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Influence of animal age and breeding activity on carcass traits, meat quality, and sensory attributes of bison bulls

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In the bison industry, both heifers and bulls are marketed and harvested at various ages, generally ranging from 20 to 30 months. Bulls represent the greatest proportion of the slaughter mix, as the bison industry does not routinely castrate, leaving males intact throughout the growing and finishing phase. This practice makes bulls available for use during the breeding season prior to the finishing phase. Therefore, the objective of this study was to evaluate the influence of bull age and use in the breeding herd on carcass characteristics, meat quality, and sensory characteristics of bison bulls. Grass-finished bison bulls were assigned to one of two finishing treatments: 1) Young bulls (n = 98) finished on fall pasture and harvested at 30 months of age with no exposure to the breeding herd, or 2) Mature bulls (n = 24) finished on early summer pasture and harvested at 36 months of age following use in the breeding herd. Bison were harvested, carcass data were recorded, and striploins were collected for the analysis of meat quality attributes. Mature bulls had greater hot carcass weight, ribeye area, kidney fat percentage, and marbling score compared to Young bulls. Objective tenderness was affected by the interaction of postmortem aging and finishing treatment. Steaks from Young bison bulls were more tender at all aging time points compared to steaks from Mature bison bulls. Variation in tenderness between treatment groups was likely not due to differences in collagen, as total collagen was greater in steaks from Young bulls. Consumer panelists rated steaks from Mature bulls higher for toughness intensity and flavor liking and lower for off-flavor intensity. Trained panelists rated steaks from Young bulls higher for flavor intensity, while ratings for toughness and juiciness were increased for Mature bulls. Collectively, results from this study indicate that bulls used in the breeding herd and marketed at 36 months of age produced heavier carcasses. However, Mature bulls were tougher at all postmortem aging days and required 21 days of aging to reach an acceptable level of tenderness, which was detected by both trained and consumer panelists.

KEYWORDS
animal age, bison, breeding activity, bulls, carcass traits, grass-finished, meat quality, sensory attributes

Introduction

The U.S. bison industry markets both heifers and bulls at various ages. Bison typically require more time to reach mature size than beef cattle and are generally harvested between 20 and 30 months of age. The U.S. Department of Agriculture, Agricultural Marketing Service (USDA-AMS) has provided a marketing report for bison (*Bison bison*) harvested in the United States since 2017. On this report, bison are classified as either young (<30 months of age) or aged (>30 months of age), and carcass value varies based on this age classification, with the average price of Young bulls always greater than the price for aged bison bulls. This spread in price is likely due to challenges with the palatability of meat from older animals. Bulls represent the greatest proportion of the slaughter mix, and the bison industry does not routinely perform castration, leaving males intact throughout the growing and finishing phase. This makes bulls available for breeding during the finishing phase, which is a novel management strategy that can be utilized by producers.

Bison exhibit a highly synchronized reproductive cycle, with a concentrated rut in late summer; most calves are born in late spring/early summer. Consequently, allowing bulls to participate in the breeding season prior to harvest inherently results in marketing animals that are chronologically older and finished later in the grazing season when forages are typically more mature, which could influence the profile of volatile compounds and fatty acids that contribute to flavor. Furthermore, as an animal ages, cartilage ossifies into bone, and the color of muscle tissue becomes darker and redder as the concentration of myoglobin in the muscle increases (Cho et al., 2015; English et al., 2016). In addition, the concentration of connective tissue in muscle increases, while the solubility of connective tissue decreases with increasing animal age (Cross et al., 1984; Shorthose and Harris, 1990). This increase in connective tissue content and decrease in solubility influences meat tenderness, resulting in tougher meat from older animals compared to meat from younger animals (Purslow, 2005). An increased pH value is also associated with a darker lean color and potential palatability issues in meat. In beef, pH values over 6.0 have been correlated with darker lean color, decreased tenderness, and increased water-holding capacity (Bureš and Bartoň, 2012; Kopuzlu et al., 2018). The pH value is a concern in older animals and intact males, as the pH value of meat tends to increase with animal age, and bull meat has an increased pH value compared to meat from castrate animals (Bureš and Bartoň, 2012; Kopuzlu et al., 2018).

While the chronological age of an animal can be known, the physiological age has a greater influence on palatability. For beef cattle, maturity can be determined by evaluating dentition or the degree of ossification of the thoracic buttons of the vertebrae and lean color of the exposed ribeye muscle when the carcass is ribbed between the 12th and 13th ribs. The degree of ossification of the thoracic buttons is also evaluated to determine bison carcass maturity; however, lean color is not included as a measure of animal age. Research investigating the influence of maturity on carcass and meat quality characteristics in bison has been limited. López-Campos et al. (2014) compared carcass and meat quality traits of bison bulls and heifers classified into youthful or intermediate physiological maturity groups according to the Canadian Bison Grading System and reported limited differences due to ossification group. However, the influence of more advanced animal age on carcass traits of bison and the influence of use in the breeding herd have not been reported. Such management and marketing decisions could have implications for both economic and ecological sustainability within grass-fed bison systems. Therefore, we hypothesized that bison bulls finished at a younger age and not used in the breeding herd would have improved carcass traits and meat quality compared to older bulls utilized in the breeding herd. To test this hypothesis, the objective of this study was to determine the influence of animal age (30 months vs 36 months), finishing season, and use in the breeding herd on carcass traits, meat quality, and sensory attributes of grass-finished bison bulls.

Materials and methods

Animals, carcass evaluation, and striploin collection

Grass-finished bison bulls (n = 122) from a commercial herd were assigned to one of two finishing treatments: 1) Young bulls (n = 98) finished on fall pasture and harvested at 30 months of age with no exposure to the breeding herd or 2) Mature bulls (n = 24) finished on early summer pasture and harvested at 36 months of age following use in the breeding herd. Bulls in both treatments were allowed to graze native rangelands in the Sandhills Ecoregion of Nebraska until harvest. Typical plant composition of these pastures is described by van Vliet et al. (2023). Unequal sample sizes between treatment groups reflected the available population structure within the commercial herd and typical industry demographics, where the number of Mature bulls used for breeding is generally substantially lower than the number of Young bulls finished for harvest. This imbalance may reduce statistical power for some measures and is acknowledged as a limitation. Mature bulls were transported approximately 370 km to a commercial harvest facility in early summer when they were approximately 36 months of age and harvested over a 1-day period. Young bulls were transported to the same commercial harvest facility in the fall when they were approximately 30 months of age and harvested over a 2-day period (49 head harvested each day). The same handling processes and facilities were utilized to gather and load bulls for harvest. In an industry benchmarking study, Velazco et al. (2024) reported that the average distance bison traveled to slaughter facilities in the United States was 823 km; therefore, bulls in this study were subject to a relatively short transportation period compared to the industry average.

Live weight was recorded at the harvest facility. After harvest, hot carcass weight was recorded, and kidney fat percentage was determined as the difference in carcass weight before and after removal of the kidney knob. Following an approximately 20-hour chilling period, carcasses were ribbed between the 12th and 13th rib. Ribeye area, backfat thickness, marbling score, skeletal maturity, subjective lean color, and subjective fat color were determined by U.S. Department of Agriculture (USDA) graders. Skeletal maturity was subjectively scored based on the ossification percentage of the thoracic cartilage buttons and assigned a number (11, 7, 5, or −5) that corresponded with the ossification percentages, as follows: 0%–24% (slight, 11), 25%–49% (moderate, 7), 50%–99% (hardbone, 5), and 100%–200% (extreme hardbone, −5). Lean maturity was subjectively scored based on the lean color of the exposed ribeye and assigned a number (11, 7, 5, 3, 1, or 0) corresponding to a color description, as follows: bright red (11), moderately bright red (7), slightly bright red (5), red (3), pale red (1), and dark cutter (0). Fat color was subjectively scored based on the external fat color of the subcutaneous fat color opposite the ribeye and assigned a number (11, 7, 5, 3, or 1) that corresponded to fat color, as follows: white (11), moderately white (7), slightly white (5), moderately yellow (3), and yellow (1). Instrumental color [Commission Internationale de l'Eclairage (CIE) L^* (0 = black, 100 = white), a^* (negative values = green, positive values = red), and b^* (negative values = blue, positive values = yellow)] of the exposed ribeye area at the 12th rib break and the subcutaneous fat of the carcass surface opposite the ribeye were recorded using a handheld Minolta colorimeter (Model CR-310, Minolta Corp., Ramsey, NJ, USA; equipped with a 2° observer and 50-mm aperture and was calibrated using a standard white tile specific to the machine).

The striploin (*M. longissimus lumborum*) was collected from the left side of all Mature bulls (n = 24) and from a subsample of Young bulls (n = 30 carcasses closest to the average hot carcass weight of the group). Striploins were vacuum-packaged and transported in a refrigerated trailer to the South Dakota State University Meat Science Laboratory.

Striploin fabrication and pH

Striploin samples arrived at the South Dakota State University Meat Science Laboratory at 2 or 3 days postmortem, depending upon harvest date. Upon arrival, all striploins were removed from vacuum packages, and the ultimate pH was recorded at the posterior end of the striploin using a handheld pH meter (Thermo-Scientific Orion Star, Beverly, MA, USA; Model #A221 and Star A321 Portable pH probe). Striploins were trimmed of external fat and fabricated into 2.54-cm steaks that were individually vacuum-packaged. Four steaks were designated for Warner-Bratzler shear force (WBSF) and assigned to a 4-, 7-, 14-, or 21-day aging period and then frozen for approximately 3 months prior to shear force analysis. One steak was designated for the determination of collagen content, assigned to a 3-day aging period, and then frozen. Two steaks were designated for a consumer sensory panel, assigned to a 14-day aging period, and then frozen. One steak was designated for a trained sensory panel, assigned to a 14-day aging period, and then frozen. All steaks were frozen in a single layer in an air-blast freezer, then packaged into boxes, and stored at −10 °C until evaluation.

Warner-Bratzler shear force and cook loss

Steaks were analyzed for WBSF according to guidelines established by the American Meat Science Association (American Meat Science Association, 2015). Briefly, frozen steaks were thawed for 24 hours at 4 °C and weighed before cooking to an internal temperature of 71 °C. Steaks were cooked on an electric clamshell grill (George Foreman 9 Serving Classic Plate Grill, Model #GR2144P, Middleton, WI, USA). Internal temperature was monitored using a digital thermometer (Cooper-Atkins Aqua Tuff NSF Series, Middlefield, CT, USA; Model #41-983430-5) placed near the geometric center of each steak. Peak temperature was recorded for each steak. After cooking, all steaks were cooled for 24 hours at 4 °C. Steaks were allowed to acclimate to room temperature and then reweighed. Cook loss was calculated as the difference between pre- and post-cooking weight expressed as a percentage of the pre-cooking weight. After weighing, five cores (1.27 cm in diameter) were removed parallel to the muscle fiber orientation and sheared once perpendicular to the muscle fiber orientation. Peak WBSF was measured using a texture analyzer (Shimadzu Scientific Instruments Inc., Lenexa, KS, USA; Model #30825535050) equipped with a Warner-Bratzler attachment (50-kg load cell), crosshead speed of 200 mm/min, and downstroke distance of 3.3 cm. Peak force was recorded for each core, and an average shear force peak value was reported for each steak.

Collagen analysis

Collagen content of steaks was determined using the procedures described by O'Sullivan et al. (2025). Briefly, frozen samples were allowed to thaw slightly, snap-frozen in liquid nitrogen, and powdered for 30 seconds in stainless steel blender cups (Waring Products Division, New Hartford, CT, USA; Model SS 110) until they achieved a uniform consistency. Heat-soluble and insoluble collagen fractions were extracted and prepared for analysis using gas chromatography–mass spectrometry. The collagen content (heat soluble or insoluble, mg/g) was calculated by multiplying the hydroxyproline concentration by a factor of 7.52 (heat soluble) or 7.25 (insoluble; Cross et al., 1973).

Consumer and trained sensory analysis

Consumer and trained sensory panels were conducted as described by O'Sullivan et al. (2025). The consumer sensory panel was conducted at the University of Minnesota Sensory Laboratory to evaluate subjective sensory characteristics of striploin steaks from Young and Mature bison bulls. Random participants (n = 82) were recruited from the student and staff population of the University of Minnesota. Participants were 18 years or older, had no food allergies or sensitivities, were willing to consume bison meat, and had consumed any type of meat at least once a year. Of the 82 participants, 35.4% were male, 63.4% were female, and 1.2% preferred not to report. Self-reported data indicated that 91.5% of

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the panelists consumed meat weekly and 8.5% consumed meat on a monthly basis. Participants were asked if they had ever consumed bison in their lifetime, and 42.7% reported consuming bison six or more times, 29.3% consumed bison two to five times, 8.5% consumed bison once, and 19.5% had never consumed bison in their lifetime. The University of Minnesota's Institutional Review Board approved all recruiting and experimental procedures (IRB #6792). Frozen steaks were removed from packaging, thawed, and cooked to an internal temperature of 71 °C (approximately 30 minutes). Each participant received two cuboids of bison steak per treatment and was provided with distilled water. The order in which the participants tasted the samples was balanced for position and carryover effects using a Williams Latin square design (Lucas, 1957). All liking ratings were made on a −100- to 100-point labeled affective magnitude scale with the left-most end labeled "Greatest Imaginable Dislike" and the right most end labeled "Greatest Imaginable Like", while intensity ratings were made on modified 51-point labeled magnitude scales with marks from left to right labeled "None", "Barely Detectable", "Slight", "Moderate", "Very", and "Extreme". Eleven sessions were conducted on the same day, with seven or eight consumer panelists seated per session.

For the trained sensory panel, participants (n = 11) were recruited from the Animal Science Department at South Dakota State University and trained to evaluate tenderness, juiciness, aroma, and bison flavor intensity of strip loin steaks. Training and sensory evaluations were performed according to AMSA training guidelines with modifications appropriate for this study (American Meat Science Association, 2015). The South Dakota State University Institutional Review Board approved all training and experimental procedures (IRB-2009013-EXM). Frozen steaks were removed from packaging, thawed, and cooked to an internal temperature of 71 °C. Panelists evaluated sensory attributes on an anchored unmarked line scale with the far-left point indicating extremely tender, extremely juicy, no aroma, or extremely bland bison flavor and the far-right point representing extremely tough, extremely dry, extreme aroma, or extremely intense bison flavor. Nine samples were evaluated in each session by each panelist, and one session was held per day, for a total of eight sessions.

Statistical analysis

Live body weight, dressing percentage, carcass measurements, objective color, pH, and collagen content were analyzed as a completely randomized design using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC, USA). Finishing treatment was specified as a fixed effect, and the individual carcass was specified as a random effect. Yield grade and subjective carcass measurements (skeletal maturity, lean color, and fat color) were analyzed using the GLIMMIX procedure of SAS for the fixed effect of finishing treatment. Least squares means were computed and separated using Least Significant Difference (LSD) with a Tukey's adjustment. Shear force and cook loss data were analyzed in the MIXED procedure of SAS with finishing treatment, day of aging, and the interaction of treatment by day of aging specified as fixed effects. Day of aging was specified as a repeated measure. The covariance structure for the repeated measure was chosen based on the smallest Bayesian Information Criterion (BIC) goodness-of-fit statistic. Heterogeneous compound symmetry provided the best fit for shear force, and compound symmetry provided the best fit for cook loss. Peak temperature was included as a covariate for shear force and cook loss. Linear and quadratic polynomial contrasts adjusted for uneven spacing of days were computed for day of aging. When finishing treatment interacted with day of aging, linear and quadratic polynomial contrasts were computed for day of aging within each treatment. Trained and consumer sensory data were analyzed using the MIXED procedures of SAS for the main effects of treatment, and panelist was included as a random effect. Least squares means were separated with the PDIFF option. Carcass was used as the experimental unit and was specified as a random effect for all assays. Statistical significance was assumed at an alpha level of ≤0.05.

Results and discussion

Carcass characteristics

There is currently no system for assigning yield or quality grades to bison in the United States; therefore, carcass measurements, yield grade, and marbling scores were calculated using the USDA beef grading standards. Bison bulls in the current study were harvested at approximately 30 and 36 months of age, which falls within the average age range of harvest (between 20 and 36 months) reported by previous studies (Hawley, 1986; Marchello et al., 1989, 1998; Marchello and Driskell, 2001; Rule et al., 2002; Galbraith et al., 2006; Janssen et al., 2021).

The effects of treatment on live weight and carcass characteristics are presented in Table 1. Although sample size differed between groups for live weight and carcass trait evaluation (n = 98 and 24 for Young and Mature bulls, respectively), this disparity reflects common industry practice and natural population structure of commercial bison herds. The smaller size of the Mature bull treatment group is a limitation of the carcass results. Mature bulls had increased (P < 0.001) live weight, hot carcass weight, dressing percentage, ribeye area, kidney fat percentage, and marbling scores compared to Young bulls. However, Young bulls had increased backfat thickness (P = 0.0003) when compared to Mature bulls (Table 1). The carcass weight of Mature bulls in this study was lower than the range reported by USDA-AMS for aged bulls (313–560 kg) in the National Monthly Bison Report for the same time period (USDA-AMS, 2021). However, the Mature bulls in this study were likely significantly younger than the average age of Mature bulls reported by the USDA, which are likely culled from the breeding herd at well over 36 months of age. Young bulls were also lighter than the USDA report for Young bulls; however, the USDA-AMS report is focused on grain-finished bulls; therefore, it is expected that grass-finished bulls in the current study would be lighter. Dressing percentage of Young (55.9%) and Mature (57.8%) bulls was less than the dressing

TABLE 1 Least square means for effect of finishing treatment[1] on live weight and carcass characteristics of bison bulls.

Variable	Young[1]	Mature[1]	SEM[2]	*P*-Value[3]	Overall mean (SD)[4]
Live weight, kg	414	510	5.4	<0.0001	433 (46.3)
Hot carcass weight, kg	232	295	3.6	<0.0001	244 (30.8)
Dressing percentage, %	55.9	57.8	0.33	<0.0001	56.3 (1.8)
Ribeye area, cm^2	59.8	64.4	1.27	0.001	60.7 (6.4)
Backfat thickness, cm	0.25	0.20	0.012	0.0003	0.24 (0.06)
Kidney fat, %	0.07	0.20	0.028	<0.0001	0.03 (0.65)
Marbling score[5]	105	191	6.1	<0.0001	122 (45.5)
Yield grade[6]					
Yield Grade 1, %	77.6	41.7	10.06	0.001	70.4 (45.6)
Yield Grade 2, %	22.5	58.3	10.06	0.001	29.5 (45.6)
Subjective skeletal maturity[7]					
Moderate, %	0.0	16.7	7.61	0.970	3.28 (17.8)
Slight, %	100.0	83.3	7.61	0.970	96.7 (17.8)
Lean maturity[7]					
Dark cutter, %	0.0	4.2	4.07	0.973	0.82 (9.02)
Pale red, %	1.0	16.7	7.60	0.010	4.10 (19.8)
Red, %	11.2	29.2	9.27	0.034	14.8 (35.5)
Slightly Bright Red, %	75.5	33.3	9.62	0.0003	67.2 (46.9)
Moderately Bright Red, %	12.2	16.7	7.6	0.567	13.1 (33.8)
Subjective external fat color[7]					
Yellow, %	3.1	16.7	7.60	0.023	5.74 (23.3)
Moderately Yellow, %	39.8	66.7	9.62	0.022	45.1 (49.8)
Slightly White, %	8.2	16.7	7.60	0.221	9.84 (29.8)
Moderately White, %	15.3	0.0	3.63	0.977	12.3 (32.8)
White, %	33.7	0.0	4.77	0.975	27.0 (44.4)

[1] Treatments: Young bison bulls finished on fall pasture and harvested at 30 months of age with no exposure in the breeding herd. Mature bison bulls finished on early summer pasture and harvested at 36 months of age following use in the breeding herd.
[2] Standard error of the mean.
[3] Probability of difference among least square means.
[4] Overall descriptive mean and standard deviation.
[5] Marbling score: 100 = Practically Devoid^0, 200 = Traces^0.
[6] Yield grade calculated according to USDA beef grading system.
[7] Assigned by USDA grader.

percentage reported by Newton et al. (2024) and Peters (1958) for grain-finished bison bulls (60.3% and 60.1%, respectively). This could be a response of grass-finishing resulting in a more developed/heavier rumen, but less backfat and lighter muscling.

The ribeye area of Mature bulls was 64.4 cm^2, which was similar to the ribeye area of grain-finished heifers (64.6 cm^2) reported by Janssen et al. (2021) and grain-finished bulls (65.1 cm^2) reported by Newton et al. (2024). Young bulls had a ribeye area of 59.8 cm^2, which is similar to the ribeye area of bison steers (60.5 cm^2) reported by Hawley (1986) and grass-finished bulls (59.8 cm^2) reported by Newton et al. (2024). Mature bison bulls had an increased ($P < 0.0001$) kidney fat percentage when compared to Young bulls (0.20% and 0.07%, respectively). While the difference in kidney fat percentage was statistically significant, the amount of kidney fat detected in both treatments was negligible. Young and Mature bulls had marbling scores of 105 and 191, respectively. Marbling scores for both treatments would fall into the practically devoid category of the USDA beef quality grading system. To compare the yield grade (YG) of bison bulls, measurements were recorded and evaluated according to the equation used to calculate beef yield grades. An increased proportion ($P = 0.001$) of Young bison bulls was categorized as YG 1 compared to Mature bulls. An increased proportion (P = 0.001) of Mature bulls were categorized as YG 2. There were no YG 3, 4, or 5 carcasses in the study.

Carcass maturity and subjective external fat and lean color

Treatment did not influence (P > 0.05) the proportion of bulls in each skeletal ossification category, and no bulls were classified in the extreme hardbone (100%–200% ossification) or hardbone (50%–99% ossification) categories for skeletal maturity (Table 1). There was no difference (P > 0.05) in the proportion of each treatment classified as dark cutter or moderately bright red (Table 1). A greater proportion of (P = 0.0003) of Young bulls were classified as having slightly bright red lean color compared to Mature bulls. However, a greater percentage ($P \leq 0.03$) of Mature bulls had lean color classified as pale red or red. Young bulls were more likely to be categorized (P = 0.0003) as having slightly bright red lean color (75.51%) and least likely to be categorized as having pale red lean color (1.02%). Mature bulls were relatively evenly distributed between pale red, red, slightly bright red, and moderately bright red, indicating that advancing age may result in less consistent lean color.

Treatment did not influence (P > 0.05) the proportion of bulls classified as slightly white, moderately white, or white for external fat color (Table 1). A greater percentage (P < 0.05) of Mature bulls were classified as having yellow or moderately yellow external fat color compared to Young bison bulls. This increase in yellow fat for Mature bulls could be due to an increased concentration of β-carotene accumulated over time within adipose tissue, which has been shown to cause a yellow color in fat when cattle are finished on grass (Yang et al., 2002; Kerth et al., 2007; Janssen et al., 2021; Newton et al., 2024). Carotenoid levels are the highest in early-season forages and decline as forage matures (Noziere et al., 2006). Therefore, increased yellowness of subcutaneous fat from Mature bulls may be due to increased concentrations of carotenoids associated with early summer grazing. Regardless of treatment, bulls in this study were most likely to be categorized as having moderately yellow external fat (39.80% and 66.67% for Young and Mature bulls, respectively), which was expected in a grass finishing system. Additionally, no Mature bulls were classified as having moderately white or white exterior fat color.

Objective color and ultimate pH

The effects of pre-harvest treatment on objective color measurements and ultimate pH are presented in Table 2. Treatment did not influence (P > 0.05) L^* or a^* values of the lean tissue or subcutaneous backfat. Galli et al. (2008) and Pflanzer and de Felicio (2011) investigated the influence of animal age on meat color in beef and also reported that age at harvest did not influence L^* or a^* values of strip steaks. The b^* value of the exposed ribeye was increased for Mature bison bulls compared to Young bulls, indicating a more yellow/less blue color to the lean. Other studies have not reported differences in b^* value related to animal age (Pflanzer and de Felicio et al., 2011; Lu et al., 2025); however, in the present study, Mature bulls had increased marbling present in the ribeye, which may have contributed to increased yellowness of the exposed ribeye muscle. The b^* value of the subcutaneous backfat was also increased for Mature bulls, which aligned with the increased proportion of Mature bulls categorized with yellow or moderately yellow fat compared to Young bulls. Increased b^* (yellowness) in fat color is commonly associated with the accumulation of carotenoids in adipose tissue of grass-finished ruminants (Yang et al., 2002; Kerth et al., 2007), and as

TABLE 2 Least square means for the effect of finishing treatment[1] on objective color measurements and ultimate pH of Young and Mature bison bulls.

Variable	Young[1]	Mature[1]	SEM[2]	P-Value[3]	Overall mean (SD)[4]
Objective color: Lean tissue in ribeye area[5]					
L^*	35.93	35.56	0.393	0.402	35.86 (1.195)
a^*	20.93	21.16	0.329	0.533	20.97 (1.602)
b^*	6.72	7.28	0.229	0.031	6.83 (1.134)
Objective color: Subcutaneous backfat[5]					
L^*	76.01	75.99	0.562	0.978	76.01 (2.731)
a^*	2.52	2.92	0.404	0.368	2.60 (1.970)
b^*	18.62	24.25	0.675	<0.0001	19.73 (3.968)
Ultimate pH	5.65	5.64	0.015	0.365	5.65 (0.071)

[1] Treatments: Young bison bulls finished on fall pasture and harvested at 30 months of age with no exposure in the breeding herd. Mature bison bulls finished on early summer pasture and harvested at 36 months of age following use in the breeding herd.
[2] Standard error of the mean.
[3] Probability of difference among least square means.
[4] Overall descriptive mean and standard deviation.
[5] Objective color measurement recorded on the exposed ribeye or subcutaneous fat opposite the ribeye following approximately 30-minute bloom time; L^*: 0 = black, 100 = white; a^*: negative values = green, positive values = red; b^*: negative values = blue, positive values = yellow.

mentioned, carotenoid levels are the highest in early-season forages and decline as forage matures (Noziere et al., 2006), which may have resulted in increased yellowness of subcutaneous fat from Mature bulls grazing early summer pasture. Treatment did not influence ($P > 0.05$) the ultimate pH of bison striploins (Table 2). Ultimate pH values from this study were similar to values reported by Newton et al. (2024) and Janssen et al. (2021) and were well within the normal ultimate pH of meat (5.3 to 5.8 according to Aberle et al., 2012).

Warner-Bratzler shear force and cook loss

Warner-Bratzler shear force was affected ($P < 0.0001$) by the interaction of postmortem aging days and treatment (Figure 1). Steaks from Young bulls were more tender at all aging time points than steaks from Mature bulls. As aging time increased from day 4 to day 21, the WBSF of Young bison bull steaks did not change (linear and quadratic $P > 0.05$); however, the WBSF of Mature bison bull steaks decreased quadratically ($P < 0.05$) over time. In beef, numerous studies have investigated how postmortem storage improves the tenderness of meat (Goll et al., 1964; Calkins and Seideman, 1988; Koohmaraie et al., 1988). In beef, postmortem proteolysis generally proceeds rapidly through the first several days, after which the rate of proteolytic activity declines (Aberle et al., 2012). The quadratic decline in the WBSF of Mature bulls in this study agrees with this. However, in meat from more mature animals, the extent of tenderization can be reduced due to a limited or slower rate of proteolysis (Parrish et al., 1973; Huff-Lonergan et al., 1996). In bison, steaks from grain-finished bulls became more tender as aging time increased from day 4 to day 14, whereas the WBSF of steaks from grass-finished bulls did not differ during this period (O'Sullivan et al., 2025). Steaks from grass-finished bulls were more tender than steaks from grain-finished bulls at 4 days and 7 days, but treatments were similar at 14 and 21 days (O'Sullivan et al., 2025). In contrast, Janssen et al. (2021) observed that steaks from grain-finished heifers were more tender than grass-finished steaks, and the WBSF of steaks from bison heifers in both treatments decreased with postmortem aging. The American Society for Testing and Materials (ASTM International, 2011) beef tenderness standards include a minimum threshold value of 4.4 kg of WBSF to be classified as *tender* and 3.9 kg to be classified as *very tender*. Although these standards were developed for beef, the shear force results in this study indicate that Mature bulls were significantly tougher at all postmortem aging days and would require 21 days of aging to reach an acceptable level of tenderness, while Young bulls would meet the threshold for very tender by 4 days of aging. The WBSF results reported for bison steaks from both Janssen et al. (2021) and O'Sullivan et al. (2025) also met the threshold for tender product being produced with minimal aging.

Cook loss was affected ($P < 0.006$) by the interaction of postmortem aging and treatment (Figure 2). As aging time increased from day 4 to day 21, cook loss of Young bison bull steaks did not change (linear and quadratic $P > 0.05$); however, cook loss of steaks from Mature bulls decreased linearly ($P < 0.05$) as aging progressed. Janssen et al. (2021) reported similar results as cook loss decreased for grass-finished heifer steaks from days 4 to 7, but remained stable from days 7 to 21. All grain-finished steaks had decreased cook loss compared to 4-day grass-finished steaks; however, only 7-day grain-finished steaks had decreased cook loss compared to grass-finished steaks aged 7, 14, and 21 days. In contrast, O'Sullivan et al. (2025) concluded that aging day did not influence cook loss percentage for bison bull steaks; however, steaks

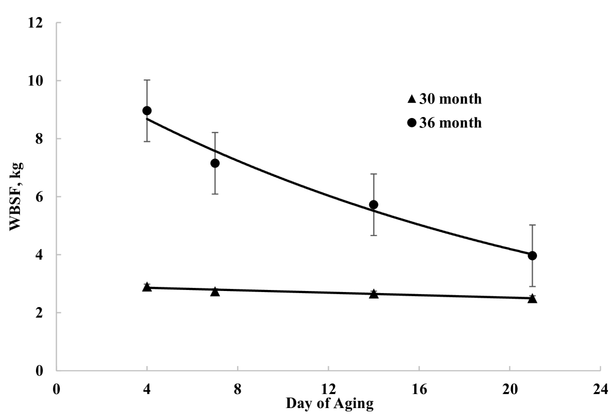

FIGURE 1
Least square means for the interaction of finishing treatment[1] and aging day on Warner-Bratzler Shear Force of striploin steaks from bison bulls. Error bars reflect standard error of the mean. Young bulls did not display linear or quadratic responses ($P > 0.05$), and Mature bulls displayed a quadratic response ($P < 0.05$). [1] Treatments: Young bison bulls finished on fall pasture and harvested at 30 months of age with no exposure in the breeding herd. Mature bison bulls finished on early summer pasture and harvested at 36 months of age following use in the breeding herd.

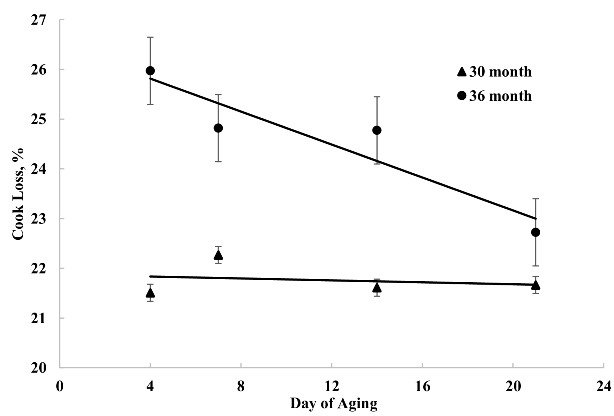

FIGURE 2
Least square means for the interaction of finishing treatment[1] and aging day on cook loss percentage of striploin steaks from bison bulls. Error bars reflect standard error of the mean. Young bulls did not display linear or quadratic responses ($P > 0.05$), and Mature bulls displayed a linear response ($P < 0.001$). [1] Treatments: Young bison bulls finished on fall pasture and harvested at 30 months of age with no exposure in the breeding herd. Mature bison bulls finished on early summer pasture and harvested at 36 months of age following use in the breeding herd.

from grass-finished bulls had greater cook loss compared to steaks from grain-finished bison bulls.

Collagen analysis

The effect of pre-harvest treatment on collagen content is presented in Table 3. Treatment did not influence ($P > 0.05$) the concentration of insoluble or heat-soluble collagen. However, total collagen was increased ($P = 0.024$) in samples from Young bulls compared to Mature bulls. Although this result was inverse to the WBSF findings, it suggests that the increased shear force of Mature bulls is not the result of increased collagen content or decreased collagen solubility. Therefore, other mechanisms that regulate tenderness, such as sarcomere length and postmortem proteolysis, should be explored to understand this impact on tenderness. A study by Mickelson and Claus (2020) reported no difference in the sarcomere length of bison from carcasses subjected to a postmortem vascular rinse compared to conventionally chilled carcasses. Furthermore, a study by O'Sullivan et al. (2025) investigated the influence of grain- or grass-finishing systems on the mechanisms that regulate tenderness in bison and also reported no differences in sarcomere length between finishing treatments. However, O'Sullivan et al. (2025) determined that samples from grass-finished bison bulls were more tender and had less intact desmin compared to samples from grain-finished bulls, concluding that postmortem proteolysis is a key mechanism regulating tenderization of bison.

Consumer and trained sensory analysis

Consumer sensory results are presented in Table 4. No treatment differences ($P > 0.05$) were detected by consumer panelists for overall liking, aroma liking, texture liking, juiciness intensity, or meat flavor intensity. Steaks from Mature bulls were rated higher ($P = 0.028$) for toughness intensity, which is supported by the objective tenderness results evaluated with WBSF. However, steaks from Mature bulls garnered higher ($P = 0.029$) ratings for flavor liking and lower ($P = 0.018$) ratings for off-flavor intensity. The reduction in off-flavor intensity is likely related to improvement in flavor liking. Given that Mature bulls were harvested in early summer and Young bulls in the fall, these findings may also reflect differences in forage diversity and forage quality associated with seasonal variation. Grasses and forbs available during early summer typically differ in nutrient composition, secondary metabolite content, mineral content, and overall maturity compared to those in late summer and fall (Grings et al., 1996; Johnson et al., 1998; Jensen et al., 2017; Verma and Shukla, 2015). These differences can influence flavor profile and off-flavor development in grass-finished meats through changes in lipid profile, lipid oxidation, and volatile compound precursors (Dewhurst et al., 2003; Fruet et al., 2018; Vaikundamoorthy et al., 2019). Consequently, slaughter season represents a confounding factor that may have contributed to the differences in sensory responses, particularly flavor liking and off-flavor intensity, between treatments. However, because bison experience a seasonal rut and the subsequent calving period is limited to a few months, controlling slaughter season independent of animal age is inherently difficult in this species. Differences in flavor perception could also be influenced by differences in intramuscular fat content, as Mature bulls had increased marbling scores compared to Young bulls. Even modest increases in marbling have been shown to enhance perceived juiciness and flavor intensity in beef and other red meats due to the solubilization of lipid-derived volatile compounds and the lubrication effects of melted fat (Smith and Carpenter, 1974; O'Quinn et al., 2012; Corbin et al., 2015). Thus, the higher flavor liking scores for Mature bulls may reflect both differences in lipid content and compositional variation in fatty acids related to forage maturity at finishing.

Trained sensory panel results are presented in Table 5. Treatment did not influence ($P > 0.05$) trained panelist perception of aroma intensity. However, panelists rated steaks from Young bulls higher ($P < 0.0001$) for flavor intensity. In contrast, results from the consumer panel indicated higher ratings for flavor liking for steaks from Mature bulls. This divergence between trained and consumer assessments likely reflects differences in the focus and expectations of the two types of panels (Ares and Varela, 2017). Trained panelists were instructed to evaluate isolated sensory attributes, emphasizing detectable intensity, while consumers were asked to assess overall liking, which can be influenced by juiciness, tenderness, and preconceived associations with mature or robust flavors. Additionally, the seasonal forage effect described earlier may have contributed to variation in flavor compounds or off-flavor notes, further influencing the panels' differing responses. Trained panelist ratings for toughness and juiciness were higher ($P < 0.0001$) for Mature

TABLE 3 Least square means for the effect of finishing treatment[1] on collagen content.

Variable	Young[1]	Mature[1]	SEM[2]	P-Value[3]	Overall mean (SD)[4]
Insoluble collagen, mg/g	2.05	1.94	0.067	0.057	2.01 (0.282)
Heat-soluble collagen, mg/g	0.22	0.20	0.055	0.247	0.21 (0.301)
Total collagen, mg/g	2.27	2.15	0.084	0.024	2.22 (0.302)

[1] Treatments: Young bison bulls finished on fall pasture and harvested at 30 months of age with no exposure in the breeding herd. Mature bison bulls finished on early summer pasture and harvested at 36 months of age following use in the breeding herd.
[2] Standard error of the mean.
[3] Probability of difference among least square means.
[4] Overall descriptive mean and standard deviation.

TABLE 4 Least square means for the effect of finishing treatment[1] on subjective meat quality attributes rated by a consumer sensory panel.

Attribute[2]	Young[1]	Mature[1]	SEM[3]	P-Value[4]	Overall mean (SD)[5]
Overall liking	19.59	24.84	3.462	0.285	22.22 (31.27)
Aroma liking	7.72	5.76	3.367	0.680	6.74 (30.32)
Flavor liking	14.94	25.76	3.472	0.029	20.35 (31.71)
Texture liking	26.02	19.62	3.679	0.221	22.82 (33.27)
Toughness intensity	12.49	15.92	1.093	0.028	14.21 (9.98)
Juiciness intensity	14.30	12.73	1.277	0.387	13.52 (11.52)
Meat Flavor intensity	19.17	19.67	1.113	0.752	19.42 (10.02)
Off-flavor intensity	9.30	5.98	0.981	0.018	7.64 (8.99)

[1] Treatments: Young bison bulls finished on fall pasture and harvested at 30 months of age with no exposure in the breeding herd. Mature bison bulls finished on early summer pasture and harvested at 36 months of age following use in the breeding herd.
[2] Liking ratings were made on a −100- to 100-point labeled affective magnitude scale, with the left-most end labeled greatest imaginable disliking and the right-most end labeled greatest imaginable liking. Intensity ratings were made on 0–51-point line scales with the left-most end labeled none and the right-most end labeled extremely intense for off-flavor.
[3] Standard error of the mean.
[4] Probability of difference among least square means.
[5] Overall descriptive mean and standard deviation.

bulls. The increased toughness ratings for steaks from Mature bulls were supported by consumer sensory results and WBSF results, as steaks from Young bulls were more tender at all aging time points than steaks from Mature bulls.

Management trade-offs and sustainability impacts

The results of this study highlight the management trade-offs inherent in grass-fed bison systems that retain bulls in the breeding herd prior to harvest. Retaining bulls for breeding enhances herd reproductive capacity and genetic diversity (Scheideman et al., 2025), which in turn supports the ecological resilience of rangeland ecosystems. Intact bulls contribute to the social structure of bison herds and maintain behaviors such as wallowing, rutting, and selective grazing that shape plant communities, nutrient cycling, and habitat heterogeneity (Ratajczak et al., 2022; Church et al., 2016). These roles promote biodiversity and strengthen the adaptive capacity of grasslands. However, retaining bulls for breeding also produces carcasses that are heavier but less tender, requiring longer aging to meet consumer expectations. These trade-offs illustrate the interconnectedness of production decisions with broader sustainability goals. By situating carcass and meat quality outcomes within the context of ecosystem services, this work reinforces that decisions about bison management must simultaneously consider animal biology, consumer acceptance, and the ecological role of bison as keystone grazers in North American grasslands.

Limitations

Several limitations should be considered when interpreting these results. First, although the number of Mature bulls (n = 24) was lower than that of Young bulls (n = 98), this imbalance reflects typical herd demographics in commercial bison operations, where relatively few bulls are retained for breeding. Nonetheless, the smaller sample size may have reduced statistical power to detect treatment differences for some traits. Second, because all animals

TABLE 5 Least square means for the effect of finishing treatment[1] on subjective meat quality attributes rated by a trained sensory panel.

Attribute[2]	Young[1]	Mature[1]	SEM[3]	P-Value[4]	Overall mean (SD)[5]
Aroma intensity	102.79	99.50	3.336	0.210	101.10 (33.91)
Flavor intensity	100.17	84.61	3.201	<0.0001	92.39 (36.35)
Toughness intensity	60.07	92.79	4.520	<0.0001	76.41 (42.10)
Juiciness intensity	67.36	81.06	2.979	<0.0001	74.15 (35.17)

[1] Treatments: Young bison bulls finished on fall pasture and harvested at 30 months of age with no exposure in the breeding herd. Mature bison bulls finished on early summer pasture and harvested at 36 months of age following use in the breeding herd.
[2] Evaluated on an anchored unmarked line scale with the far-left point indicating extremely tender, extremely juicy, no aroma, or extremely bland bison flavor, and the far-right point representing extremely tough, extremely dry, extreme aroma, or extremely intense bison flavor.
[3] Standard error of the mean.
[4] Probability of difference among least square means.
[5] Overall descriptive mean and standard deviation.

originated from a single herd in the Sandhills Ecoregion of Nebraska, these results are most directly applicable to bison managed under similar environmental and forage conditions. Forage species composition, mineral availability, and climatic factors can influence growth rates, fat deposition, and meat color characteristics; thus, extrapolation to other ecological contexts is cautioned. Third, seasonal differences in forage maturity between early summer and fall pastures may have introduced confounding effects, particularly on flavor and color attributes. These effects are difficult to fully separate from age-related factors due to the highly synchronized breeding and calving cycles of bison, which constrain the ability to harvest animals of comparable physiological age across seasons.

Conclusions

We hypothesized that bison bulls finished at a younger age and not used in the breeding herd would have improved carcass traits and meat quality compared to older bulls utilized in the breeding herd. Mature bison bulls had increased live weight, carcass weight, dressing percentage, ribeye area, kidney fat percentage, and marbling score when compared to Young bulls. We reject the hypothesis that bison bulls finished at a younger age and not used in the breeding herd would have improved carcass traits. Mature bulls had improved carcass traits, but did not have improved meat quality traits. Young bulls had improved meat quality, as Mature bulls were tougher at all postmortem aging days and required 21 days of aging to reach an acceptable level of tenderness. This difference in tenderness was perceived by both trained and consumer panelists.

This study provided some of the first data evaluating the influence of bison age and use in the breeding herd on carcass and palatability attributes of bison bulls. Furthermore, these results provided insight into how to avoid palatability issues for carcasses or primal cuts from bison bulls that have been utilized in the breeding herd and marketed as older animals. Based on these findings, it is recommended that cuts from Mature bulls used in the breeding herd be aged for a minimum of 21 days to ensure tenderness and maintain demand for bison products. The contrasting carcass and sensory profiles observed between Young and Mature bulls highlight important trade-offs that have implications for both economic and ecological sustainability within grass-fed bison systems. Young bulls provided improved tenderness, supporting consumer acceptability, while Mature bulls contributed heavier carcasses that would have an economic benefit and potentially more distinctive flavor characteristics that may appeal to niche markets. From a systems perspective, our findings contribute to the broader goals of bison conservation and sustainable management. By evaluating the effects of age and use in the breeding herd on carcass and meat quality attributes, this study can guide management strategies that balance economic viability and ecological function. Retaining Mature bulls for breeding supports natural reproductive behaviors and aligns with low-input, grass-based production systems that promote ecosystem restoration and resilience. At the same time, understanding the trade-offs in tenderness and flavor informs meat production practices that sustain consumer demand and market value, contributing to the economic sustainability of bison herds across sectors.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Rearing and harvesting of bison were performed in accordance with relevant guidelines and regulations set forth by the United States Department of Agriculture. This study evaluated bison from commercial ranches and did not involve intervention by the research team; therefore, Institutional Animal Care and Use Committee approval was not necessary. Written informed consent was obtained from the owners for the participation of their animals in this study. The studies involving humans were approved by University of Minnesota Institutional Review Board (IRB #6792) and South Dakota State University Institutional Review Board (IRB-2009013-EXM). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

LO'S: Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. CN: Data curation, Formal analysis, Investigation, Visualization, Writing – review & editing. KU: Investigation, Writing – review & editing. JG: Investigation, Writing – review & editing. CB: Investigation, Writing – review & editing. KC: Formal analysis, Writing – review & editing. TD: Investigation, Writing – review & editing. CK: Conceptualization, Methodology, Resources, Writing – review & editing. AB: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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This research forms the basis of a chapter of C.N.'s master's thesis. All authors confirm that the following manuscript is a transparent and honest account of the reported research. This research is related to a previous study by the same authors titled "Influence of finishing systems on sensory characteristics and the mechanisms regulating tenderness formation in the *longissimus lumborum* of bison bulls". The previous study was performed on grain- and grass-finished bison bulls, and the current submission is focused on management systems (animal age and use in the breeding herd). The study follows methodologies outlined in the Materials and Methods, as well as those referenced from the previous study. The content of this manuscript has been presented in part at the International Congress of Meat Science and Technology; O'Sullivan, L.M., C.J. Newton, K.R. Underwood, J.K. Grubbs, C.E. Bakker, K.M. Cammack, T. Dinh, C. Kruse, A.D. Blair. Influence of management systems on carcass traits, meat quality and sensory attributes of bison bulls. *69th International Congress of Meat Science and Technology*, Padova, Italy. 2023.

Conflict of interest

Turner Institute of Ecoagriculture provided funding, and CK is employed by Turner Enterprises, Inc. He was involved in the conceptualization and provided resources for the study but had no role in the decision to publish or the collection, analysis, or interpretation of the data.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Correction note

This article has been corrected with minor changes. These changes do not impact the scientific content of the article.

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