific feed requirements of an operation or maintenance downtime which would increase the assumed sprout production costs. These considerations should be made on a case-by-case basis.

The TFC was divided by total gain (kg.), hot carcass weight (kg.), and marbling score to derive COG, FC:HCW, and FC:MS, respectively. The NR over feed costs was calculated as the expected revenue minus TFC and the initial feeder steer cost. Expected revenue and feeder steer costs were based on dressed and beginning weights, using five-year (2019–2023) historical 5-market-average auction prices (LMIC, 2024a). The final dressed price for each animal was calculated using grid pricing to account for carcass weight, quality grade, and yield grade variation. The grid values were taken from the USDA, AMS report (USDA-AMS, 2024). Total feed cost analysis is straightforward—higher relative TFC indicates increased feeding expenses. Cost of gain in this study represents the marginal change in feed cost to achieve one additional kilogram of weight gain. The FC:HCW reflects the average cost in dollars associated with an increase in hot carcass weight by one kilogram, while FC:MS indicates the average cost in dollars associated with an increase in the marbling score by one unit. Net return accounts for feed costs, assuming fixed costs remain constant across treatments, and provides an average profitability measure for comparison across treatments.

Table 2
Sprouted barley production assumptions and costs.

Assumption	Value
Cost of Production System	\$30,000
Useful Life (years)	20
Salvage Value (10 %)	\$3000
Depreciable value	\$27,000
Yearly Depreciation	\$1350
Daily Depreciation Expense	\$3.70
Feed Produced (kgs./day)	523.6
Input Seed Required (kgs./day)	97.5
Input Seed Price (\$/kg.) ^c	\$0.29
Input Seed Expense (\$/day)	\$28.67
Input Seed Cleaning Rate (\$/kg.)	\$0.07
Input Seed Cleaning Expense (\$/day)	\$6.45
Water Rate (\$/liter)	\$0.0009
Water Consumption (liters/day)	667
Water Expense (\$/day) ^d	\$0.63
Labor Rate (\$/hour) ^e	\$18.41
Labor Required (hrs./day)	0.5
Labor Expense (\$/day)	\$9.20
Power Usage Rate (kwh/kg. of sprouts produced)	0.043
Power Consumption (kwh/day)	22.6
Power Rate (\$/kwh) ^f	\$0.16
Power Expense (\$/day)	\$3.71
Total Operating Costs (\$/day)^a	\$52.36
Total Operating Costs (\$/kg.)^b	\$0.10

^a Equal to the summation of daily sprout production expenses highlighted in grey within a column

^b Equal to Total Operating Costs (\$/day) divided by Feed Produced (kgs./day)

^c Five-year historical average price of malting barley (LMIC, 2024)

^d Inflation adjusted rate from Utah Division of Water Resources (UDWR, 2010)

^e Five-year inflation adjusted average labor rate: Labor, Hired - Wage Rate, Measured in \$/hour (USDA-NASS, 2024)

^f Five-year inflation adjusted electricity rate (BLS, 2024b).

2.9. Statistical analysis

The MIXED procedure of SAS (SAS v 9.4, Cary, NC, USA) was used to analyze all data, with a mixed-effect model in which diet, day and their interaction as fixed effect and source of cattle and pen as random effects. A variance components covariance structure was selected because residual diagnostics indicated that assumptions of normality and variance homogeneity were adequately met under this model. Animals were randomly assigned to each treatment and individual animal served as the experimental unit in this model. All model estimates are presented as the least squares (LS) means $\pm$ SEM. Analyzed outcomes included steer BW, feeding behavior, ruminal pH, VFA profile, PUN, REA, REFT, ADG, and G:F. Carcass characteristics, adjusted carcass metrics and economic metrics were analyzed using the MIXED procedure of SAS. Significance level is specified at 0.05 level, while tendencies were discussed at 0.10 level. When significant diet differences were detected, LS means were separated using Tukey-Kramer adjustments. When interactions were found to be significant, the main effects of diet and day of that variable were not discussed individually.

3. Results

3.1. Animal performance

Body weight (BW) was not impacted by diet $\times$ day ($P = 0.51$) or diet ($P = 0.62$) but day did show that BW increased ($P < 0.0001$) over time in all animals, regardless of treatment (Fig. 1A). DMI was not affected by diet $\times$ day ($P = 0.08$). However, both diet ($P < 0.001$), and day ($P < 0.001$) altered DMI. Steers fed SB had a lower ($P \leq 0.004$) DMI throughout the trial (Fig. 1B). Dry matter intake (DMI) of all steers, regardless of treatment, decreased ($P < 0.0001$) at d 17 then increased ($P < 0.0001$) at d 24 and again at d 60 ($P = 0.02$) where it remained consistent until d 90, where it then decreased ($P < 0.0001$; Fig. 1B) at d 128. Steer ADG was impacted by diet $\times$ day ($P = 0.01$), demonstrated by CON steers had an increased ADG later in the trial, but no differences ($P \geq 0.37$) were observed between the specific time points assessed (Fig. 1C). The G:F was altered by diet $\times$ day ($P = 0.003$) such that on d 30 and 60, SB had increased ($P \leq 0.03$) G:F when compared to CON. However, on d 90 and 128, there were no differences ($P \geq 0.49$) between

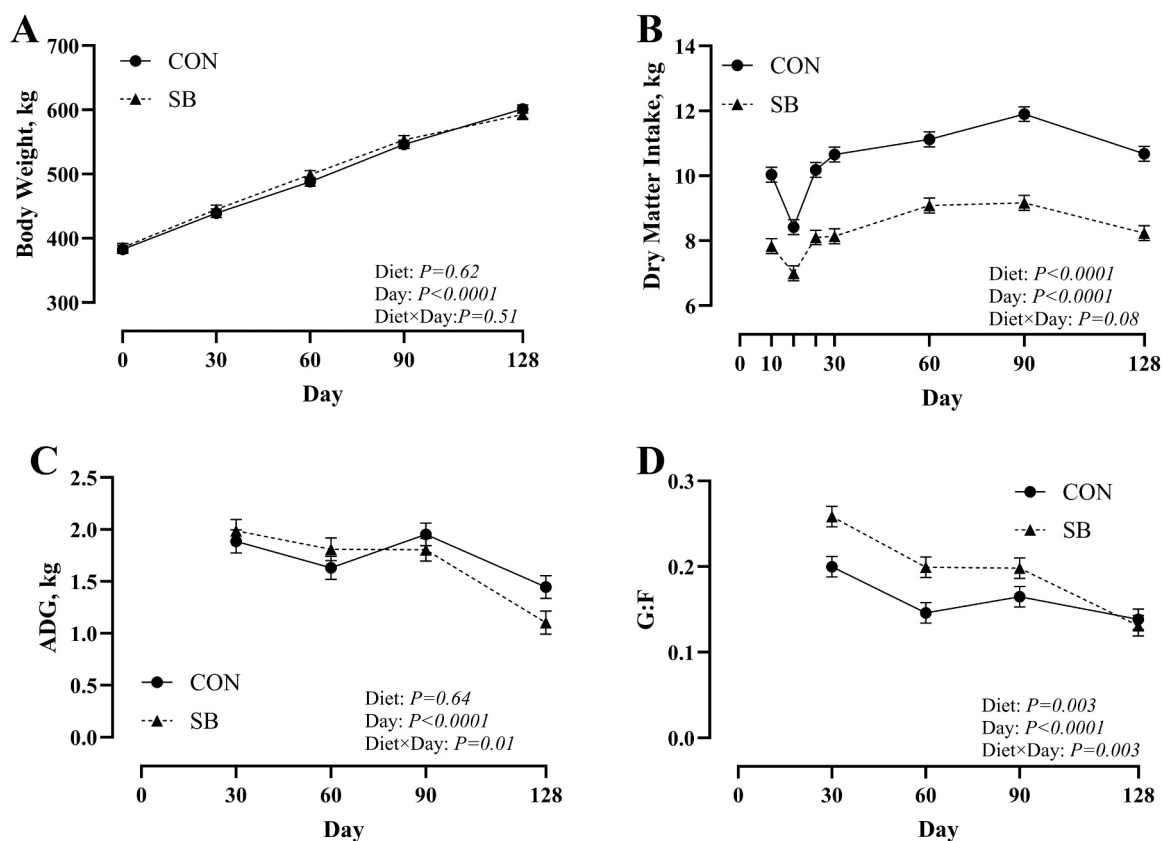


Fig. 1. Steer performance data (body weight (BW);A), dry matter intake (DMI);B), average daily gain (ADG);C), and feed efficiency (G:F);D) was collected as described in the materials and methods. Sixty Steers were used and were fed either a conventional finishing ration for the Intermountain West (CON; $n = 30$) or the same diet but corn silage and some barley grain was replaced for sprouted barley (SB; $n = 30$) for a feeding period of 128 d. All data were analyzed using the MIXED procedure of SAS with day as a repeated measure to determine the main effects of diet $\times$ day, diet, and day.

diets (Fig. 1D).

Additionally, average values for starting and final BW, DMI, ADG and G:F, along with carcass adjusted values were analyzed. Start weight, final weight, and HCW were not impacted by diet ($P \geq 0.65$; Table 3). However, cattle fed SB had decreased ($P < 0.0001$) DMI (Table 3). Further, cattle fed SB had an increased ($P = 0.006$) G:F compared to CON cattle (Table 3). Carcass adjusted final weight and carcass adjusted ADG were not impacted by diet ($P \geq 0.61$; Table 3). Interestingly, carcass adjusted G:F was increased ($P < 0.0001$) in SB cattle (Table 3).

3.2. Feed nutrient intake

Crude protein (CP) intake was not altered by diet $\times$ day ($P = 0.13$) but diet ($P < 0.0001$) and day ($P = 0.007$) each had an effect. Steers receiving CON had increased ($P < 0.0001$) CP intake (Fig. 2A). A diet $\times$ day ($P = 0.02$) effect was noted for NE_m /day which can be explained by CON having increased NE_m /day at each timepoint, but a slight decrease was observed early in the trial ($P \leq 0.04$; Fig. 2B). Similarly, there was a diet $\times$ day ($P = 0.01$) interaction seen in NE_g /day, which follows a similar pattern to for NE_m /day (Fig. 2C). Both NDF and ADF intake were impacted by diet $\times$ day ($P \geq 0.21$), but there was an effect of both diet ($P < 0.0001$) and day ($P < 0.0001$). Steers receiving CON had increased ($P < 0.0001$) intake of both NDF and ADF throughout the trial (Fig. 2D, E).

3.3. Plasma urea nitrogen

Plasma urea nitrogen was unaffected by diet $\times$ day ($P = 0.75$) and diet ($P = 0.14$), but there was an effect of day ($P = 0.0007$); PUN did not change ($P = 0.22$) from d 0–60 but decreased ($P = 0.0004$) by d 128 (Fig. 3).

3.4. Feeding behavior

It was determined that neither FB nor BV were altered by diet $\times$ day ($P \geq 0.66$) or diet ($P \geq 0.91$), but there was an effect of time ($P < 0.0001$). Both FB and BV decreased ($P < 0.0001$) for both diets over the 128 d study (Fig. 4). Further, FBDUR and BVDUR were not changed by diet $\times$ day ($P \geq 0.36$), but were both impacted by diet ($P < 0.0001$) and day ($P < 0.0001$). Steers receiving CON had increased ($P < 0.0001$) FBDUR and BVDUR (Fig. 4). For all treatments, FBDUR and BVDUR decreased ($P < 0.0001$) over the course of the study.

Table 3
Feedlot performance and carcass traits.

	CON ^a	SB ^b	SEM	P-Value
Feedlot performance				
Steers (n)	30	30		
Start Wt, kg	381.62	384.58	14.515	0.65
Final Wt, kg	600.13	591.63	20.291	0.99
DMI ^c , kg	11.27	8.48	0.315	< 0.0001 [†]
ADG ^d , kg	1.69	1.60	0.220	0.54
G:F ^e	0.15	0.19	0.011	0.006 [†]
Adj Final Wt ^f , kg	563.34	569.15	17.829	0.61
Adj ADG ^g , kg	1.41	1.44	0.061	0.79
Adj G:F ^h	0.13	0.17	0.007	< 0.0001 [†]
Carcass traits				
HCW ⁱ , kg	358.81	359.50	11.339	0.91
Liver Score	0.73	0.77	0.272	0.90
Dressing %	59.85	60.81	1.253	0.59
USDAYG ^j	2.32	2.82	0.361	0.03 [†]
Ribeye Area, cm ²	82.81	79.78	2.949	0.16
Marbling Score	427.03	450.16	16.394	0.32

^a CON: Diet consisted of a typical ration for the Intermountain West, an 80 % rolled barley concentrate

^b SB: Diet consisted of the same diet as control but corn silage and some rolled barley was replaced with sprouted barley at 20 % dry matter inclusion

^c DMI: Dry matter intake

^d ADG: Average daily gain

^e G:F: Gain to feed ratio

^f Adjusted final weight, calculated by assuming an industry standard 63.5 % dressing percent and diving HCW by 0.635 to assume an adjusted final weight

^g Adjusted ADG: average daily gain calculated based on the carcass adjusted final weight

^h Adjusted G:F: gain to feed ratio calculated on the carcass adjusted ADG

ⁱ HCW: Hot carcass weight

^j USDAYG: United States Department of Agriculture yield grade.

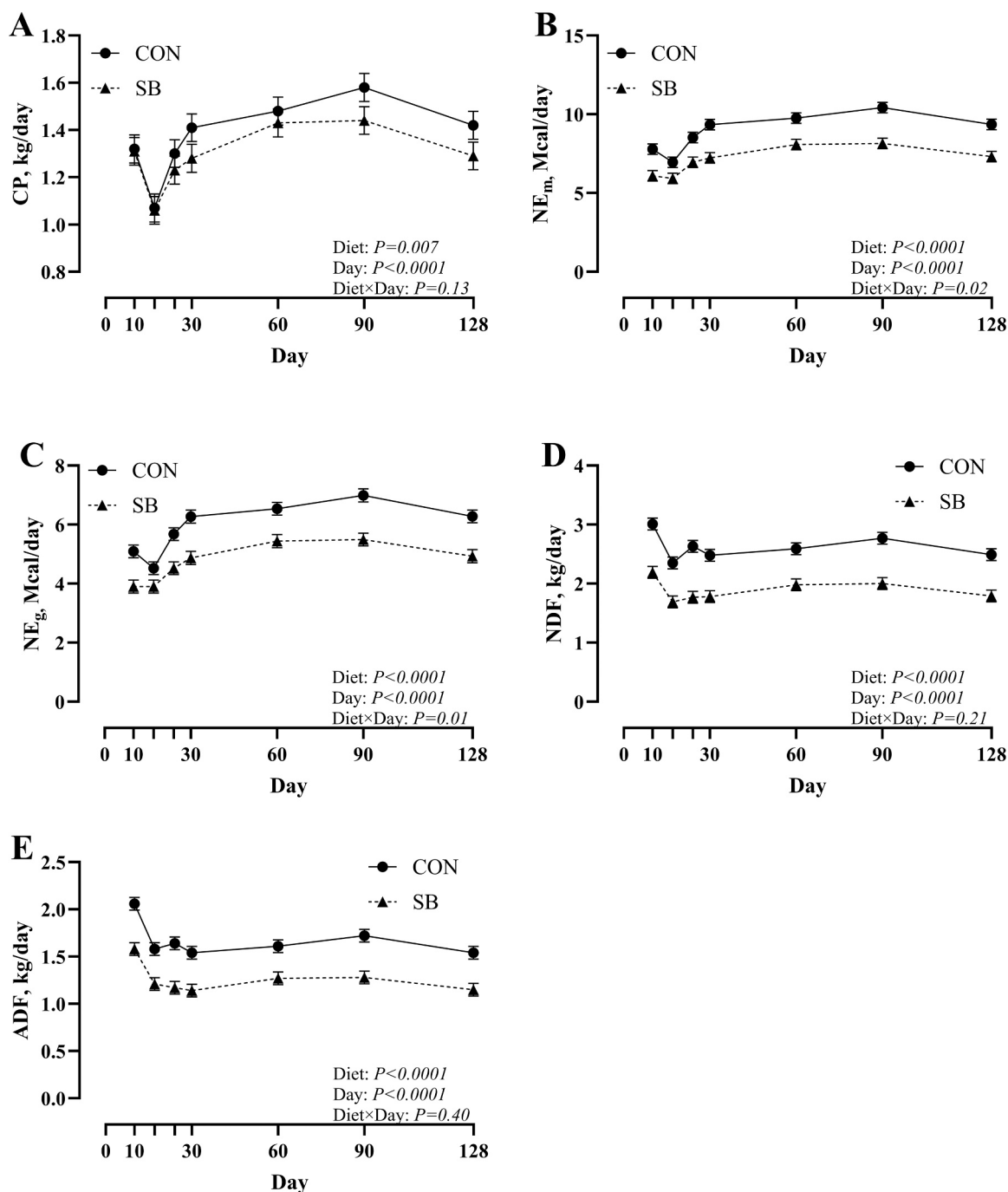


Fig. 2. Steer nutrient intake (Crude protein (CP);A), net energy maintenance per day (NE_m, Mcal/day;B), net energy gain per day (NE_g, Mcal/day;C), neutral detergent fiber (NDF;D) acid detergent fiber (ADF;E), was collected as described in the materials and methods. Sixty Steers were used and were fed either a conventional finishing ration for the Intermountain West (CON; n = 30) or the same diet but corn silage and some barley grain was replaced for sprouted barley (SB; n = 30) for a feeding period of 128 d. All data were analyzed using the MIXED procedure of SAS with day as a repeated measure to determine the main effects of diet×day, diet, and day.

3.5. pH and VFA concentrations in ruminal fluid

Ruminal pH was impacted by diet×day ($P = 0.0007$) which can be described by CON decreasing ($P = 0.18$) from d 0–30, then remaining consistent ($P \geq 0.99$) until d 128; while SB increased ($P = 0.11$) from d 0–30, decreased ($P = 0.07$) to d 60, increased ($P = 0.56$) at d 90, then decreased ($P = 0.22$) again at d 128 (Fig. 5). Additionally, total VFA concentration was affected by diet×day

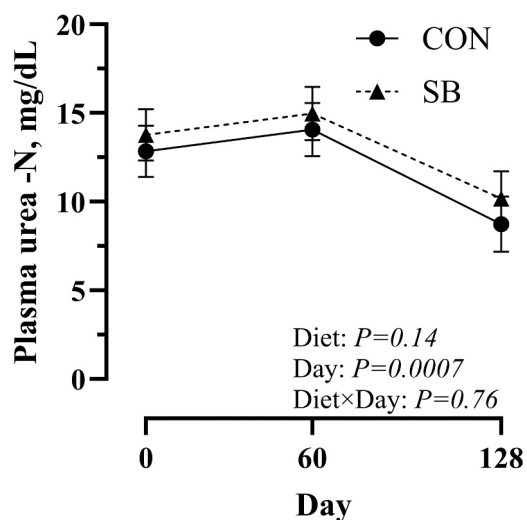


Fig. 3. Steer plasma urea nitrogen (PUN) was collected as described in the materials and methods. Sixty Steers were used and were fed either a conventional finishing ration for the Intermountain West (CON; $n = 30$) or the same diet but corn silage and some barley grain was replaced for sprouted barley (SB; $n = 30$) for a feeding period of 128 d. All data were analyzed using the MIXED procedure of SAS with day as a repeated measure to determine the main effects of diet $\times$ day, diet, and day.

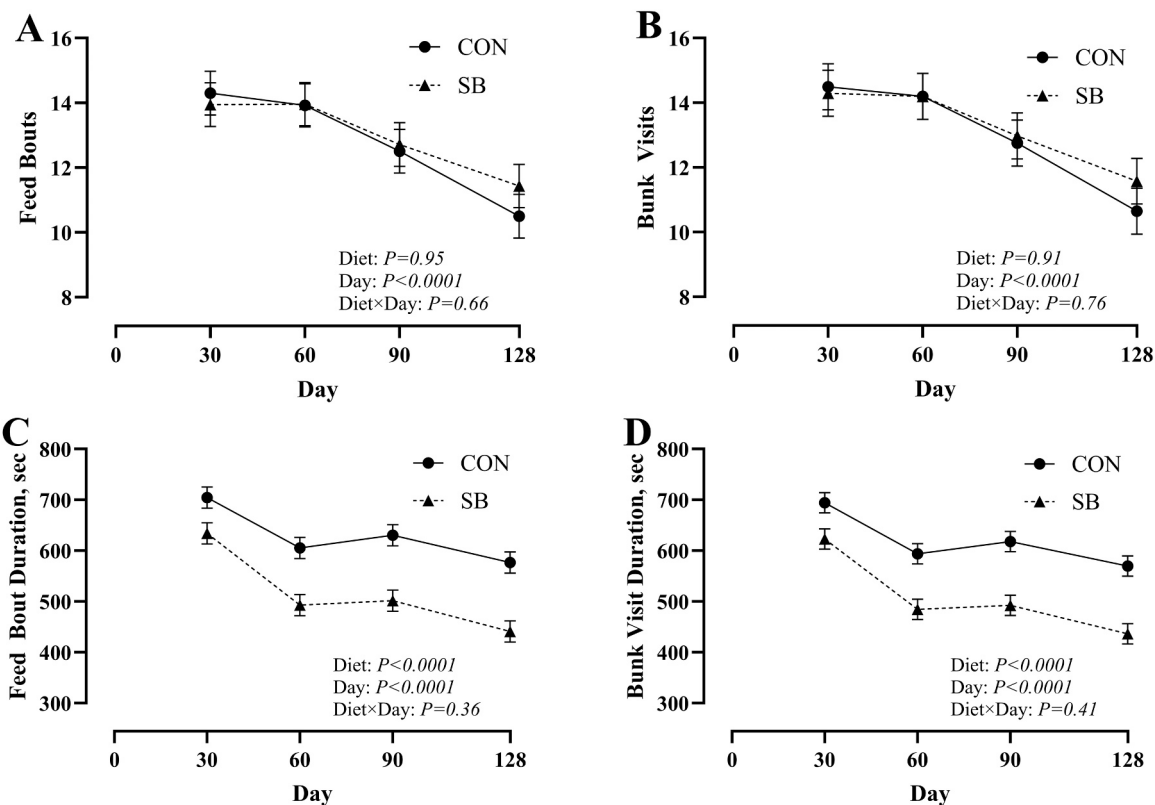


Fig. 4. Steer feeding behavior data (Feed bouts (FB);A), bunk visits (BV);B), feed bout duration (FBDUR;C), bunk visit duration (BVDUR;D) was collected as described in the materials and methods. Sixty Steers were used and were fed either a conventional finishing ration for the Intermountain West (CON; $n = 30$) or the same diet but corn silage and some barley grain was replaced for sprouted barley (SB; $n = 30$) for a feeding period of 128 d. All data were analyzed using the MIXED procedure of SAS with day as a repeated measure to determine the main effects of diet $\times$ day, diet, and day.

($P = 0.007$) where no differences ($P = 0.48$) were evident on d 0, but on d 60, SB had increased ($P = 0.0005$) total VFA concentration compared to CON. By d 128, no difference ($P = 0.72$) was observed between the two diets (Fig. 6A). There was also a diet×day ($P < 0.0001$) effect for Ac:Pr and can be described by CON having a slightly increased ($P = 0.09$) Ac:Pr at d 0, but no differences ($P = 0.96$) were shown on d 60. However, on d 128, SB had an increased ($P < 0.0001$) Ac:Pr compared to CON (Fig. 6B). Total mM of acetate was not altered by diet×day ($P = 0.14$), however diet ($P = 0.0002$) and day ($P < 0.0001$) both impacted acetate concentration. Steers receiving SB generally had increased acetate compared to CON throughout the trial with significant differences noted at d 60 ($P = 0.0009$; Fig. 6C). The percentage of acetate was altered by diet×day ($P = 0.03$), but no differences were noted at specific timepoints ($P \geq 0.74$; Fig. 6D). Propionate concentrations were also impacted by diet×day ($P = 0.0001$) such that no differences ($P = 0.84$) were found on d 0, but SB had increased ($P = 0.001$) propionate on d 60 compared to CON, then no differences were evident at d 128 ($P = 0.87$; Fig. 6E). The percentage of propionate was altered by diet×day ($P < 0.0001$) where no differences ($P \geq 0.61$) were shown on d 0 or d 60, but CON was increased ($P < 0.0001$) compared to SB on d 128 (Fig. 6F). There was a diet×day ($P = 0.004$) for butyrate concentration which can be characterized by SB generally having greater butyrate than CON, with differences being significant at d 60 ($P < 0.0001$) but not on d 0 ($P = 0.55$) or d 128 ($P = 0.13$; Fig. 6G). Additionally, butyrate percentage was influenced by diet×day ($P = 0.004$) such that SB had increased ($P \leq 0.004$) butyrate on d 60 and 128 compared to CON but not on d 0 ($P = 0.99$; Fig. 6H).

3.6. Carcass results

Ribeye area measured by ultrasound was not altered by diet×day ($P = 0.62$) or diet ($P = 0.08$) but was affected by day ($P < 0.0001$); REA of all animals increased ($P < 0.0001$) over time (Fig. 7A). Fat at the 12th rib did not change due to diet×day ($P = 0.15$) or diet ($P = 0.09$) but it did increase ($P < 0.0001$) over time in all animals, regardless of diet (Fig. 7B).

At harvest, there were no differences ($P \geq 0.16$) due to diet in liver score, HCW, dressing percent, MS, or REA (Table 3). However, steers receiving SB had increased ($P = 0.03$) USDAYG compared to CON (Table 3).

3.7. Economic results

Analysis of estimated economic metrics demonstrated differences ($P < 0.05$) in TFC, COG, FC/kg HCW, FC/MS, and NR across diets (Table 4). Over the 128 d feeding trial, steers receiving the CON ration had a lower TFC ($P < 0.0001$), COG ($P = 0.002$), FC/kg HCW ($P < 0.0001$), and FC/MS ($P = 0.002$) compared to the SB diet, while the CON also had increased NR ($P = 0.002$; Table 4). All economic results collectively point towards added benefit to feeding CON relative to SB.

4. Discussion

The objective of this study was to evaluate the effects of feeding sprouted barley on feedlot performance, carcass characteristics, and economic viability of finishing beef steers. Climate variability, feed price volatility, and land use pressures drive the need for alternative, sustainable feed sources making this research key to the sustainability of beef production. Sprouting barley in a VFS offers a potential solution by providing consistent, high-quality feedstuff independent of environmental constraints. Where relevant, findings from studies in dairy cattle and other livestock species are referenced to provide context.

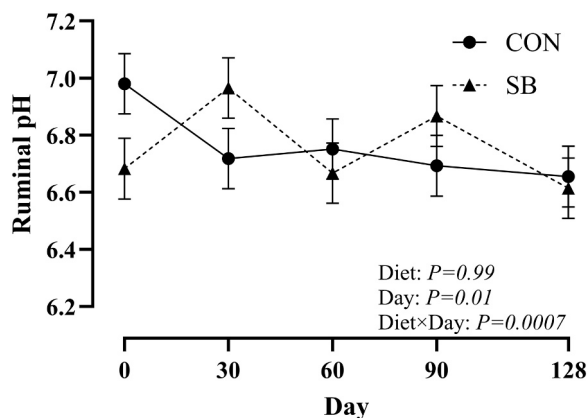


Fig. 5. Steer ruminal pH data was collected as described in the materials and methods. Sixty Steers were used and were fed either a conventional finishing ration for the Intermountain West (CON; $n = 30$) or the same diet but corn silage and some barley grain was replaced for sprouted barley (SB; $n = 30$) for a feeding period of 128 d. All data were analyzed using the MIXED procedure of SAS with day as a repeated measure to determine the main effects of diet×day, diet, and day.

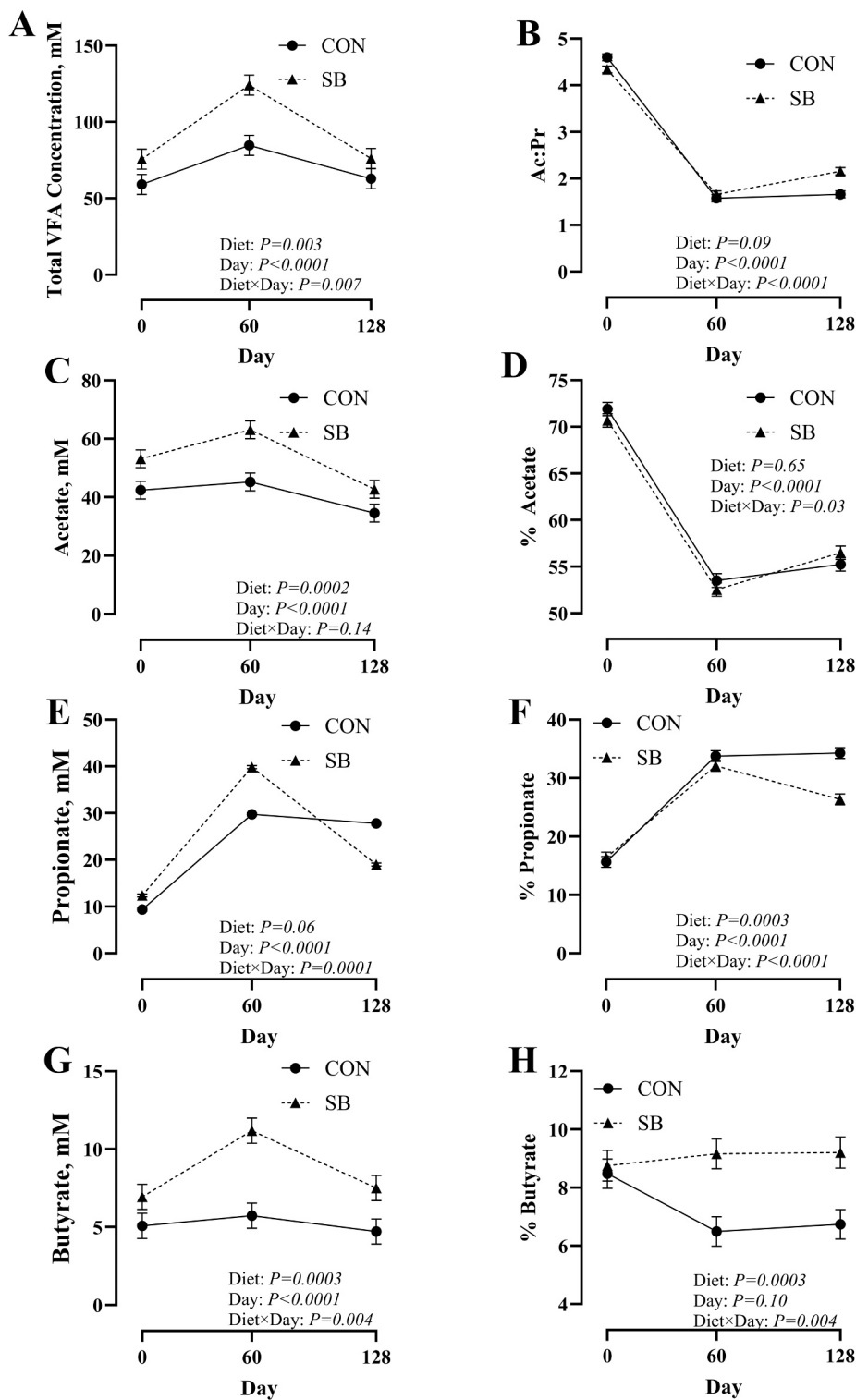


Fig. 6. Steer ruminal VFA data (Total volatile fatty acid (VFA) concentration (A), acetate to propionate ratio (Ac:Pr;B) acetate concentration (C), acetate percentage (D), propionate concentration (E), propionate percentage (F), butyrate concentration (G) butyrate percentage (H), was collected as described in the materials and methods. Sixty Steers were used and were fed either a conventional finishing ration for the Intermountain West (CON; $n = 30$) or the same diet but corn silage and some barley grain was replaced for sprouted barley (SB; $n = 30$) for a feeding period of 128 d. All data were analyzed using the MIXED procedure of SAS with day as a repeated measure to determine the main effects of diet×day, diet, and day.

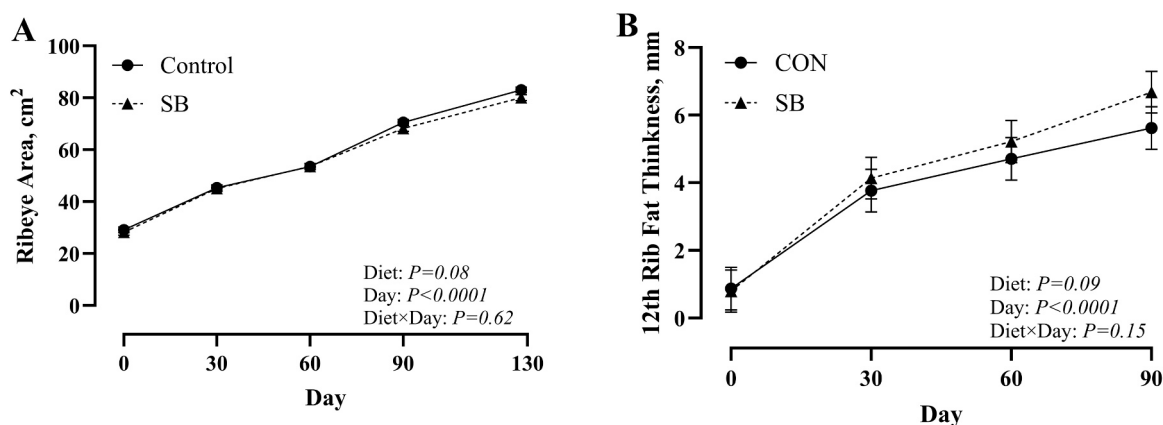


Fig. 7. Steer ribeye area (REA;A) and 12th rib fat thickness (REFT;B) data was collected via ultrasound as described in the materials and methods. Sixty Steers were used and were fed either a conventional finishing ration for the Intermountain West (CON; $n = 30$) or the same diet but corn silage and some barley grain was replaced for sprouted barley (SB; $n = 30$) for a feeding period of 128 d. All data were analyzed using the MIXED procedure of SAS with day as a repeated measure to determine the main effects of diet×day, diet, and day.

Table 4

Effects of feeding sprouted barley on Total Feed Costs (TFC), Cost of Gain (COG), Feed Cost to Hot Carcass Weight (FC:HCW), Feed Cost to Marbling Score (FC:MS), and Net Return (NR) over feed costs of finishing feedlot steers.

	CON ^a	SB ^b	SEM	P-Value
TFC ^c	\$381.03	\$477.14	10.81	$< 0.0001^{\dagger}$
COG ^d	\$1.76	\$2.35	0.18	$0.002^{\dagger}$
FC:HCW ^e	\$1.06	\$1.33	0.03	$< 0.0001^{\dagger}$
FC:MS ^f	\$0.91	\$1.10	0.06	$0.002^{\dagger}$
NR ^g	-\$23.40	-\$116.56	28.15	$0.002^{\dagger}$

^a CON: Diet consisted of a typical ration for the Intermountain West, with 80 % rolled barley concentrate

^b SB: Diet consisted of the same diet as control but corn silage and some rolled barley was replaced with sprouted barley at 20 % dry matter inclusion

^c TFC: The total feed cost (\$) associated with feeding each treatment for the 128d feeding period

^d COG: The cost of gain (\$/kg.) (feed costs only) and is equal to the TFC/total weight gain

^e FC:HCW: The feed cost per kg. of hot carcass weight and is equal to the TFC/hot carcass weight

^f FC:MS: The feed costs per marbling score and is equal to TFC/marbling score

^g NR: The net return over feed costs (\$/hd.).

4.1. Dry matter intake and efficiency

Animal performance is a main indicator producers use to evaluate if a specific feedstuff is a viable alternative (Bagley, 1993; Koknaroglu et al., 2005). In this study, it was demonstrated that SB cattle had increased G:F as well as carcass adjusted G:F. Sprouted barley fed cattle had decreased DMI, but their growth rate was similar to CON cattle, which resulted in an improved G:F. Additionally, the increased moisture content of SB can impact rumen fill. Previous research carried out in dairy cattle showed that an increase in moisture content decreased DMI and increased ration sorting (Miller-Cushon and DeVries, 2009).

4.2. Nutrient intake

Cattle receiving SB had decreased nutrient intakes of DM, NE_m, NE_g, ADF, and NDF. However, the CP portion of total daily intake differed, with SB cattle receiving an increased percentage of CP in their diet due to the nature of SB. Even though a greater percentage of the diet in SB cattle was CP compared to CON, DMI was decreased enough so the total amount of CP intake was the same, which can be corroborated with no differences in PUN being detected. Observing a decrease in these major nutrients while maintaining performance may benefit producers by reducing nutrient inputs without compromising productivity, or by indicating that cattle are utilizing available nutrients more efficiently due to improved digestibility.

4.3. Feeding behavior

Given shifts in nutrient intake and efficiency, evaluating feeding behavior provides additional insight into intake regulation. It has previously been shown that DMI can be predicted by assessing feeding behavior metrics (McGee et al., 2014). In the current study, FB and BV were not impacted by diet, but the duration of each were impacted, with SB spending less time at the bunk. This shorter

duration could be due to the increased moisture content in SB diets, impacting overall ruminal fill. Research in growing wethers demonstrated similar findings, with animals fed a diet containing sprouted barley showing reduced time at the bunk compared to those on a control diet (Crump et al., 2025). This decrease in DMI is often associated with decreased performance due to decrease in nutrient intake (Rayburn et al., 2022). In the current study, however, no differences in performance were noted. Authors postulate that due to the SB cattle having an increase in total VFA in the rumen compared to CON, SB cattle have increased energy available for growth. This could also be linked to the potential increase in digestibility of SB.

4.4. Plasma urea nitrogen

Previous research has shown that a decrease in CP intake and increased G:F could both lead to decreased PUN levels (Hammond, 1983; Hammond et al., 1994; Clemmons et al., 2023). However, cattle fed SB had decreased CP intake, but PUN levels remained the same. This could indicate that more of the CP within the diet of the SB steers is being absorbed into circulation compared to steers receiving the conventional diet. Although improved G:F is often associated with greater nitrogen use for muscle accretion, this relationship was not reflected in PUN or measurements of muscle yield. In the present study, no differences in muscle deposition (REA, HCW) or PUN concentration were observed between diets, with improved G:F of SB cattle being driven by a decrease in DMI.

4.5. Fermentation dynamics

Volatile fatty acids concentrations and proportions provide insight into how composition of different diets impacts ruminal health and fermentation. In the present study ruminal pH, VFA concentrations, and percentages were consistent with previously published data and were all considered to be within healthy, normal ranges (Bergman, 1990; van Houtert, 1993; Dijkstra, 1994). However, multiple diet, day, and diet×day differences in specific ruminal VFA were observed. Consistent with previously published results, Ac:Pr decreased from approximately 4:1–1.5–2:1 in both diets over time, which was expected as the amount of concentrate increased (Penner et al., 2009). Other research has demonstrated the acetate, propionate and butyrate ratio for finishing cattle to be 40:40:10 (Bergman, 1990; Penner et al., 2009), and in the present study a ratio of approximately 50:30:10 was observed with some variability between diets, which will be discussed below. Although these differences were noted statistically, their biological relevance was minimal, particularly as all values remained within normal and acceptable ranges.

Steers fed SB had increased concentrations of each of the three primary VFA (acetate, propionate, and butyrate) throughout the study resulting in increased total VFA. Authors postulate that this is because sprouted grains have increased digestibility compared to conventional feeds (Al-Baadani et al., 2022). As sprouted barley is readily digested as it enters the rumen, an increase in VFA in SB cattle would be expected. However, Crump et al. (2024) found that when including SB in the diet of cow calf pairs at 12.6 % DM, there was no difference in VFA concentration. Differences in the current study could be due to increased overall proportion of SB in the diet compared to other studies.

Greater VFA concentrations increases the amount of available energy as well as methanogenesis occurring, as there is more fermentation occurring in the rumen (Cholewińska et al., 2020). However, the present study did not directly measure these variables. In the present study, SB cattle generally had increased propionate concentration, which can act as a hydrogen sink, decreasing available hydrogen for methanogenesis potentially reducing greenhouse gas emissions (Guyader et al., 2017). Potential increased fermentation in SB cattle is consistent with changes in seed compounds during the germination process, enhancing nutrient availability for ruminal microbes (Farghaly et al., 2019; Alharthi et al., 2022). Additionally, Reed et al. (2005) reported similar findings when feeding sprouted durum wheat to finishing cattle. Additional research examining greenhouse gas emissions, more fermentation dynamics, and the ruminal microbiome is needed before definitive conclusions can be drawn. Such shifts typically increase overall fermentation rate and total VFA concentration increasing available energy to the animal which can have direct impacts on carcass outcomes (Alharthi et al., 2022).

4.6. Carcass results

Carcass weight is the largest driver that impacts producer payout, followed by quality grade, and YG (Tatum et al., 2006; Wilken et al., 2015; Sperber et al., 2024). In the present study, REFT thickness in SB cattle via ultrasound increased over the first 90 days. At harvest, USDAYG was the only difference observed in carcass data, which is consistent with SB having increased REFT and subsequent fat deposition. Fat thickness at the 12th rib (REFT) and KPH fat are components of USDAYG, and increases in those traits are generally linked with increased intramuscular fat deposition (Gotoh et al., 2009). However, there were no differences found in MS between carcasses from steers fed the two different diets. Traditionally an increase in REFT correlates with an increase in MS (Pyatt et al., 2005; Streeter et al., 2012). Authors postulate that the degree of increase in REFT was not substantial enough to have positive impacts on MS. These results indicate that statistical differences were observed, however, biologically these differences were negligible.

4.7. Economic analysis

The decreased NR associated with SB relative to CON is primarily driven by the increased TFC. Steers in both diet groups entered and exited the feeding trial at similar average weights. Additionally, no differences in carcass traits that would drive relative differences in the grid dressed price were observed across treatments. This suggests that both the input cost of the steers as well as output revenue would be similar across diets. Therefore, the significant difference observed in NR can be attributed to significantly increased

TFC for SB relative to CON. Total as-fed consumption for SB was 1.68 times more than CON. The average ration cost (\$/per kg. as-fed) was reduced for the SB diet but not at a significant enough margin to offset the increased as-fed consumption. This resulted in higher TFC and COG with a lower expected NR for SB relative to CON. The comparatively lower FC:HCW and FC:MS for the CON diet suggest that the CON diet outperforms SB in costs to produce hot carcass yield as well as improve marbling. A favorable advantage to utilizing a VFS is a consistent feed supply regardless of external conditions such as drought, extreme temperatures, soil variability, and land availability. Since no measurable differences in performance were observed, the decision to include sprouted barley in growing steer diets should be determined by market prices and feedstuff availability, which can vary substantially between year to year and across regions (Godde et al., 2021; Langemeier, 2023). Furthermore, the economic viability of these systems will vary with fluctuations in grain and energy prices.

5. Conclusions

Due to increased challenges, such as drought and rapid urbanization, which are impacting the agriculture industry, sustainable alternative practices need to be adopted to meet production needs. Innovative technology, such as a VFS, has the potential to ease the challenges faced by producers. This study identified several shifts in rumen fermentation and intake dynamics, including changes in total and individual VFA, dry matter intake, feed efficiency, and carcass fat deposition. Despite these differences, the biological implications were minimal. Feeding sprouted barley at a 20 % dry matter inclusion did not negatively affect health, feedlot performance, or carcass quality of feedlot cattle when compared to a typical diet for the Intermountain West region of the US and may improve some aspects of production performance. Feed costs can fluctuate over time and typically account for 75 % of total beef production expenses, making the economic feasibility of sprouted barley dependent on its cost of production compared to conventional feedstuffs. Sprouted barley composition can differ depending on VFS technology that is used. The findings of this study may not be directly applicable to systems with alternative lighting, tray, or watering designs. However, sprouted barley is expected to have a negative impact on economic performance as indicated by increased TFC and COG combined with lower NR. These findings suggest that while sprouted barley offers some benefits through sustainability and a reduction in land and water use, its adoption in feedlots will require cost reduction in production or increased efficiency gains to be economically competitive. Future research should evaluate optimal inclusion rates, strategies to reduce production costs, and mechanistic effects of sprouted barley on ruminal fermentation, microbial populations, and nutrient utilization.

CRedit authorship contribution statement

Kara Jean Thornton: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Anthony Fernando Alberto:** Writing – review & editing, Investigation. **Zachary Cal Crump:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ryan Arthur Spurling:** Writing – review & editing, Investigation. **Lillian Lelehua Okamoto:** Writing – review & editing, Investigation. **Bryce Wayne Roholt:** Writing – review & editing, Investigation. **Xin Dai:** Writing – review & editing, Validation, Methodology, Formal analysis. **Bailee Lynn Brown:** Writing – review & editing, Investigation. **Brady Morris Blackett:** Writing – review & editing, Resources, Investigation, Conceptualization. **Robert Edward Ward:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Lex Peterson:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Ryan Feuz:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sanjeewa Dilshan Ranathunga:** Writing – review & editing, Resources, Investigation, Conceptualization. **Robert Lynn Harding:** Writing – review & editing, Resources, Investigation, Conceptualization.

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

During the preparation of this work, the authors used ChatGPT (GPT-5) in order to check for grammar and sentence syntax errors. No content of the manuscript was generated by AI or AI-assisted technologies. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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Declaration of Competing Interest

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References

- Al-Baadani, H.H., Alowaimier, A.N., Al-Badwi, M.A., Abdelrahman, M.M., Soufan, W.H., Alhidary, I.A., 2022. Evaluation of the nutritive value and digestibility of sprouted barley as feed for growing lambs: in vivo and in vitro studies. *Animals* 12 (9). <https://doi.org/10.3390/ani12091206>.
- Alexandratos, N., and J. Bruinsma. 2012. World agriculture towards 2030/2050: the 2012 revision.
- Alharthi, A.S., Al-Baadani, H.H., Abdelrahman, M.M., Alhidary, I.A., 2022. Effects of feeding different levels of sprouted barley on fermentation characteristics, bacterial quantification, and rumen morphology of growing lambs. *Vet. Sci.* 10 (1). <https://doi.org/10.3390/vetsci10010015>.
- Bagley, C.P., 1993. Nutritional management of replacement beef heifers: a review. *J. Anim. Sci.* 71 (11), 3155–3163. <https://doi.org/10.2527/1993.71113155x>.
- Bergman, E.N., 1990. Energy contributions of volatile fatty acids from the gastrointestinal tract in various species. *Physiol. Rev.* 70 (2), 567–590. <https://doi.org/10.1152/physrev.1990.70.2.567>.
- BLS. 2024b. Electricity per KWH in U.S. city average, average price, not seasonally adjusted. In: U. S. B. o. L. Statistics (ed.).
- Cholewińska, P., Czyż, K., Nowakowski, P., Wyrostek, A., 2020. The microbiome of the digestive system of ruminants - a review. *Anim. Health Res Rev.* 21 (1), 3–14. <https://doi.org/10.1017/s1466252319000069>.
- Clemmons, B.A., Ault-Seay, T.B., Henniger, M.T., Martin, M.G., Mulon, P.Y., Anderson, D.E., Voy, B.H., McLean, K.J., Myer, P.R., 2023. Blood parameters associated with residual feed intake in beef heifers. *BMC Res Notes* 16 (1), 177. <https://doi.org/10.1186/s13104-023-06444-6>.
- Crump, Z.C., Alberto, A.F., Brown, B.L., Roholt, B.W., Okamoto, L.L., Sego, M.L., Spurling, R.A., Ward, R.E., Blackett, B.M., Harding, R.L., Ranathunga, S.D., Thornton, K.J., 2024. The effects of including sprouted barley with alfalfa hay in the diet on ruminal health and performance of cow-calf pairs. *J. Anim. Sci.* 102. <https://doi.org/10.1093/jas/skae074>.
- Crump, Z.C., Alberto, A.F., Brown, B.L., Roholt, B.W., Okamoto, L.L., Spurling, R.A., Johnson, F.L., Feuz, R., Harding, R.L., Ranathunga, S.D., Blackett, B.M., Atkinson, J.R., Page, C.M.B., Thornton, K.J., 2025. Effects of including sprouted barley in the diets of western white face feeder wether lambs. *Transl. Anim. Sci.* <https://doi.org/10.1093/tas/txaf040>.
- Dijkstra, J., 1994. Production and absorption of volatile fatty acids in the rumen. *Livest. Prod. Sci.* 39 (1), 61–69. [https://doi.org/10.1016/0301-6226\(94\)90154-6](https://doi.org/10.1016/0301-6226(94)90154-6).
- Farghaly, M.M., Abdullah, M.A.M., Youssef, I.M.I., Abdel-Rahim, I.R., Abouelezz, K., 2019. Effect of feeding hydroponic barley sprouts to sheep on feed intake, nutrient digestibility, nitrogen retention, rumen fermentation and ruminal enzymes activity. *Livest. Sci.* 228, 31–37. <https://doi.org/10.1016/j.livsci.2019.07.022>.
- Foraker, B.A., Frink, J.L., Woerner, D.R., 2022. Invited review: a carcass and meat perspective of crossbred beef × dairy cattle. *Transl. Anim. Sci.* 6 (2). <https://doi.org/10.1093/tas/txac027>.
- Godde, C.M., Mason-D'Croz, D., Mayberry, D.E., Thornton, P.K., Herrero, M., 2021. Impacts of climate change on the livestock food supply chain; a review of the evidence. *Glob. Food Secur.* 28, 100488. <https://doi.org/10.1016/j.gfs.2020.100488>.
- Gotoh, T., Albrecht, E., Teuscher, F., Kawabata, K., Sakashita, K., Iwamoto, H., Wegner, J., 2009. Differences in muscle and fat accretion in Japanese Black and European cattle. *Meat Sci.* 82 (3), 300–308. <https://doi.org/10.1016/j.meatsci.2009.01.026>.
- Guyader, J., Ungerfeld, E.M., Beauchemin, K.A., 2017. Redirection of metabolic hydrogen by inhibiting methanogenesis in the rumen simulation technique (RUSITEC). *Front. Microbiol.* 8, 393.
- Hadfield, J.A., Waldron, B.L., Isom, S.C., Feuz, R., Larsen, R., Creech, J.E., Rose, M.F., Long, J., Peel, M.D., Miller, R.L., Rood, K.A., Young, A., Stott, R., Sweat, A., Thornton, K.J., 2021. The effects of organic grass and grass-birdfoot trefoil pastures on Jersey heifer development: Heifer growth, performance, and economic impact. *J. Dairy Sci.* 104 (10), 10863–10878. <https://doi.org/10.3168/jds.2020-19524>.
- Hammond, A.C., 1983. The use of blood urea nitrogen concentration as an indicator of protein status in cattle. *Bov. Pract.* 114–118.
- Hammond, A.C., Bowers, E.J., Kunkle, W.E., Genho, P.C., Moore, S.A., Crosby, C.E., Ramsay, J.H., Essig, H.W., 1994. Use of blood urea nitrogen concentration to determine time and level of protein supplementation in wintering COWS1,2. *Prof. Anim. Sci.* 10 (1), 24–31. [https://doi.org/10.15232/S1080-7446\(15\)31923-9](https://doi.org/10.15232/S1080-7446(15)31923-9).
- van Houtert, M.F.J., 1993. The production and metabolism of volatile fatty acids by ruminants fed roughages: a review. *Anim. Feed Sci. Technol.* 43 (3), 189–225. [https://doi.org/10.1016/0377-8401\(93\)90078-X](https://doi.org/10.1016/0377-8401(93)90078-X).
- Koknaroglu, H., Loy, D.D., Wilson, D.E., Hoffman, M.P., Lawrence, J.D., 2005. Factors affecting beef cattle performance and profitability. *Prof. Anim. Sci.* 21 (4), 286–296. [https://doi.org/10.15232/S1080-7446\(15\)31220-1](https://doi.org/10.15232/S1080-7446(15)31220-1).
- Langemeier, M. 2023. Impact of Lower Corn Prices on Feeding Cost of Gain for Cattle Finishing.
- Leeper, R.D., Bilotta, R., Petersen, B., Stiles, C.J., Heim, R., Fuchs, B., Prat, O.P., Palecki, M., Ansari, S., 2022. Characterizing U.S. drought over the past 20 years using the U.S. drought monitor. *Int. J. Climatol.* <https://doi.org/10.1002/joc.7653>.
- LMIC. 2024. Monthly U.S. Ag. Prices Feedgrains and Hay. Livestock Marketing Information Center.
- LMIC. 2024a. Monthly Weighted Average: 5 Markets. Livestock Marketing Information Center.
- McGee, M., Welch, C.M., Ramirez, J.A., Carstens, G.E., Price, W.J., Hall, J.B., Hill, R.A., 2014. Relationships of feeding behaviors with average daily gain, dry matter intake, and residual feed intake in Red Angus-sired cattle. *J. Anim. Sci.* 92 (11), 5214–5221.
- Miller-Cushon, E.K., DeVries, T.J., 2009. Effect of dietary dry matter concentration on the sorting behavior of lactating dairy cows fed a total mixed ration. *J. Dairy Sci.* 92 (7), 3292–3298. <https://doi.org/10.3168/jds.2008-1772>.
- Penner, G.B., Taniguchi, M., Guan, L.L., Beauchemin, K.A., Oba, M., 2009. Effect of dietary forage to concentrate ratio on volatile fatty acid absorption and the expression of genes related to volatile fatty acid absorption and metabolism in ruminal tissue. *J. Dairy Sci.* 92 (6), 2767–2781. <https://doi.org/10.3168/jds.2008-1716>.
- Pyatt, N., Berger, L., Faulkner, D., Walker, P., Rodriguez-Zas, S., 2005. Factors affecting carcass value and profitability in early-weaned Simmental steers: II. Days on feed endpoints and sorting strategies. *J. Anim. Sci.* 83 (12), 2926–2937.
- Rayburn, E., E. Miller-Cushon, and T. DeVries. 2022. Dry Matter Intake by Cattle.
- Reed, J.J., Bauer, M.L., Loe, E.R., Caton, J.S., Lardy, G.P., 2005. Effects of processing on feeding value of sprouted barley and sprouted durum wheat in growing and finishing diets for beef cattle. *Prof. Anim. Sci.* 21, 7–12. [https://doi.org/10.15232/S1080-7446\(15\)31159-1](https://doi.org/10.15232/S1080-7446(15)31159-1).
- Reichhardt, C.C., Messersmith, E.M., Brady, T.J., Motsinger, L.A., Briggs, R.K., Bowman, B.R., Hansen, S.L., Thornton, K.J., 2021b. Anabolic Implants Varying in Hormone Type and Concentration Influence Performance, Feeding Behavior, Carcass Characteristics, Plasma Trace Mineral Concentrations, and Liver Trace Mineral Concentrations of Angus Sired Steers. *Anim. (Basel)* 11 (7). <https://doi.org/10.3390/ani11071964>.
- Reichhardt, C.C., Feuz, R., Brady, T.J., Motsinger, L.A., Briggs, R.K., Bowman, B.R., Garcia, M.D., Larsen, R., Thornton, K.J., 2021a. Interactions between cattle breed type and anabolic implant strategy impact circulating serum metabolites, feedlot performance, feeding behavior, carcass characteristics, and economic return in beef steers. *Domest. Anim. Endocrinol.* 77, 106633. <https://doi.org/10.1016/j.domaniend.2021.106633>.
- Salas-Solis, G.K., Vicente, A.C.S., Arce-Cordero, J.A., Siregar, M.U., Johnson, M.L., Vinyard, J.R., Lobo, R.R., Sarmikassoglou, E., Faciola, A.P., 2026. Hydroponically sprouted grains: effects on in situ ruminal nutrient degradation, fractional disappearance rate, and effective ruminal degradation. *Fermentation* 12 (1), 55.
- Sperber, J.L., Bondurant, R.G., Erickson, G.E., Bruns, K., Funston, R.N., MacDonald, J.C., 2024. Effect of extended days on feed on carcass gain, efficiency, and quality of individually fed beef steers. *Transl. Anim. Sci.* 8, txae081. <https://doi.org/10.1093/tas/txae081>.

- Streeter, M., Hutcheson, J., Nichols, W., Yates, D., Hodgen, J., Vander Pol, K., Holland, B., 2012. Review of large pen serial slaughter trials-growth, carcass characteristics, feeding economics. *Plains Nutr. Counc.* 26, 58–72.
- Tatum, J.D., Belk, K.E., Field, T.G., Scanga, J.A., Smith, G.C., 2006. Relative Importance of Weight, Quality Grade, and Yield Grade as Drivers of Beef Carcass Value in Two Grid-Pricing Systems. *Prof. Anim. Sci.* 22 (1), 41–47. [https://doi.org/10.15232/S1080-7446\(15\)31059-7](https://doi.org/10.15232/S1080-7446(15)31059-7).
- UDWR. 2010. The Cost of Water in Utah. In: U. D. o. W. Resources (ed.).
- USDA. 2023. Crop Production 2022 Summary. In: D. o. Agriculture (ed.).
- USDA-AMS. 2024. National Weekly Direct Slaughter Cattle- Premiums and Discounts. In: A. M. S. United State Department of Agriculture (ed.).
- USDA-NASS. 2024. Labor, Hired - Wage Rate, Measured in \$/hour. In: N. A. S. S. United States Department of Agriculture (ed.).
- USDA-NASS. 2024b. Barley, Malting - Price Recieved, Measured in \$/BU. In: N. A. S. S. United States Department of Agriculture (ed.).
- Van Soest, P.J., Robertson, J.B., Lewis, B.A., 1991. Methods for Dietary Fiber, Neutral Detergent Fiber, and Nonstarch Polysaccharides in Relation to Animal Nutrition. *J. Dairy Sci.* 74 (10), 3583–3597. [https://doi.org/10.3168/jds.S0022-0302\(91\)78551-2](https://doi.org/10.3168/jds.S0022-0302(91)78551-2).
- Wilken, M.F., MacDonald, J.C., Erickson, G.E., Klopfenstein, T.J., Schneider, C.J., Luebke, K.M., Kachman, S.D., 2015. Marketing strategy influences optimum marketing date of steers in relation to corn price and days on feed11A contribution of the University of Nebraska Agricultural Research Division, supported in part by funds provided through the Hatch Act. *Prof. Anim. Sci.* 31 (3), 224–236. <https://doi.org/10.15232/pas.2014-01325>.
- Zang, Y., Richards, A.T., Seneviratne, N., Gutierrez-Oviedo, F.A., Harding, R., Ranathunga, S., McFadden, J.W., 2024. Replacing conventional concentrates with sprouted barley or wheat: effects on lactational performance, nutrient digestibility, and milk fatty acid profile in dairy cows. *J. Dairy Sci.* 107 (8), 5529–5541. <https://doi.org/10.3168/jds.2023-24071>.