Cattle and carcass performance, and life cycle assessment of production systems utilizing additive combinations of growth promotant technologies

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ABSTRACT: The objective of this study was to determine the impact of beef production systems utilizing additive combinations of growth promotant technologies on animal and carcass performance and environmental outcomes. Crossbred steer calves (n =120) were stratified by birth date, birth weight, and dam age and assigned randomly to one of four treatments: 1) no technology (NT; control), 2) antibiotic treated (ANT; NT plus therapeutic antibiotics and monensin and tylosin), 3) implant treated (IMP; ANT plus a series of 3 implants, and 4) beta-agonist treated (BA; IMP plus ractopamine-HCl for the last 30 d prior to harvest). Weaned steers were fed in confinement (dry lot) and finished in an individual feeding system to collect performance data. At harvest, standard carcass measures were collected and the United States Department of Agriculture (USDA) Yield Grade and Quality Grade were determined. Information from the cow-calf, growing, and finishing phases were used to simulate production systems using the USDA Integrated Farm System Model, which included a partial life cycle assessment of cattle production for greenhouse gas (GHG) emissions, fossil energy use, water use, and reactive N loss. Body weight in suckling, growing, and finishing phases as well as hot carcass weight was greater ($P < 0.05$) for steers that received implants (IMP and BA) than non-implanted steers (NT and ANT). The average daily gain was greater ($P < 0.05$) for steers that received implants (IMP and BA) than non-implanted steers during the suckling and finishing phases, but no difference ($P = 0.232$) was detected during the growing phase. Dry matter intake and gain:feed were greater ($P < 0.05$) for steers that received implants than non-implanted steers during the finishing phase. Steers that received implants responded ($P < 0.05$) with a larger loin muscle area, less kidney pelvic and heart fat, advanced carcass maturity, reduced marbling scores, and a greater percentage of carcasses in the lower third of the USDA Choice grade. This was offset by a lower percentage of USDA Prime grading carcasses compared with steers receiving no implants. Treatments did not influence ($P > 0.05$) USDA Yield grade. The life cycle assessment revealed that IMP and BA treatments reduced GHG emissions, energy use, water use, and reactive nitrogen loss compared to NT and ANT. These data indicate that growth promoting technologies increase carcass yield while concomitantly reducing carcass quality and environmental impacts.

Key words: beef, beta agonist, carcass, growth promotant technology, implant, life cycle assessment

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INTRODUCTION

It is estimated that global food production must increase by 70% to feed a projected nine billion people by 2050 (FAO, 2009). Growth promotant technologies including hormone-based implants, beta-agonists, and antibiotics are known to improve animal productivity resulting in more efficient meat production (Vogel and Laudert, 1994; Lawrence and Ibarburu, 2007; Duffield, et al., 2012; Johnson et al., 2013). However, the average American beef consumer is several generations removed from production agriculture and given this disconnect, the use of technologies is often questioned and have created a growing demand for beef with credence attributes such as, "raised without the use of added hormones" and "raised without antibiotics" (Umberger et al., 2009; Capper, 2012; Lourenco et al., 2016). Cattle producers are faced with a dichotomy between producing more beef versus producing beef without growth promotant technologies, which may impact operational sustainability.

More data regarding the emission reduction and resource preservation that could be gained by improved animal productivity in systems that utilize additive combinations of growth promotant technology are needed. Therefore, the hypothesis of this research was that raising cattle with growth promoting technologies would result in improved animal performance and reduced environmental impacts compared to cattle raised without technology. The first objective was to determine the effects of production systems using additive combinations of growth promotant technologies on animal and carcass performance. The second objective was to predict the use of natural resources and production of greenhouse gas (GHG) and nitrogen (N) emissions using simulation modeling.

MATERIALS AND METHODS

Animals and Experimental Design

All animal care and experimental protocols were approved by the South Dakota State University (SDSU) Animal Care and Use Committee (approval number 15-091E). Angus × Simmental steer calves (n = 120) born within a 45 d period at the SDSU Antelope Range and Livestock Research Station near Buffalo, SD, were utilized. Calves were stratified by birth date, birth weight, and dam age to 1 of 4 production system treatments in a completely randomized design. Calves assigned to treatment 1 received no technology (NT; control). Calves assigned to treatment 2 were treated with antibiotics and antimicrobials (ANT; NT plus therapeutic antibiotics and fed 300 mg monensin [Rumensin 90, Elanco Animal Health, Greenfield, IN]) and 90 mg tylosin [Tylan 40, Elanco Animal Health] during the finishing phase). Calves assigned to treatment 3 were administered ANT technologies and implanted (IMP; ANT plus a series of three implants including a suckling calf implant [36 mg zeranol; Ralgro, Merck Animal Health, Madison, NJ] at an average of 74 ± 12 d of age on June 29, a moderate-potency initial feedyard implant [80 mg trenbolone acetate and 16 mg estradiol; Revalor-IS, Merck Animal Health] at an average of 235 ± 12 d of age on December 8, and a high potency finishing implant [200 mg trenbolone acetate and 20 mg estradiol; Revalor-200, Merck Animal Health] at an average of 330 ± 12 d of age on March 11). Calves assigned to treatment 4 were administered all IMP technologies plus a beta-agonist (BA; IMP plus fed a beta-agonist [200 mg ractopamine hydrochloride (RH) per steer daily [Optaflexx 45; Elanco Animal Health]]) for the last 30 d before harvest. Across all treatments, cattle were treated with therapeutic antibiotics as needed for disease intervention. Within the NT treatment, any cattle treated with antibiotics were removed from the experiment.

Pre-Weaning Calf Management and Backgrounding (Growing Period)

The study was initiated on June 29, 2015, when all steers were branded, vaccinated with a killed vaccine for clostridial diseases (Vision 7 Somnus with SPUR, Merck Animal Health), and individually weighed without shrink in a hydraulic squeeze chute with load cells mounted under the chute (Weigh-Tronix model 1015; Avery Weigh-Tronix, Fairmont, MN). All steers allocated to IMP and BA received a pre-weaning implant. On September 16, steers were provided a clostridial disease booster and administered a modified-live vaccine for the prevention of respiratory viruses and *Mannheimia haemolytica* (Pyramid 5+ Presponse SQ, Boehringer Ingelheim Vetmedica, Inc., St. Joseph, MO). At weaning on October 26, steers were provided a booster for the respiratory disease vaccine, weighed, and shipped approximately 322 km to the SDSU Cottonwood Range and Livestock Field Station near Phillip, SD. Steers were fed grass hay and dried distillers grains with soluble as a common group during a two week weaning period. On November 9, steers were administered an anthelmintic (Dectomax Pour-On Solution, Zoetis, Parsippany, NJ). Initial backgrounding period body weights (BW) were recorded on November 9 and 10 without restriction from feed and water. On November 10, steers were assigned to one of 12 pens according to BW blocks (light, medium, or heavy), resulting in a total of three blocks per treatment. Steers received a high-roughage growing ration (Table 1) during a 56 d backgrounding period (until January 5, 2016). Mean dry matter intake (DMI) during the backgrounding period was 5.8 ± 0.5 (mean ± SD) kg/d. Feed was delivered with a mixer wagon (Farm Aid, model 340; Corsica, SD) each morning at 0900 h.

Table 1. Composition of the growing and finishing diets for steers assigned to different production systems utilizing additive combinations of growth promotant technologies

Item	Growing	Finishing
Ingredient composition, % of DM		
Dry-rolled corn	20.0	47.8
Wet corn gluten feed		40.0
Grass hay	65.0	7.2
Dried distiller's grains with solubles	14.1	
Limestone	0.9	
Supplement*		5.0
Nutrient composition		
NE_m, Mcal/kg	1.4	2.0
NE_g, Mcal/kg	0.8	1.4
ADF, % of DM	27.2	7.5
CP, % of DM	12.8	13.9

*Supplement contained 58.3% ground corn, 29.6% limestone, 5.6% iodized salt, 4.7% ammonia chloride, 0.93% trace mineral mix, 0.25% thiamine, and 0.21% Vitamins A, D, and E. Supplement for antibiotic treated, implant treated, and beta-agonist treated steers also included 300 mg monensin and 90 mg tylosin per steer daily. Further, the supplement for the beta-agonist treatment included 200 mg ractopamine HCl per steer daily during the last 30 days before harvest.

On December 8 steers were weighed and IMP and BA steers were administered the initial feedlot implant. At the termination of backgrounding, steers were weighed on consecutive days (January 4 and 5), re-vaccinated for respiratory diseases (Bovi-Shield Gold 5, Zoetis, Parsippany, NJ), and shipped approximately 430 km to the University of Nebraska-Lincoln West Central Research and Extension Center in North Platte, NE.

Feedlot Management

Upon arrival at the West Central finishing facility, all steers were maintained within their original pen assignment and received three concentrate-adaptation diets fed for 7, 7, and 40 d, respectively. Steers received the final finishing diet (Table 1) from day 55 to slaughter. Each morning (0800 h) and evening (1600 h) a feed truck (Roto-Mix, model 274; Dodge City, KS) delivered the diet. For steers assigned to ANT, IMP, and BA, the ration included monensin and tylosin. To ensure that steers in the NT treatment did not receive any carryover monensin or tylosin, the feed truck was flushed with ground hay before feeding the NT diet during the evening feed delivery and the NT diet was fed first during the morning feeding. Additionally, a separate feed wagon (Roto-mix, 220; Dodge City, KS) was utilized to deliver the BA treatment containing RH during the last 30 d before harvest.

On March 11, all steers were administered an anthelmintic (Ivermax Pour-On, Aspen Veterinary Resources Ltd., Greeley, CO) and weighed. Steers on IMP and BA treatments were re-implanted with the finishing implant. All steers were placed into a GrowSafe feeding system (GrowSafe Systems Ltd., Airdrie, AB Canada) to collect individual feed intake data. Steers were allowed an 18 d adaptation period to the feeders with data collection beginning on March 29 and continuing until harvest. Steers were allocated to be fed in four groups according to the treatment protocol. Individual BW was recorded on March 28 and 29 and the two day mean BW were used as initial BW for the GrowSafe feeding period. On April 26, steers were ultrasounded and Cattle Performance Enhancement Company (Oakley, KS) technology was used to predict the terminal harvest date for each treatment to achieve a common carcass compositional endpoint [~1.5 cm 12th rib backfat thickness (FT)]. The ultrasound software predicted two separate harvest dates. Steers from NT and IMP treatments were harvested on June 8 and steers from the ANT and BA treatments were harvested on June 27. Individual daily DMI data were collected from the GrowSafe system for 71 d for steers in the NT and IMP treatments, and for 90 d for steers in the ANT and BA treatments. On the day of harvest, steers were transported approximately 100 km to the packing plant. The final calculated body weight (FCBW) was determined as a hot carcass weight (HCW) divided by 0.635.

Three NT steers were removed from the study because they required an antibiotic for the treatment of respiratory disease and three steers died during finishing due to reasons unrelated to treatment; including one steer each from NT, ANT, and BA treatments (one case each of traumatic reticulopericarditis, euthanasia due to right-side congestive heart failure caused by pulmonary hypertension, and euthanasia due to respiratory disease including chronic pneumonia). A total of 114 steers were included in the analysis (NT = 26, ANT = 29, IMP = 30, and BA = 29).

Carcass Evaluation and Sample Collection

Carcasses were tracked individually through harvest. Following carcass chilling (approximately 24 h), trained SDSU personnel recorded the longissimus muscle (LM) area, FT, and kidney, pelvic, and heart fat (KPH) to calculate yield grade (YG). Marbling score and carcass maturity were also recorded. United States Department of Agriculture (USDA) assigned YG and quality grade (QG) were utilized for analysis of the proportion of carcasses within each USDA YG and QG category.

Life Cycle Assessment

To predict net carbon emissions, fossil energy use, water use, and total reactive nitrogen (N) loss, a process level simulation with life cycle assessment (LCA) was conducted for each production system. Nutrients inputs and outputs were estimated to predict the losses at each segment and potential net accumulation or depletion in the environment (Rotz et al., 2015). These losses included volatilization, nitrification, denitrification, leaching and runoff losses of N, erosion of sediment across farm boundaries, and the runoff of soluble and sediment bound P (Rotz et al., 2016).

Simulation modeling procedure. Each segment was simulated using typical production practices for the Northern Plains region based upon production information gathered for this study and supplemented with data reported by Asem-Hiablie et al. (2016) for this region. The Integrated Farm Systems Model (IFSM) is a software tool (USDA-ARS, 2016) used to assess the environmental impact of agricultural production systems including beef operations (Rotz et al., 2015). The IFSM simulates feed production and use, animal intake and performance, manure production and handling, and nutrient cycling through time to estimate average annual emissions of production systems at a given location (Stackhouse-Lawson et al., 2012). Each segment (cow-calf, backgrounding, and finishing) was simulated to quantify crop and pasture production, feed use, animal performance, and return of manure nutrients back to the land as described by Rotz et al. (2016).

To predict the environmental impact of each production system, information (major inputs needed for IFSM) was gathered from in-person interviews at each production segment where the cattle were raised using surveys developed by Rotz et al. (2016). The survey characterized soil and grazing conditions, animal and feeding information, and manure handling practices of each segment. Survey respondents were university-employed managers of each segment including cow-calf, backgrounding, and finishing.

The production system simulation also included emissions and resource use for the production of pre-chain resources. Pre-chain sources included emissions occurring during the production of purchased feed and energy. National emission factors were used for pre-chain energy sources (Rotz et al., 2013) and factors for purchased feed were obtained from IFSM simulations of crop farms (Rotz et al., 2015). Direct and pre-chain emissions and resource use were collectively totaled then divided by each production system's total 4% shrunk body weight (SBW) produced to quantify the impacts per unit of production (Rotz et al., 2015). Values based upon SBW were divided by the dressing percentage (DP; 63.5%) to determine the environmental footprint on an HCW basis.

Each segment was simulated over 25 years using actual daily weather data (1990 to 2014) collected at a station near the location of that segment. Weather data were: Dickinson, ND (cow-calf), Phillip, SD (backgrounding), and North Platte, NE (finishing). Hourly meteorological data were obtained from the National Climatic Data Center (NOAA, 2014) and processed into daily values needed for IFSM utilizing U.S. Environmental Protection Agency procedures (USEPA, 2004).

Equipment, transportation, and energy. Through simulation of field, feeding, and manure handling operations, machinery use and associated fuel consumption were determined for each segment. Equipment included tractors, mixer wagons, loaders, and trucks used for cattle feeding and management (Rotz et al., 2016). Energy use during transportation between segments was determined using an energy consumption factor of 1.22 kJ per km · kg BW, which produced a carbon emission of 0.088 g CO_2e per km · kg BW (Rotz et al., 2015). Simulated average annual fuel use was 33 L per cow, 7.7 L per feeder calf, and 3.7 L per feeder calf for the cow-calf, backgrounding, and feedlot segments, respectively. Simulated electricity use averaged 65 kWh per cow, 15 kWh per feeder calf, and 42 kWh per feeder calf for the cow-calf, backgrounding, and feedlot segments, respectively. These values were comparable with data previously reported for the Northern Plains Region (Asem-Hiablie et al., 2016).

Animal feeding and performance. Within the IFSM, animal diets for each segment were determined and feed intakes were predicted for all treatments. Diets were formulated to meet animal requirements for energy, protein, and minerals using functions from the Cornell Net Carbohydrate and Protein System, level 1 (Fox et al., 2004; Rotz et al., 2015). Allocation among feeds was set to approximately match the annual feed use reported for each segment to assure proper representation of feed consumption. Animal growth was set to meet the initial and final SBW measured for each segment. For the finishing segment, the animal performance was determined as the average daily gain (ADG) calculated between the initial and final SBW where the model decreased ADG 10% linearly each month until reaching the final SBW (Rotz et al., 2005, 2016). When a growth promoting implant was administered during any segment, the potential ADG was increased by 10% while the target final SBW was increased 5% (Rotz et al., 2005). Further, a fiber ingestive capacity (FIC) was adjusted monthly for treatment groups receiving growth promoting implants and ionophores (Rotz et al., 2005). The FIC was used to provide a limit of the potential fiber intake and was a function of total body capacity affected by leanness (Tess and Kolstad, 2000; Rotz et al., 2005). The FIC increased 10% during each implant administration, whereas the use of an ionophore decreased FIC by 3–6%. Because the BA treatment provided no HCW improvement over the IMP treatment, no further adjustments for BA supplementation were made as performance was proportionate to the initial and final SBW.

All production systems were managed similarly within each segment except for any deviations due to the use of growth promotant technology. The annual herd replacement rate was modeled as 20%, mortality was 3%, and the DP of cull cows was 55%. To predict the number of calves finished, a 2% twin rate, a 12% mortality rate, and a 2.5% annual post-weaning mortality rate were assumed during the cow-calf segment. Within the model, the IMP and BA calves were administered a pre-weaning implant and all calves were weaned at six months (number of months is the closest accuracy available) of age and transported (322 km) to the backgrounding segment. All manure was returned to pasture, which is typical for a rangeland-based Northern Plains cow-calf operation (Asem-Hiablie et al., 2016).

The backgrounding segment was simulated using a 4,000 head feedlot. For all treatments, the backgrounding segment lasted three months and steers were fed grain prior to being transported 438 km to the finishing segment. For both backgrounding and finishing, all of the manure was exported from the feedlot for other agricultural use.

The finishing segment was simulated using a 5,000 head feedlot. Animal feed intake and performance were simulated on a monthly time step, so cattle were fed for either five (NT and IMP) or six months (ANT and BA) to best capture the biological terminal endpoint goal of 1.5 cm FT. The simulation used each production system's actual initial feedlot SBW (270.0, 269.2, 280.1, and 274.8 kg for NT, ANT, IMP, and BA, respectively) and final SBW (518.7, 534.6, 585.6, and 587.5 kg for NT, ANT, IMP, and BA, respectively) to represent animal response and predict environmental impacts for each production system.

The environmental impacts were summed across the three segments and divided by HCW produced (finished cattle plus cull animals) to obtain the collective environmental impacts per production system. Environmental impacts included: net GHG emission (CO_2e per kg HCW), fossil energy use (MJ per kg HCW), non-precipitation water consumption (kg H_2O per kg HCW), and reactive N loss (N per kg HCW). Net GHG emission was the sum of all important direct and prechain sources of emission totaled in CO_2 equivalent units using global warming potentials of 28 kg CO_2e/kg of methane, 265 kg CO_2e/kg of nitrous oxide, and 1 kg CO_2e/kg CO_2 (Myhre et al., 2013). Fossil energy use included the total of all sources used on the operations plus that used to produce resources used to produce the cattle. Non-precipitation water use was primarily that used to irrigate feed crops with a small amount used as cattle drinking water. Reactive N loss was the sum of all nitrogen lost through ammonia volatilization, nitrate leaching and runoff, nitrous oxide emission, and NO_x emitted through denitrification and the combustion of fossil fuels (Rotz et al., 2016).

Statistical Analysis

Treatments were evaluated using PROC MIXED of SAS 9.4 (SAS Inc., Cary, N.C.) in three phases. A suckling-phase implant in the IMP and BA treatments was the only technology applied during phase 1. Because implants were applied to individual calves and the calves resided with their dams in one pasture-based herd, calves were considered the experimental units during this phase. Calf BW was analyzed using a completely randomized design with production system treatment, time of BW measurement (branding and weaning), and the treatment x time interaction as fixed effects in a factorial treatment structure. Time was considered a repeated measure and the variance-covariance matrix was chosen using the Schwarz's Bayesian Information Criteria goodness of fit statistic. Calf Julian's date of birth, birth BW, and cow age were included in the model as covariates. Calf BW was also analyzed substituting 205 d BW for actual weaning BW using the same experimental design and treatment structure. In this case, only cow age was used as a covariate. Calf ADG from branding to weaning was analyzed in a completely randomized design with treatment as the fixed effect and calf Julian's date of birth, birth BW, and dam age were included as covariates. Denominator degrees of freedom were approximated using the Kenward-Roger option for all analyses. During Phase 2, steers were pen-fed with three replicate pens of each treatment in a randomized complete block design with the pen as the experimental unit using the same statistical treatment structure as phase 1. In phase 2, times of BW measurement were initiation of the backgrounding period, implanting of IMP and BA steers, initiation of the finishing period, and end of the pen-feeding period. Measuring BW four times created three periods of ADG (initiation to implant, implant to finishing, finishing to end of Phase 2), so Phase 2 ADG was also analyzed using the previously described treatment × time factorial treatment structure. During Phase 3, because steers individually received their treatments using the GrowSafe® system, individuals were considered experimental units. Therefore, BW was analyzed using a completely randomized design with the previously described treatment x time factorial treatment structure. Times of BW measurement was initiation of the GrowSafe feeding period and FCBW. Average daily gain, DMI, and gain:feed (G:F) were analyzed with treatment as the only fixed effect. For all Phase 3 response variables, calf Julian's date of birth, birth BW, and dam age were included in the model as covariates.

Carcass (HCW, FT, LM area, KPH, YG, overall maturity, and marbling score) characteristics were evaluated in a completely randomized design with the steer as the experimental unit. In all cases, treatment was the only fixed effect. The influence of treatment on the proportion of carcasses assigned to each USDA YG and QG were analyzed using a binary distribution in PROC GLIMMIX of SAS. Treatment was tested as a fixed effect and the intercept was specified as a random effect. All statistical analyses used dam age as a covariate and the denominator degrees of freedom were approximated using the Kenward-Roger option in the model statement.

Least squares means and SEM were computed for all variables and separated using the least significant differences (PDIFF) when tests for fixed effects were significant at $P \le 0.05$. For all statistical models, a pre-planned contrast of non-implanted (NT + ANT) vs. implanted (IMP + BA) treatments were tested. Responses were considered significant at $P \le 0.05$, and tendencies were considered at $P > 0.05$ to $P \le 0.10$.

RESULTS

Animal Performance

Production system treatment influenced BW ($P < 0.05$) in all production phases (Table 2). During the pre-weaning phase (Phase 1) actual BW tended to display ($P = 0.07$) an implant treatment contrast, with suckling implanted calves heavier than non-implanted calves. Further, BW based on 205 d BW tended to display a treatment × time interaction ($P = 0.10$). In this case, calf BW at branding was similar among treatments, with BW greater ($P = 0.04$) for implanted calves at 205 d than non-implanted calves. During Phase 1 the implant contrast indicated implanted calves had greater ($P = 0.03$) ADG than non-implanted calves.

During the post-weaning pen-fed phase (backgrounding and initial finishing; Phase 2), the implant contrast indicated BW was greater ($P < 0.001$) in implanted (IMP and BA) steers, despite similar ($P = 0.23$) ADG across all treatments. During the GrowSafe feeding period (Phase 3) BW displayed a treatment × time

Table 2. Least squares means for production system influence on animal performance

	Treatment[*]						
	NT	ANT	IMP	BA	SEM	*P*-value[†]	*P*-value[‡]
				Phase 1[‖]			
Weaning BW, kg[$]	180.0	183.2	188.4	185.6	3.07	0.24	0.07
205 d BW, kg, Treatment × Time[¶]							
Branding	118.2	121.5	122.3	121.4	5.30	0.10[$$]	0.64
205 d	254.4^{y}	258.8^{yz}	268.9^{z}	264.9^{yz}			0.04
ADG, kg	1.039	1.048	1.093	1.089	0.0227	0.18	0.03
				Phase 2[‖]			
BW, kg	300.3^{a}	300.7^{a}	313.4^{b}	309.8^{b}	21.9	<0.001	<0.001
ADG, kg	1.039	0.939	1.070	1.057	0.0567	0.44	0.23
				Phase 3[‖,**]			
BW, kg, Treatment × Time[††]							
Initial[‡‡]	432.2^{a}	425.9^{a}	461.2^{b}	450.2^{b}	7.54	<0.001[$$]	<0.001
Final[‖‖]	541.5^{a}	556.4^{a}	610.8^{b}	610.7^{b}			<0.001
ADG, kg	1.534^{a}	1.459^{a}	2.104^{c}	1.783^{b}	0.0474	<0.001	<0.001
DMI, kg	11.53^{b}	10.83^{a}	12.88^{c}	12.57^{c}	0.230	<0.001	<0.001
Gain:Feed	0.1334^{a}	0.1348^{a}	0.1633^{b}	0.1427^{a}	0.00370	<0.001	<0.001

[*]NT = received no technology, ANT = administered antibiotics but no other technology, IMP = administered antibiotics and implants, BA = administered antibiotics, implants, and a beta-agonist.

[†]Probability of a greater F for test of the treatment fixed effect.

[‡]Probability of a greater F for the contrast of non-implanted (NT + ANT) vs. implanted (IMP + BA) treatments.

[‖]Phase 1 = suckling phase from initiation of experiment at branding to weaning, Phase 2 = postweaning growth and initiation of finishing wherein steers were pen-fed, Phase 3 = finishing to slaughter wherein steers were individually fed in a GrowSafe® feeding system.

[$]BW analysis based on actual weaning BW

[¶]BW analysis based on 205 d BW, which displayed a tendency for a treatment × time interaction.

[**]Days on feed during phase 3 were 154 d for NT and IMP, and 173 d for ANT and BA.

[††]BW analysis displayed a treatment × time interaction.

[‡‡]BW analysis based on 4% shrink applied to initial BW.

[‖‖]Final calculated body weight, determined as hot carcass weight divided by 0.635.

[$$]Probability of a greater F for test of treatment × time interaction.

[a,b,c]Least squares means within row with different superscripts differ ($P \leq 0.05$).

[y,z]Least squares means within row with different superscripts tend to differ ($P \leq 0.10$).

interaction ($P < 0.001$). Regardless of the interaction, the BW of all implanted steers was greater ($P < 0.001$) than all non-implanted steers at both initiation and end (FCBW) of the GrowSafe feeding period. The interaction appears to be the result of ANT having the numerically lightest initial BW, but the numerically second-lightest final BW in phase 3. During the GrowSafe phase ADG was greater ($P < 0.001$) for all implanted steers versus all non-implanted steers; additionally, ADG was greater ($P < 0.001$) for IMP steers than BA steers. Dry matter intake was least ($P < 0.03$) for ANT, intermediate for NT, and greatest for IMP and BA, while IMP and BA were similar ($P = 0.31$). Additionally, the implant contrast indicated all implanted steers consumed more DM ($P < 0.001$) than non-implanted steers. During the GrowSafe phase, feed conversion (G:F) was greater ($P < 0.001$) for all implanted steers versus all non-implanted steers based on the pre-planned contrast comparing NT and ANT to IMP and BA. Additionally, based on mean comparisons using LSD, G:F was improved ($P < 0.001$) for IMP compared to all other treatments, which were similar ($P > 0.07$).

Carcass Performance

Steers in the IMP and BA treatments had similar HCW ($P > 0.05$) but were heavier ($P < 0.001$) than NT and ANT, which were similar ($P > 0.05$; Table 3). Based on mean separations using LSD, the loin muscle area was largest ($P < 0.001$) for IMP, while ANT and BA were similar ($P > 0.05$) and BA was greater ($P < 0.001$) than NT, which was similar ($P > 0.05$) to ANT. As expected, no differences ($P = 0.35$) were observed between treatments for FT as steers were intentionally harvested at a similar FT endpoint. Percent KPH was greater ($P < 0.001$) for steers in the ANT treatment compared to NT, IMP, and BA which were similar ($P > 0.05$). Yield grade did not differ ($P > 0.05$) among treatments. Production system treatments influenced carcass maturity with each technology increasing ($P < 0.001$) maturity relative to the NT control. Among the technology treatments, IMP advanced maturity the least and BA advanced maturity the most with ANT intermediate. However, all treatments produced A maturity carcasses, thus these differences did not affect QG determination. Based on the preplanned contrast, IMP and BA were similar ($P = 0.48$) but had reduced ($P < 0.05$) marbling scores compared to NT and ANT, which were similar ($P = 0.76$). The implant contrast indicated that implanting altered ($P < 0.001$) all carcass response variables with the exception of FT and YG.

The proportion of carcasses in each USDA YG category did not differ ($P > 0.05$) among treatments (Table 3). However, the implant contrast indicated that the use of implants reduced ($P = 0.04$) the proportion of carcasses grading USDA Prime and increased ($P = 0.05$) the proportion grading in the lower third of USDA Choice. The proportion of carcasses classified in the upper two-thirds of USDA Choice grade did not differ ($P = 0.55$) due to the implant contrast. This resulted in a tendency for an increase ($P = 0.08$) in the proportion of implanted carcasses grading USDA Choice.

Environmental Impact of Production Systems

Results of the LCA (Table 4 and Figure 1) indicated that the use of the growth promoting technologies reduced GHG emissions relative to the NT control, with the greatest reduction in GHG emissions through the use of IMP. The treatments that received implants (IMP and BA) were predicted to have reductions in energy use compared with the non-implanted treatments (NT control and ANT), which did not differ appreciably. The IFSM predicted that ANT had little effect on water use and reactive N loss relative to the NT control, whereas the treatments that received implants (IMP and BA) displayed improvements in both water use and reactive N loss.

DISCUSSION

The objectives of this study were to evaluate production systems using additive combinations of growth promotant technology. Other studies have investigated conventional versus organic production systems (Fernandez and Woodward, 1999; Woodward and Fernandez, 1999), conventional versus cattle administered no antibiotics or hormones and fed no animal by-products (Cooprider et al., 2011), and conventional versus natural production systems (Maxwell et al., 2014). Stackhouse et al. (2012) and Maxwell et al. (2015) examined the differences between cattle administered no technology, implanted cattle, and implanted cattle fed zilpaterol hydrochloride (ZH). The current study utilized animals from a common herd with similar genetic background, and initiated treatments prior to weaning to compare NT, ANT, IMP, and BA production systems. The BA treatment in the present

Table 3. Least squares means for production system influence on carcass characteristics

	Treatment*						
	NT	ANT	IMP	BA	SEM	*P*-value†	*P*-value‡
Hot carcass weight, kg	343.1^{a}	353.7^{a}	387.4^{b}	388.6^{b}	6.64	<0.001	<0.001
12th rib backfat, cm	1.50	1.34	1.49	1.50	0.081	0.35	0.34
LM area, cm^2	81.9^{a}	83.9^{ab}	92.2^{c}	87.6^{b}	1.50	<0.001	<0.001
KPH, %	1.78^{a}	2.19^{b}	1.75^{a}	1.85^{a}	0.050	<0.001	<0.001
Yield grade	2.83	2.66	2.67	2.93	0.108	0.19	0.58
Carcass maturity‖	122.2^{a}	132.5^{c}	127.4^{b}	142.9^{d}	1.66	<0.001	<0.001
Marbling score$	553.9^{b}	561.6^{b}	486.5^{a}	503.7^{a}	18.1	0.004	<0.001
USDA yield grade¶							
Yield grade 2, %	27.3	44.3	53.0	26.9	9.63	0.14	0.70
Yield grade 3, %	65.0	51.9	36.8	58.7	9.63	0.21	0.27
Yield grade 4, %	6.4	3.2	6.0	12.3	6.35	0.60	0.38
USDA quality grade**							
Prime, %	17.0	16.5	6.2	3.0	7.59	0.25	0.04
Upper 2/3 choice, %	65.0	65.8	53.6	65.7	9.63	0.74	0.55
Lower 1/3 choice, %	15.4	16.4	35.7	30.3	9.17	0.24	0.05
All choice, %	82.3	83.1	90.3	96.8	7.70	0.35	0.08

*NT = received no technology, ANT = administered antibiotics but no other technology, IMP = administered antibiotics and implants, BA = administered antibiotics, implants, and a beta-agonist.

†Probability of a greater F for test of treatment fixed effect.

‡Probability of a greater F for contrast of non-implanted (NT + ANT) vs. implanted (IMP + BA) treatments.

‖Combined skeletal and lean maturity: 100 = A0; 200 = B0; 300 = C0.

$Marbling score: 400 = Small^0; 500 = Modest^0; 600 = Moderate^0.

¶GLIMMIX analysis failed to converge for USDA Yield Grade 1 (n = 1) or 5 (n = 0).

**GLIMMIX analysis failed to converge for USDA Select Quality Grade (n = 1).

a,b,c,d Least squares means within row with different superscripts differ ($P \leq 0.05$).

Table 4. Greenhouse gas emissions and natural resource use for production systems utilizing additive combinations of growth promotant technology per kg of final hot carcass weight

	Treatment*			
	NT	ANT	IMP	BA
GHG emissions,† $kgCO_2e$	18.1	17.9	16.7	17.0
Energy use, MJ	43.3	43.1	41.0	41.8
Water use,‡ L	2,997	2,966	2,824	2,866
Reactive N loss,‖ g N	136.0	137.0	129.0	135.0

*NT = received no technology, ANT = administered antibiotics but no other technology, IMP = administered antibiotics and implants, BA = administered antibiotics, implants, and a beta-agonist.

†Greenhouse Gas emissions including methane and nitrous oxide converted to CO_2 equivalents (CO_2e) using global warming potentials of 28 CO_2e/kg CH_4 and 265 CO_2e/kg N_2O.

‡Non-precipitation water use primarily includes water to irrigate feed crops and drinking water

‖Includes all forms of reactive N loss, including ammonia volatilization, nitrate leaching, and runoff, nitrous oxide and NOx from nitrification and denitrification processes and NOx from the combustion of fossil fuels.

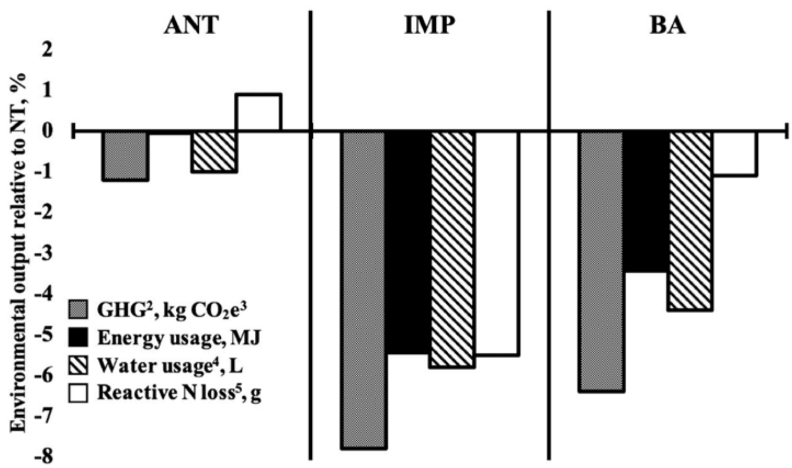

Figure 1. Influence of beef production system[1] on relative differences in sustainability outcomes expressed per kg of hot carcass weight. [1]NT = received no technology, ANT = administered antibiotics but no other technology, IMP = administered antibiotics and implants, BA = administered antibiotics, implants and a beta-agonist. [2]Greenhouse Gas emissions including methane and nitrous oxide converted to CO2 equivalents (CO2e) using global warming potentials of 28 CO2e/kg CH4 and 265 CO2e/kg N2O. [4]Non-precipitation water use primarily includes water to irrigate feed crops and drinking water. [5]Includes all forms of reactive N loss, including ammonia volatilization, nitrate leaching and runoff, nitrous oxide and NOx from nitrification and denitrification processes and NOx from combustion of fossil fuels.

study utilizes RH, which is the only beta-adrenergic agonist currently marketed in the United States. Further, to best represent commercial production, steers were finished to a common FT using predictive ultrasound.

Animal Performance

Steer BW and ADG were improved by administration of a zeranol implant during the pre-weaning phase (Phase 1), similar to other studies. The 205 d BW was improved by an average of 10.3 kg (4% improvement) in the implanted treatments. Bayliff et al. (2017) reported that administration of zeranol to suckling calves increased weaning BW by 8 kg (3.2% improvement). Further, the 6% improvement in ADG was similar to a meta-analysis conducted by Selk et al. (1997) indicating that suckling implants provide a 5–6% advantage in ADG. Improved BW of the implanted steers compared with non-implanted steers persisted in the backgrounding and initial finishing phase (Phase 2) and the GrowSafe feeding period (Phase 3). The FCBW of implanted steers averaged 62 kg (11.3%) heavier than non-implanted steers, while ADG increased by 0.43 kg per d (34%), DMI increased by 0.72 kg per day (14%), and G:F increased by 14%. Similarly, when compared with non-implanted cattle, Maxwell et al. (2014) reported a 0.42 kg per day increase in ADG of steers receiving a backgrounding implant followed by a terminal implant during feedlot finishing. Cooprider et al. (2011) reported a 0.46 kg per day (34%) increase in the ADG of cattle receiving monensin, tylosin, and implants on d 1 and 70 of the finishing phase compared to cattle administered no antibiotics or hormones and fed no animal byproducts, along with a significant improvement in G:F and tendency for increased final BW. Additionally, Maxwell et al. (2015) reported a 52 kg (9.6%) increase in final BW, a 0.39 kg per day (33%) improvement in ADG, and a 27% improvement in G:F of steers receiving a terminal implant containing 40 mg of estradiol and 200 mg of trenbolone acetate, monensin, and tylosin compared with cattle administered no antibiotics or growth implants. However, no difference in DMI was reported by Maxwell et al. (2015).

The inclusion of monensin and tylosin did not induce an appreciable increase in performance in this study with the exception of DMI, which was lowest for ANT. Steers in the ANT treatment had a reduction in DMI of 6%; similar to the 6.4% reduction reported by Goodrich et al. (1984) in a summary of performance data of nearly 16,000 cattle. The reduction in DMI following supplementation with monensin or the combination of monensin and tylosin has been reported by others (Russel and Strobel, 1989; Galyean et al., 1992; Stock et al., 1995; Meyer et al., 2009). However, the influence of these technologies on ADG and G:F varies in the literature. Stock et al. (1995) reported increases in ADG and feed efficiency with supplementation of monensin and tylosin, while Meyer et al. (2009) reported that supplementation of monensin and tylosin improved G:F compared with a non-supplemented control with no change in ADG. Similar to the present study, Depenbusch et al. (2008) and Galyean et al. (1992) did not observe significant differences in ADG or G:F with the inclusion of these technologies.

Supplementation of RH did not improve the feedlot performance of cattle in the BA treatment compared to IMP. This may be related to the dose of RH provided (200 mg per animal daily). Lean et al. (2014) conducted a meta-analysis that included an investigation of the effects of RH on feedlot performance. Their analysis revealed improvements in BW and ADG of 8 kg and 0.19 kg per day, respectively, in cattle supplemented with RH compared with non-supplemented controls. However, Johnson et al. (2013) suggested that performance responses to inclusion of RH during the last 20 to 42 days of the finishing period are variable. Similar to the present study, Quinn et al. (2008) reported no difference in final BW or DMI in heifers supplemented with 200 mg per animal per day compared with a non-supplemented control. Similarly, Strydom et al. (2009) showed no difference in final BW or DMI between RH supplementation and a non-supplemented control. Both of these studies reported that RH improved ADG compared to controls. In the present study, ADG was decreased in the present study compared with IMP but was improved compared with NT and ANT. Boler et al. (2012) suggested that successive implantation maximizes growth potential and reduces the opportunity for improvement in growth efficiency from RH supplementation. This suggestion could partially explain the lack of improvement in the performance of BA compared with IMP in the current study.

Carcass Performance

The HCW of implanted steers (IMP and BA) averaged 39.6 kg (11.4%) heavier than non-implanted steers (NT and ANT). Further, the LM area of implanted steers was 6 cm^2 larger and KPH was decreased by 0.19% compared with non-implanted steers. A study comparing steers receiving successive feedyard implants [80 mg trenbolone acetate and 16 mg estradiol-17ß (Revalor-IS) followed 56 d later with 120 mg trenbolone acetate and 24 mg estradiol-17ß (Revalor-S)] to non-implanted controls reported similar improvements in HCW (41 kg) and LM area (7.8 cm^2) of implanted steers (Bryant et al., 2010). Bryant et al. (2010) also reported a similar reduction in KPH (0.17%) to the present study. Further, Maxwell et al. (2015) indicated the inclusion of a terminal implant, monensin, and tylosin improved HCW by 38 kg (10.9%) and LM area by 8.51 cm^2 (10.6%). As steers were harvested at a similar FT endpoint, FT did not differ among treatments in the present study. Because cattle are typically harvested in the United States cattle industry based on FT as a compositional endpoint, this study aligns with current commercial production practices. It is not surprising that YG and the proportion of carcasses within each YG category did not differ between implanted steers and non-implanted steers given the antagonistic relationship of LM area with HCW and KPH within the YG equation.

A reduction in marbling score observed for implanted steers in the present study aligns with other reports indicating that successive use of implants reduces intramuscular fat content (Duckett and Andrae, 2001; Platter et al., 2003; Scheffler et al., 2003; Duckett and Pratt, 2014). It has been suggested that implanting alters the amount of marbling through a dilution effect due to increased LM area (Duckett et al., 1999), which appears to align with the results of this study. Successive implantation has also been reported to linearly increase overall maturity (Duckett et al., 1996; Platter et al., 2003). Carcass maturity scores in this study likely also reflected harvest dates as NT and IMP were harvested 19 days earlier than ANT and BA. Regardless, all carcasses were well within the A-maturity range; therefore statistical differences in carcass maturity did not influence QG determination. The proportion of carcasses in each USDA QG category reflect their respective marbling scores with 12% more non-implanted steer carcasses assigned to the USDA Prime grade and 17% more implanted steer carcasses assigned to the lower third of USDA Choice.

The addition of monensin and tylosin did not alter carcass characteristics beyond that of the NT treatment, with the exception of KPH. Limited information exists regarding the influence of monensin and tylosin on KPH, however, the increase in KPH of steers in the ANT treatment compared to NT may be due to increased days on feed, not a direct result of these supplements. Increasing days on feed has been shown to increase KPH (Hunter-Beasley et al., 2018).

Supplementation with RH did not improve the HCW or LM area of the BA treatment compared to IMP but resulted in advanced carcass maturity. Others have reported no difference in HCW (Quinn et al., 2008; Strydom et al., 2009; Hales et al., 2016; Hunter-Beasley, et al., 2018; Trotta et al., 2019) or LM area (Walker et al., 2006; Quinn et al., 2008; Strydom et al., 2009; Hales et al., 2016; Hunter-Beasley, et al., 2018) of RH supplemented cattle compared with non-supplemented controls. However, it is unclear why the LM area of BA was 4.6 cm^2 smaller than IMP in the present study. The advanced carcass maturity of RH supplemented (BA) compared with IMP is in contrast to other reports that carcass maturity is not influenced by RH supplementation (Scramlin et al., 2010; Woerner et al., 2011). However, this difference is likely due to the additional days on feed experienced by the BA treatment compared with IMP.

Environmental Impact of Production Systems

Greenhouse gas emissions. Production systems utilizing growth promoting technology have been shown to result in increased sustainability as measured through the marginal return of production (HCW) over GHG emissions. To evaluate the beef supply chain in the Southern Plains, Rotz et al. (2015) evaluated GHG emissions on an HCW basis among 28 beef production systems in Kansas, Oklahoma, and Texas and reported that carbon footprints ranged from 13.8 to 25.8 kg CO_2e per kg HCW across production systems in this region (Rotz et al., 2015). Results of the present study are within this reported range. Stackhouse et al. (2012) also utilized the IFSM to simulate the environmental impacts of producing cattle in California. Use of an ionophore, tylosin, and successive implants with and without ZH decreased the C footprint by 7% and 9%, respectively, compared with a production system utilizing no growth promotant technology (Stackhouse et al., 2012). In the current study, the successive use of implants (IMP) resulted in a similar reduction (7.8%) in C footprint. However, the addition of RH only produced a 6.4% reduction in GHG relative to NT, which was due to increased time on feed with lack of growth response relative to IMP in this study.

Energy use. Based on IFSM modeling of historical production systems of the US Meat Animal Research Center in Clay Center, NE, Rotz et al. (2013) encouraged the use of new technology interventions to reduce life cycle energy use in cattle production. Energy utilization in this study determined through LCA was within the range (26 to 83 MJ per kg HCW) for production systems reported by Rotz et al. (2015) for cattle production in the Southern Plains. In the current study, the IFSM results indicated that ANT did not influence life cycle energy use relative to the NT control. The successive use of implants resulted in the greatest predicted reduction in energy use, while BA was 2% less effective in this study than IMP at reducing energy use; again, due to the added days on feed necessary for BA to reach the compositional FT endpoint relative to IMP.

Water use. The IMP and BA treatments were predicted to reduce life cycle, non-precipitation water use for beef cattle production by 5.5% and 4.4%, respectively, compared with the NT control. The successive use of implants resulted in the greatest predicted reduction in water use in this study, while BA was 1% less effective than IMP at reducing water use. Across all treatments, the current study used a greater volume of water (2,913 L per kg HCW) in comparison to Rotz et al. (2015; 2,180 L per kg HCW) due to differences in feeding duration and use of irrigated feed production. In the current study, steers were fed for five or six months compared with a four or five month feeding period in the largest feedyard operations evaluated by Rotz et al. (2015). Additionally, Rotz et al. (2015) utilized larger feedyard operations (10,000 - 180,000 head) that had access to some cropland for corn grain and silage production. The feedlot phase of the current study relied on purchased, irrigated feedstuffs that required considerable amounts of water to produce.

Reactive N loss. Reactive N loss values were within the range (75 to 222 kg N per kg HCW) reported for cattle production systems by Rotz et al. (2015). The IMP and BA treatments were predicted to reduce N loss for beef production by 5.5% and 1.1%, respectively, compared with the NT control. Similarly, Stackhouse et al. (2012) reported that the use of technologies (ionophore, tylosin, and implants with and without supplementation of ZH) decreased ammonia emissions by 6% (14 g per kg HCW) in comparison with a production system not utilizing growth promotant technologies. The use of anabolic steroids (implants) can improve N retention because they affect metabolic anabolism and catabolism causing protein accretion while decreasing or causing no change in protein degradation (Hayden, et al., 1992; Lone, 1997). Given the added days on feed and limited improvements in animal or carcass performance in this study, reactive N loss was increased only about 1% in the ANT treatment relative to the NT control.

IMPLICATIONS

These data support our hypothesis that the use of growth promoting technologies can effectively improve the production of beef to meet growing global food demand while simultaneously reducing predicted net natural resource use (water, energy) and environmental pollutants (GHG, reactive N loss). These responses in the improvement of beef yield and sustainability were consistent across life cycle animal production and carcass performance. Of the growth promotant technologies evaluated in this study, hormone-based growth promoting implants yielded the greatest improvement in live animal and carcass performance while reducing net GHG emissions and natural resource utilization. The use of antibiotics and a beta-agonist (RH) demonstrated small and inconsistent impacts in this study. The use of implants reduced marbling and USDA QG. Producers will need to balance the use of technologies with their management goals for production, yield, carcass quality, and environmental impacts. Further, consumer acceptance and demand for beef from cattle receiving implants and other growth promoting technologies will be influenced by a balance of their willingness to accept the meat yield and sustainability improvements demonstrated herein with their desire to avoid exogenous hormones in meat and reduced meat quality. Further research is needed to understand consumer acceptance of beef products raised with growth promoting technologies in light of these contrasting desires and expectations.

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