South Dakota State University
Department of Animal Science

FINAL REPORT

Understanding Sustainable Precision Livestock Strategies to Minimize the Carbon Footprint of Beef Production

Submitted to: Iowa Beef Industry Council

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NON-TECHNICAL SUMMARY

The experiment titled "**Understanding Sustainable Precision Livestock Strategies to Minimize the Carbon Footprint of Beef Production**" was conducted at the South Dakota State University Cottonwood Field Station in Cottonwood, SD, and the Cow-Calf Education and Research facility located in Brookings, SD. The study was led by Hector Menendez III, Ph.D., an Assistant Professor in the Department of Animal Science at South Dakota State University (Email: Hector.Menendez@sdstate.edu ; Office #: 605-394-2236). The project was designed to evaluate whether different grazing approaches and stocking rates during the stocker phase could influence beef quality later in the production chain, while also supporting long-term goals related to efficiency and carbon footprint reduction. The work builds on ongoing research focused on improving economic and environmental sustainability in beef production.

This project used yearling steers managed under two grazing systems: a continuous grazing system and a precision rotational grazing system using virtual fencing technology. Steers were also managed under light, moderate, or heavy stocking rates. After the grazing phase, cattle were finished using standard industry feedlot conditions followed by carcass evaluation (carcass characteristics). Strip loins (n=94) were collected at a commercial beef processing plant to perform carcass quality assessment including measures of meat quality (Warner-Bratzler shear force and sensory panel) as well as proximate composition. Further, a carbon footprint tool was developed to evaluate g CO_2e/kg hot carcass weight for three distinct phases: dry lot, stocker, and finishing.

Overall, the project showed that the grazing treatment and stocking rate combinations tested in this study **had no major effect on final carcass characteristics, sensory panel responses, or meat quality attributes**. Most carcass measurements, including hot carcass weight, ribeye area, marbling, backfat, dressing percentage, final body weight, and calculated yield grade, were similar across treatments. The only carcass trait that showed some evidence of a difference was internal fat deposition (kidney, pelvic and heart fat; KPH), where cattle in the moderate stocking group tended to be slightly higher. In practical terms, the study suggests that producers may have flexibility to use precision grazing strategies without causing negative effects on carcass value or meat quality.

Tenderness also showed differences early in aging (d 3 through d 7) but were mitigated by day 21. Aging time improved tenderness, which is expected in beef, but treatment and stocking rate did not create major differences in shear force values. Sensory panel results followed a similar pattern. Panelists did not detect meaningful differences in beef identity, tenderness, connective tissue, juiciness, or off-flavors among treatment groups. Proximate analysis also showed that moisture, protein, fat, and ash did not differ among treatments. Taken together, these results indicate that the grazing systems tested here did not substantially change the final beef product from a performance or consumer standpoint.

Carbon footprint analysis was conducted to estimate greenhouse gas emissions across the dry lot, grazing (stocker), and feedlot phases of production using IPCC (2019) Tier 2 methodologies and GreenFeed enteric methane measurements. Emissions included contributions from enteric fermentation, manure management, fuel use, and electricity depending on the production phase. When expressed relative to production (kg CO_2e per kg hot carcass weight), the overall carbon footprint ranged from **5.47 to 6.03 kg CO_2e/kg HCW** across pastures, with an overall average of approximately **5.78 kg CO_2e/kg HCW**. The grazing phase accounted for a substantial portion of total emissions due to the longer duration of the stocker period, while the feedlot phase contributed the largest absolute emissions because of higher animal intake and additional energy inputs such as fuel and electricity. Despite these differences across phases, the carbon footprint estimates were relatively similar among pastures and grazing treatments, suggesting that the grazing strategies evaluated did not produce large differences in total life-cycle greenhouse gas emissions when expressed per unit of beef produced.

From a producer perspective, this is an encouraging outcome. It means that adopting precision grazing tools such as virtual fencing may offer management and sustainability advantages without sacrificing carcass performance or consumer-relevant meat quality traits or sustainability metrics. This research supports the idea that precision livestock technology can be part of practical beef production systems aimed at improving efficiency, maintaining beef quality, and helping producers respond to future economic and environmental challenges.

TECHNICAL REPORT

Impacts

Based on carcass characteristics, tenderness measurements, trained sensory panel evaluations, and proximate analysis, producers can consider precision grazing strategies without expecting major negative impacts on beef composition or quality. Across the treatment and stocking combinations evaluated, carcass value and eating quality remained largely stable. These findings support the use of precision grazing technology as a potential management tool for improving flexibility and sustainability in beef production systems while maintaining a consistent end product.

List of quantitative impacts:

- Most carcass traits, including hot carcass weight, ribeye area, marbling, backfat, dressing percentage, and calculated yield grade, were not significantly affected by treatment or stocking rate.

- The majority of carcasses graded in the choice category, with relatively few grading prime or select.
- Most carcasses were yield grade 3 or 4, indicating moderate and commercially acceptable cutability.
- Moderate stocking showed some evidence of greater KPH, but that result was not consistent across statistical tests and should be interpreted with caution.
- Meat tenderness, sensory traits, and proximate composition were generally similar across treatments, suggesting that grazing strategy did not materially alter the final eating experience of the beef.
- Carbon footprint estimates ranged from 5.47 to 6.03 kg CO_2e per kg hot carcass weight**,** with no meaningful difference between continuous grazing and precision rotational grazing (virtual fencing) systems when emissions were expressed per unit of beef produced.

Introduction

Identifying management strategies that improve sustainability without sacrificing beef quality is an important goal for the beef industry. Grazing cattle, particularly during the stocker phase, contribute substantially to total enteric methane emissions in U.S. beef production, and producers continue to seek approaches that improve efficiency, reduce environmental impact, and maintain profitability. In the Northern Great Plains and similar production regions, summer grazing is widely used to grow stocker cattle before finishing, but grazing conditions can vary greatly depending on forage quality, stocking pressure, and pasture use. These management decisions may influence not only animal performance during grazing, but also carcass merit and meat quality later in the supply chain.

Precision livestock technology, including virtual fencing, offers producers a transformative way to manage cattle distribution and grazing intensity. However, there has been limited research examining whether these grazing strategies influence carcass characteristics, tenderness, sensory attributes, and overall beef quality. This project was developed to help fill that gap and provide information relevant to Iowa beef producers and others interested in practical tools that desired to enhance grazing management and reduce the carbon footprint while maintaining or improving beef value.

The objective of this study was to determine the effects of grazing management strategy and stocking rate on carcass traits, carcass quality, sensory characteristics, and proximate composition of beef from stocker steers that were later finished under similar feedlot conditions. The broader goal was to evaluate whether precision grazing can be adopted as a sustainable production strategy without negatively affecting the final beef product.

Materials and Methods

Animal management, harvest, and strip loin collection

All procedures involving the use of animals in this experiment were approved by the South Dakota State University Institutional Animal Care and Use Committee (Approval# 2501-010E).

Angus Yearling steers (n = 150) from a common origin (Jorgensen Land and Cattle) were received in the spring of 2024, trained to precision technologies in a dry lot, and managed throughout both grazing and finishing phases (Figure 1). The dry lot and grazing phases were conducted at the SDSU Cottonwood Field Station (Cottonwood, SD). The experimental design was a factorial arrangement of two grazing management treatments and three stocking rates.

Grazing management treatments included: 1) Continuous grazing (CG), in which steers had access to the entire pasture for the duration of the grazing season, and 2) Precision grazing (PG), in which steers were managed using virtual fencing technology and rotated among virtual paddocks. Stocking rate treatments included light, moderate, and heavy stocking. The long-term pasture design consisted of six pastures arranged in two replicate blocks with three grazing intensities. Steers grazed for approximately 3 months during the summer beginning in mid-May. All cattle assigned to the precision grazing treatment were fitted with Vence™ virtual collars to monitor animal location and enforce virtual boundaries.

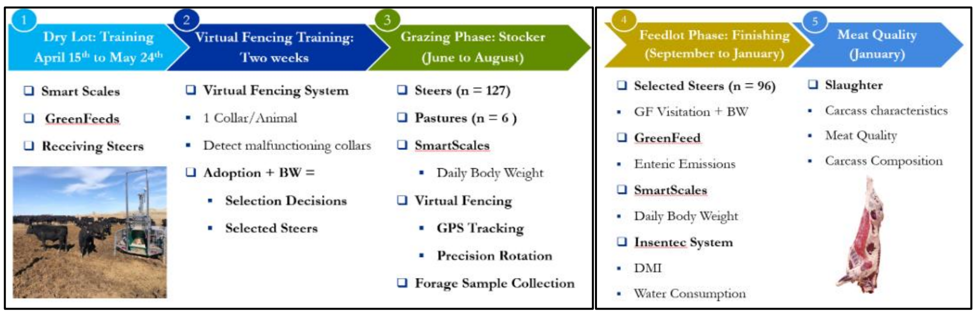

Figure 1. Overview of the 2024-2025 steer grazing trial at the SDSU Cottonwood Field Station and the SDSU Cow-Calf Education and Research Center.

After the grazing phase, a subsample of steers (n = 96) selected to represent the average body weight and performance within treatment groups were moved to the feedlot at the SDSU Cow-Calf Education and Research Facility (CCERF; located in Brookings, SD) for finishing under common conditions until harvest. Steers were harvested at a commercial packing facility. At harvest, cattle were tracked individually and carcass measurements including hot carcass weight, ribeye area, backfat thickness, kidney-pelvic-heart fat, marbling score, dressing percentage, quality grade, and yield grade were recorded. A strip loin from one side of each carcass was collected for additional meat quality testing. Strip loins were transported to the South Dakota State University Meat Laboratory for fabrication and subsequent evaluation of objective tenderness, cook loss, trained sensory attributes, and proximate composition. Strip loins were cut into 1-inch steaks and individually vacuum packaged. Four steaks were assigned to aging periods of 3, 7, 14, or 21 days for Warner–Bratzler shear force evaluation, and additional steaks aged for 14 days were used for trained sensory and proximate composition analyses.

Warner-Bratzler shear force and cook loss

Objective tenderness was evaluated using Warner–Bratzler shear force (WBSF) analysis. Steaks assigned to WBSF were aged for 3, 7, 14, or 21 days then frozen until shear force evaluation. Average shear force was recorded in kilograms-force (kgf). Cook loss was also determined for each steak and expressed as a percentage. Peak cooking temperature was recorded and included as a covariate in the statistical analysis for both WBSF and cook loss.

Trained sensory evaluation

Trained sensory evaluation was conducted using steaks aged for 14 days. Panelists (n = 12 – 14 per session) were asked to evaluate samples for sensory traits including beef identity, muscle fiber tenderness, connective tissue amount, juiciness, and off-flavor incidence. Beef identity, connective tissue, and juiciness were analyzed as ordinal responses, muscle fiber tenderness was analyzed as a continuous response, and off-flavor was analyzed as a binary outcome. Panelist and session effects were accounted for statistically to address repeated scoring and differences in scale use among panelists.

Proximate composition

Proximate composition analysis was conducted on steaks from the strip loin subsample. Traits evaluated included percent moisture, crude fat, crude protein, and ash. These measurements were used to characterize the basic chemical composition of beef samples across treatment groups.

Beef carbon footprint

Greenhouse gas (GHG) emissions were estimated using Tier 2 methodologies from the Intergovernmental Panel on Climate Change (2019), emission factors from the United States Environmental Protection Agency GHG Emission Factors Hub (2025), and enteric methane data collected using the C-Lock Inc. GreenFeed Pasture System (Rapid City, SD). Emissions were calculated separately for three production phases (dry lot, grazing, and feedlot) at the pasture level and then summed to estimate total system emissions. Enteric methane (CH_4) emissions were derived directly from GreenFeed measurements, while methane (CH_4) and nitrous oxide (N_2O) emissions from manure management were estimated using IPCC (2019) equations, including both direct and indirect pathways (volatilization and leaching), with parameters adjusted for management system and diet. Fuel-related CO_2 emissions were calculated from equipment use and EPA emission factors, and electricity-related emissions during the feedlot phase were estimated from energy consumption data derived from the CCERF manager and standard emission factors for CO_2, CH_4, and N_2O. All emissions were expressed as CO_2 equivalents (CO_2e) and aggregated at the herd level, accounting for animal numbers and duration of each phase. Total emissions were then divided by hot carcass weight (HCW) to estimate the carbon footprint (kg CO_2e/kg HCW) for each pasture.

Statistical analysis

Carcass traits were analyzed using linear mixed models in Program R for Statistical Computing with the lmerTest package. For each carcass response, the fixed effects included treatment, stocking, and their interaction (treatment × stocking), with pen included as a random effect. Warner-Bratzler shear force and cook loss were analyzed using linear mixed-effects models. Fixed effects included treatment, stocking, aging day, all two-way and three-way interactions among these variables, and peak temperature as a covariate. Striploin ID was included as a random intercept to account for repeated observations collected from the same strip loin.

Sensory traits were analyzed using mixed-effects models appropriate to the response scale. Ordinal sensory responses were analyzed using cumulative link mixed models (CLMM) with treatment, stocking, and their interaction as fixed effects, and striploin ID, panelist, and session included as random effects. Muscle fiber tenderness was analyzed using a linear mixed model (LMM) with the same fixed and random effects structure. Off-flavor incidence was analyzed using a generalized linear mixed model (GLMM) with a binomial distribution and logit link. Statistical significance was declared at $P \leq 0.05$, and tendencies were discussed at $0.05 < P \leq 0.10$.

Results

Carcass and Meat Quality Summary

Overall, grazing system and stocking rate had minimal impact on carcass performance and beef quality. Hot carcass weight (~943–960 lb; P = 0.341), ribeye area (~13.3–13.5 in^2; P = 0.441), marbling (P = 0.319), backfat (~0.66–0.71 in; P = 0.342), dressing percentage (~62.9–63.2%; P = 0.597), final body weight (~1499–1529 lb; P = 0.667), and calculated yield grade (~3.8–4.0; P = 0.385) were all similar across treatments and stocking rates (Table 1). The only carcass trait showing some evidence of a difference was internal fat (KPH; ~1.88–1.96%; P = 0.0279 for stocking), where moderate stocking tended to be slightly higher; however, this result was not consistent across all statistical tests and should be interpreted cautiously. Most carcasses graded **Choice** (55.9%), with fewer grading Select (17.2%) or Prime (5.4%), and the majority fell into **Yield Grade 3 (53.2%) or 4 (37.2%)**, indicating typical, commercially acceptable carcass outcomes.

Tenderness and Cooking Performance

Tenderness improved with aging, which is expected in beef production. Treatment had a modest effect on shear force (P = 0.024), with rotational grazing tending to produce slightly more tender beef early in aging (d 3 to d 7); however, these differences diminished over time (d 7 through d 21). Stocking rate did not have a consistent effect (P = 0.276). Cook loss increased with aging and cooking temperature, but treatment (P = 0.988) and stocking rate (P = 0.514) did not meaningfully influence cooking performance (**Table 2**).

Table 1. Carcass characteristics of steers managed under different stocking rates (light, moderate, heavy) and grazing treatments (continuous grazing, C_G; rotational grazing, R_G). Traits include hot carcass weight (HCW; lb), ribeye area (REA; in²), marbling score (unitless), backfat thickness (in), kidney-pelvic-heart fat (KPH; %), dressing percentage (DP; %), initial shrunk body weight (ISBW; lb), final shrunk body weight (FSBW; lb), and calculated yield grade (CALC_YG; unitless). Values are presented as means with standard errors of the mean (SEM). P-values represent the effects of stocking rate, treatment (Trt), and their interaction.

Item	Stocking			SEM	Treatment		SEM	P-Values		
	Light	Moderate	Heavy		C_G	R_G		Stocking	Trt	Interaction
HCW	962.55	941.6	951.5	13.29	943.98	959.79	10.84	0.341	0.892	0.604
REA	13.5	13.3	13.47	0.22	13.34	13.5	0.18	0.441	0.91	0.577
MARBLING	464.74	452.85	468.7	16.47	464.51	459.68	14.7	0.319	0.565	0.356
BACKFAT	0.66	0.71	0.67	0.02	0.66	0.7	0.02	0.342	0.711	0.243
KPH	1.88	1.96	1.92	0.03	1.91	1.93	0.02	0.0279	0.149	0.167
DP	63.1	63.03	62.94	0.26	62.88	63.16	0.21	0.597	0.839	0.446
ISBW	849.7	826.54	817.44	11.9	831.83	830.62	9.76	0.676	0.596	0.581
FSBW	1528.83	1499.52	1515.42	18.76	1510.62	1518.56	15.3	0.667	0.978	0.968
CALC_YG	3.96	3.99	3.83	0.13	3.83	4.03	0.12	0.385	0.342	0.693

Table 2. Warner–Bratzler shear force (WBSF; kgf) and cook loss (%) of beef strip loins aged for 3, 7, 14, and 21 days from steers managed under different stocking rates (light, moderate, heavy) and grazing treatments (continuous grazing, C_G; rotational grazing, R_G). Values are presented as least-squares means with standard errors of the mean (SEM). P-values represent the effects of stocking rate, treatment (Trt), and their interaction.

Item	Stocking			SEM	Treatment		SEM	P-Values		
	Light	Moderate	Heavy		C_G	R_G		Stocking	Trt	Interaction
WBSF (kgf) - Day 3	4.09	4.15	4.22	0.15	4.42	3.89	0.13	0.276	0.0242	0.121
WBSF (kgf) - Day 7	3.47	3.6	3.48	0.15	3.71	3.33	0.12	0.276	0.0242	0.121
WBSF (kgf) - Day 14	2.99	3.19	3.1	0.15	3.28	2.9	0.12	0.276	0.0242	0.121
WBSF (kgf) - Day 21	2.89	2.96	2.9	0.15	2.95	2.88	0.12	0.276	0.0242	0.121
Cook Loss (%) - Day 3	20.68	20.52	21.36	0.54	20.74	20.97	0.44	0.514	0.988	0.833
Cook Loss (%) - Day 7	22.47	22.08	22.56	0.53	22.27	22.47	0.43	0.514	0.988	0.833
Cook Loss (%) - Day 14	22.95	23	22.18	0.53	23.21	22.21	0.43	0.514	0.988	0.833
Cook Loss (%) - Day 21	23.52	22.19	23.47	0.53	22.62	23.51	0.43	0.514	0.988	0.833

Sensory evaluation

Consumer-relevant traits—including beef flavor, tenderness, juiciness, and connective tissue—were not significantly affected by grazing system or stocking rate (**P > 0.05**). Off-flavor detection showed a slight tendency for a stocking effect (P = 0.069), where moderate stocking had a lower probability of off-flavors compared to light stocking, but overall differences were minimal (**Table 3**).

Table 3. Sensory panel evaluation of beef strip loins from steers managed under different stocking rates (light, moderate, heavy) and grazing treatments (continuous grazing, C_G; rotational grazing, R_G). Traits include beef identity, muscle fiber tenderness (MF tenderness), connective tissue, juiciness (panel scores), and off-flavor probability (proportion). Values are presented as least-squares means with standard errors of the mean (SEM). P-values represent the effects of stocking rate, treatment, and their interaction.

Item	Stocking			SEM	Treatment		SEM	P-Values		
	Light	Moderate	Heavy		C_G	R_G		Stocking	Treatment	Interaction
Beef Identity	8.07	8.15	7.87	0.89	8.09	7.96	0.89	0.631	0.439	0.909
MF Tenderness	8.91	8.59	8.86	0.3	8.64	8.93	0.29	0.326	0.894	0.341
Connective Tissue	8.48	8.68	8.74	0.56	8.72	8.55	0.56	0.147	0.443	0.273
Juiciness	10.77	10.31	10.57	0.65	10.42	10.68	0.64	0.706	0.502	0.983
Off-Flavor Probability	0.12	0.06	0.11	0.04	0.08	0.12	0.04	0.069	0.796	0.378

Proximate Composition

Moisture (~70.7–71.1%; P = 0.846), crude fat (~5.1–5.5%; P = 0.880), crude protein (~21.5–21.6%; P = 0.821), and ash (~1.01–1.02%; P = 0.936) were not affected by treatment or stocking rate, indicating that the basic nutritional composition of the beef remained consistent across production systems (Table 4).

Table 4. Proximate composition of beef strip loins from steers managed under different stocking rates (light, moderate, heavy) and grazing treatments (continuous grazing, C_G; rotational grazing, R_G). Traits include moisture (%), crude fat (%), crude protein (%), and ash (%) expressed on a dry matter basis. Values are presented as least-squares means with standard errors of the mean (SEM). P-values represent the effects of stocking rate, treatment (trt), and their interaction.

Item	Stocking			SEM	Treatment		SEM	P-Values		
	Light	Heavy	Heavy		C_G	R_G		Stocking	Trt	Interaction
Moisture	70.77	71.05	70.88	0.23	70.82	70.98	0.19	0.846	0.671	0.757
Crude Fat	5.53	5.1	5.35	0.29	5.44	5.21	0.23	0.88	0.802	0.701
Crude Protein	21.58	21.61	21.58	0.16	21.64	21.54	0.15	0.821	0.895	0.722
Ash	3.49	3.5	3.49	0.08	3.48	3.51	0.06	0.929	0.978	0.828

Carbon Footprint

Carbon footprint estimates ranged from 5.47 to 6.03 kg CO_2e per kg hot carcass weight**,** representing about a 10% difference among individual pastures. When grouped by grazing system, continuous grazing (P1, P5, P6) and precision rotational grazing using virtual fencing (P2, P3, P4) both averaged approximately 5.78 kg CO_2e/kg HCW, indicating no meaningful difference (< 0.1%) in greenhouse gas emissions per unit of beef produced between systems (Table 5).

Table 5. Greenhouse gas emissions and carbon footprint of beef production across pastures, partitioned by production phase (dry lot, grazing, and feedlot). Emissions are reported as herd-level carbon dioxide equivalents (kg CO_2e) for each phase, along with total emissions per pasture, total hot carcass weight (HCW; kg), and carbon footprint expressed as kg CO_2e per kg HCW.

Pasture	Dry lot	Grazing	Feedlot	Total emissions	Total HCW	Carbon footprint
1	5779	12277	21522	39578	6765	5.85
2	5795	12822	20600	39217	6765	5.80
3	5561	12180	21217	38957	6765	5.76
4	5561	11959	21509	39029	6765	5.77
5	4932	11886	20167	36986	6765	5.47
6	5997	11988	22793	40778	6765	6.03

Conclusions

Across carcass traits, meat quality, and the carbon footprint, the grazing systems evaluated in this study performed similarly. These results suggest that **precision grazing technologies such as virtual fencing can be adopted without negatively affecting beef quality or increasing emissions**, giving producers flexibility to improve pasture management while maintaining performance and product consistency. No unexpected problems or negative outcomes were observed during the course of this study.

Project Deliverables

Refereed Journal Publication: Plan to submit the results from this experiment to either Journal of Animal Science (JAS) or Translational Animal Science (TAS) by July 2026.

Reviewed Abstracts: Results from this experiment will be prepared for submission as reviewed abstracts to relevant scientific meetings and professional conferences, with submissions anticipated in upcoming conference cycles.

Extension Publications: Results from this experiment will be developed into a producer-focused extension article and integrated into an ongoing extension series on feed management and sustainability through the National Animal Nutrition Program. In collaboration with the NANP Feed Management Committee, these findings will also support the launch and outreach of the **Beef Carbon Footprint Calculator**, available as both an Excel-based and online decision-support tool through the NANP website and SDSU Extension. This effort will help translate research outcomes into practical tools and guidance for producers to improve efficiency and evaluate carbon footprint in real-world beef production systems.

Personnel Support: A Ph.D. student was partially supported by this grant, which covered 7 months of a graduate research assistant stipend, fringe benefits, and tuition.